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Simulation of a Pumped Stormwater System and Evaluation of the Solar Potential for Pumping

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Abstract
Renewable energy investments are increasing in countries that want to reduce their dependence on foreign energy and prevent damage to nature. As the request for green vitality generation is emerging, specialists over the globe have been attempting to generate power with better approaches. Rainwater harvesting can also be a non-conventional energy source, just like wind and solar energy. Generating energy, even on a small scale, can reduce environmentally harmful and costly methods of energy production. Various endeavours have been made so far to generate electricity using rain, one of the world's most abundant resources; however, this may be one of the most compelling studies. The goal of this study is to provide electricity from rainwater in areas with a lot of rainfall but minimal electricity. In terms of power generated, raindrops will never be able to compete with a hydroelectric power station. However, they have one significant advantage – they are free. With the increasing energy prices and developing new technology, the commercial use of rain energy does not seem far away. Energy generated from solar cells and a pump power-stormwater system reduced variable electricity costs by $ 572. In the energy storage dimension represented by a pumped stormwater reservoir in the study, the economic benefit potential is very low. Minimizing operating costs, maximizing storage capacity and efficiencies, as well as filling and unloading times of approximately one hour are recommended.

Keywords
Renewable energy; Stormwater; Pump-hydro; Solar PV; Energy storage; Optimization

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1 Introduction

In order to reduce global warming and respond to rising energy costs, the energy supply must shift from relying heavily on fossil energy sources to more renewable and sustainable energy sources[1,2]. According to research on energy supply, despite the increasing number of electric vehicles, it is possible to meet the electricity supply in Turkey from renewable resources[3,4]. Renewable energy sources with their intermittent nature are potentially problematic in terms of operational reliability, risk of power outages, transmission bottlenecks, and frequency and voltage stability in the power grid[5].

There is also a revolution in small-scale energy solutions that can create opportunities which lead to more robust energy supplies and reduce environmental impact[1,6]. Solar energy and other renewable energy that can be used to generate electricity for people's own consumption are overgrowing. This opens up enormous possibilities for energy independence.

Since electricity price in the market depends on supply and demand, higher intermittent electricity supply in Turkey also causes fluctuations in electricity price. Figure 1 shows the evolution of the average electricity price and the standard deviation of electricity prices each year in the field of electricity price between 2018 and 2023. Electricity prices are taken from Market Clearing Price in Energy Exchange Istanbul (EXIST)[7]. Market Clearing Price is the hourly energy price that is determined with respect to others that are cleared according to total supply and demand.

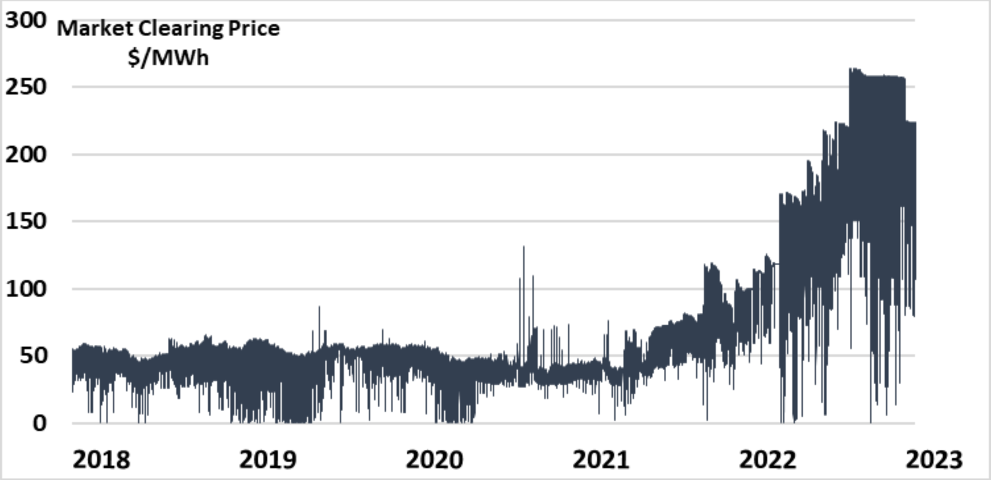


Figure 1. Hourly electricity prices.

Technologies and control tools of varying degrees of innovation such as smart electricity grids, flywheels, electricity tariffs, energy storage, the Internet of things, pumped power plants, and battery storage are all possible ways to stabilize the electricity grid's fluctuations[8]. Storage technology has the potential to store unused energy and then use it when energy is needed[9]. Storing water in pump-type or reservoir-type hydroelectric power plants means storing energy.

The lifetime of a pumped power plant is approximately 70 years[10], and it is seen as a more viable infrastructure investment than batteries, whose lifespan is generally accepted as 20 years. As energy storage, it is estimated that the pump-type hydropower plant emits half as much carbon dioxide (CO_2) as the battery storage of the same size, and its profitability is up to 18 times more profitable[11].

One way to generate electricity from water is to use pump technology as a turbine[12-14], where a pump will act as a turbine by reversing the flow direction so that it can generate electricity without any change in casing design or pump geometry. The same electric motor that rotates the pump shaft and pushes the water to a higher height can be used as a generator in the upstream direction. Compared to traditional pump power systems turbines, generators, and pumps are covered by a single pump. As a turbine, the pump can use its hydropower potential in a highly efficient and economical with uncomplicated technical approaches. Thanks to its low investment cost, it can have a very short payback period.

For small renewable electricity producers, there is often a price differential between the electricity sold and purchased[15]. Therefore, small producers' investment in solar cell systems is increasing day by day, as most of the financial benefit is not having to buy electricity. One way to make personal use profitable is to store the excess energy produced for later use. It is thus replacing the revenue from the sale of electricity with the savings from not having to buy electricity later.

New photovoltaic (PV) technology is being developed to exploit the large surface area. The number of PV patent applications fell between 2012 and 2016, but the number of multifunctional PV applications jumped, accounting for 29% of the total applications (see Figure 2)[16].

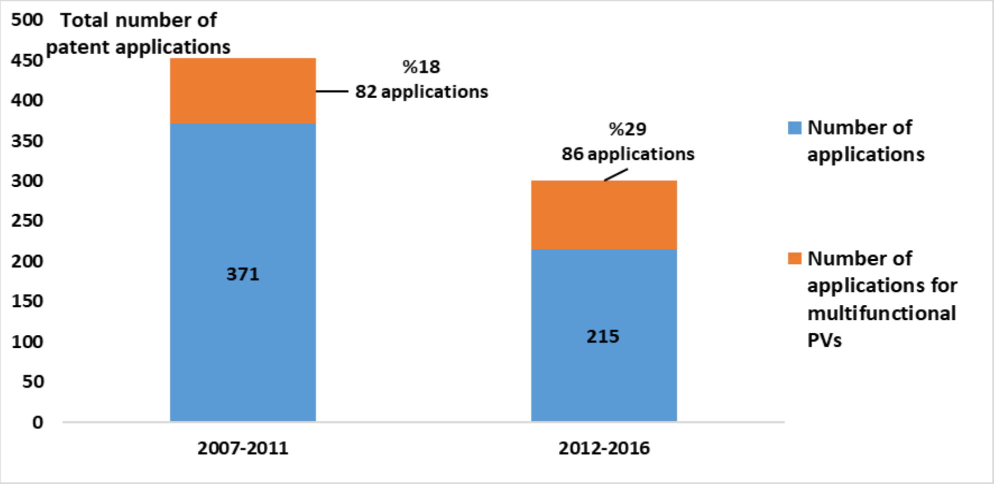


Figure 2. Number of the patent application for PV applications

Efficiency, legal regulations, and environmental effects are the determining factors in PV plant location selection. Decisions about the shape, colour, and composition of the roof and walls of a building are crucial because they determine its overall generation performance. In the energy consumption of the pump, which is used to generate energy from rainwater, the electricity requirement will be met by the solar energy system. Thanks to the electricity produced by the installed solar energy system, the water is transferred from the lower reservoir to the upper reservoir. With this system, rural residents can meet their pump energy needs at zero cost, and they are also saved from common electricity bills.

There are several ways to generate energy from rainwater, some of them are in use today, but most are still in the experimental or prototype stage[17-19]. Here are a few examples.

Hydroelectric power: Stormwater can be collected in reservoirs or dams and then released through turbines to generate electricity. This is similar to how traditional hydroelectric power plants work, but on a smaller scale. This is the most common method of generating electricity from stormwater. It involves using the energy of falling water to turn a turbine, which generates electricity.

Stormwater harvesting: Stormwater can be collected on rooftops or other surfaces and then stored in tanks or cisterns for later use. This water can be used for irrigation, flushing toilets, or even to generate electricity through a process called "micro-hydropower." This method involves collecting and storing stormwater in a tank or reservoir and then using it to generate electricity through hydroelectric power or other means.

Stormwater-powered fuel cells: Some researchers are working on developing fuel cells that can generate electricity using stormwater as a source of hydrogen. These fuel cells could potentially be used in remote or off-grid locations where access to traditional sources of electricity is limited.

It is important to note that generating energy from stormwater is not currently a widespread or mainstream technology, and further research and development are needed before it becomes more widespread. Overall, generating electricity from stormwater is a sustainable and renewable energy source that can help reduce reliance on fossil fuels and decrease carbon emissions.

Focus of this study: In this study, solar cells were placed on the roofs of some houses within the framework of micro-generating in order to reduce their environmental impact and electricity costs for pumping. It is aimed to construct a stormwater reservoir to manage the flow of stormwater generated when it rains on an area of approximately 20 hectares. Since the selected area is located approximately 25 m above a nearby waterway, it has the potential to contribute to a sustainable energy supply and lower electricity costs. Thus, if placed at a high enough altitude, a stormwater reservoir that treats stormwater in a residential area can be used as an overhead reservoir in a pumped power plant and thus act as an energy store. Also, the interoperability of the small-scale solar power plant with the pump-powered energy storage system is one of the innovative fields of study[20]. In addition, the pumped stormwater system for energy storage, and the ability to receive energy reinforcement from the stormwater when it rains in the drainage area of the stormwater pool is another innovative aspect of the study.

The aim of the study is to evaluate the feasibility of energy storage potential in the form of small-scale pumped reservoir power plants in different usage areas of stormwater reservoirs. In addition, it is to lead a more sustainable society by evaluating a potential energy storage system. Also, this study investigated the use of solar energy and the economic benefit of a solar cell system for micro-generating when implementing pumped stormwater systems.

2 Pump-Type Hydropower Plant Technology

The method of generating energy from high-altitude water is essentially the same as using hydropower when it dams the water to generate electricity via a turbine and generator[21]. The difference is that in pump-storage plants, not only is the water discharged when electricity is needed but it is also pumped back into the reservoir when there is a surplus of energy or cheap electricity prices. Storing water in a reservoir means storing energy. Water stored at a relatively higher altitude has potential energy. When water is released from a height, this energy turns into kinetic energy. There are two ways to operate the facility; storing excess energy for later use, or alternatively buying and selling electricity where it is cheap and expensive respectively. When there is a surplus of usable energy, it is to be able to store the energy until a time when it becomes more advantageous to use it. It can be profitable to store excess energy and use it later. Thus, instead of first selling electricity from the grid and repurchasing it, the system can pump water with excess electricity and then generate potentially cheaper electricity despite conversion losses during energy storage. In general, turbines and generators in pump-type hydropower plants are large and costly. Also, a water pump is needed to pump water into a reservoir for energy storage. Its main disadvantage is the high investment cost. In the business model for pumped storage facilities, high reliability is compensated by efficiency and low service requirements[22,23]. An unconventional way to generate electricity from water is to use a pump as a turbine[24-26]. A pump can act as a turbine by reversing the flow direction, thereby generating electricity without changing the casing design or pump operation.

2.1 Operating Strategy for Pump Hydro-Based Energy Storage

The algorithm for the optimal operating strategy iteratively processes one or more years of electricity prices to determine which hours the energy storage should be filled and emptied respectively to achieve maximum profitability. The optimal operating strategy algorithm is summarized in the following six steps that are repeated for hours in a selected time slot.

Step 1:

Determine the maximum electricity price hours. These hours are prioritized as hours for production operation. In subsequent iterations, hours that are already defined as high-price hours will be ignored and the next maximum electricity price will be determined.

Step 2:

In this step, the previous hours should be examined to determine the earliest hour before the high electricity price at which the pump can be operated and the latest hour after this time. The created interval is the time interval during which it is possible to empty and fill the reservoir. This time interval is defined in the following two basic steps.

a. Before the hour when the electricity price is high

If the pump is to be started before the hour when the electricity price is high, there must be space in the reservoir to store the energy for use during the hours when the electricity price is high. If the reservoir is full, the pump cannot be started, so the earliest hour before the price at which the pump can be started is high, which is the hour after the last tank is filled.

b. After the hour when the electricity price is high

If the pump is to be started after the high price hour, there must be energy in the reservoir for the turbine to operate during the high price hour. If the reservoir is empty, no water is leaving for the turbine to use at the high price hour.

Step 3:

Determine the hour when the electricity price is lowest. These hours are given priority as pump operating hours. In the next iterations, the hours determined as the lowest hour are not taken into account and the next lowest electricity price is determined.

Step 4:

Calculate the marginal operating cost using the following Equation 1, based on the lowest electricity price from step 3.

$$OMC_{ph} = OMC_t + \left(\frac{P_{el} + OMC_p}{\eta_t . \eta_p}\right) \tag{1}$$

where

OMC_{ph} - Total operating and management cost of pumped hydropower plant (*$/kWh*);

OMC_t - operating and management cost in turbine operation (*$/kWh*);

P_{el} - electricity price for pump operation (*$/kWh*);

OMC_p - operating and management cost in pump operation (*$/kWh*);

η_t - efficiency of the turbine (%);

η_p - efficiency of the pump (%).

Step 5:

Determine the operational situation except when the electricity price is lowest and highest. If the pump operating hours are equal to the same turbine operating hours, no operational problems will occur. Otherwise, the pump or turbine will have to be run at reduced capacity to compensate.

Step 6:

Run the turbine at hours of maximum electricity price and pump at hours of minimum electricity price at the capacities determined in step 5 and update the level of the water reservoir.

For initial power calculation, the first step is to calculate the rainwater flow rate based on the area and rainfall intensity. The volumetric flow of water entering the pipe is determined by the following Equation 2.

$$Q = I{\cdot}A \tag{2}$$

where

Q - water flow rate in $m^3\ s^{-1}$;

I - rainfall intensity $l\ s^{-1}$;

A - the adjusted area in m^2.

2.2 The Potential Energy in Energy Storage

The power generated from hydraulic turbines is a function of the flow rate, the efficiency of the turbine, and the available net head. It can be estimated by Equation 3[27]:

$$P = Q{\cdot}H{\cdot}g{\cdot}\eta{\cdot}\rho \tag{3}$$

where

P - hydropower generation capacity of the plant in kW;

Q - water discharge in $m^3\ s^{-1}$;

H - net head of water in meter;

g - gravity acceleration constant ($9.81\ m\ s^{-2}$);

η - total efficiency (%);

ρ - density ($kg\ m^{-3}$)

As for the dimensioning of the stormwater reservoir, the time-area method can be used to control and calculate dimensioning flows according to the following Equation 4.

$$Q_{strm}=A{\cdot}\varphi{\cdot}i(t){\cdot}cf \tag{4}$$

where
Q_{strm} - dimensioning stormwater flows ($l\ s^{-1}$);
A - the catchment area (m^2);
φ - the combined runoff coefficient;
i - the rain intensity ($l/s \cdot ha$);
t – the duration of the rain;
cf – the climate factors.

Stormwater reservoirs are dimensioned according to the following parameters.

i. Different flow factors are taken into account on the surface where the stormwater will be collected. (Roofs, asphalt, concrete, gravel, lawns, and rain gardens)
ii. Climate factors should be taken into account. The feasibility study area may be subject to more variable weather conditions in the future.
iii. Duration is the amount of time the rain intensity is expected to last at its maximum.
iv. The amount of stormwater flow collected into the reservoir is an important factor. When multiplied by the climate factor and rainfall duration, it gives the volume of stormwater in the reservoir.
v. Because evaporation is very small, it was neglected in this study in the context of stormwater storage.

3 Method

3.1 Dimensioning the Stormwater Reservoir

The stormwater calculation is made according to the precipitation coefficients according to the provinces and the amount of rainwater falling on the roof surface area. It depends on how large the stormwater reservoir (energy storage) actually needs to be for the results of the simulations to be realistic. The climate factor for Kirsehir city is 25%, the rain intensity is 386 $l\ s^{-1}$ Ha, and the maximum outflow is assumed to be 10 $l\ s^{-1}$. The calculation method used in this study is based on those presented in the theory section and uses the flow factors presented in Table 1.

Table 1. Dimensioning streams by optimized area.

Surface	Area [m^2]	Runoff Coefficient	Reduced Area [m^2]	Q_{strm} [$l\ s^{-1}$]
Roof	40.000	0.9	36.000	1,389.6
Asphalt	80.000	0.8	64.000	2,470.4
Sand-Grass	40.000	0.2-0.1	6.000	231.6
Pavement	40.000	0.7	28.000	1,080.8
Total	200.000		134.000	5,172.4

Pump technology as a turbine is the technology used in the simulation. It is assumed that the efficiency of the turbine and pump is 85% each, and that the flow rate in turbine operation is 25% higher than in pump operation. In turbine operation and pump operation, efficiencies of 85% are used as system efficiencies. Assuming pump-like conditions with effective reservoir storage capacity and a turbine as a turbine for simulation models, one pump and turbine can be designed for a 6-hour fill and discharge time. For this reason, it is assumed that a pump is dimensioned for a filling time of six hours. One-sixth of the capacity of the energy tank should be able to be emptied in an hour. Thus, the turbine drive power is approximately 9.76 kW and the pump power is 7.80 kW.

All data and statistics used in this study are per hour and are taken from electricity spot prices[7]. Solar panels are used to pump powerful stormwater, which will be defined as financial benefits or savings in this study. In this study, a fixed purchase price of $ 0.12/kWh and spot prices for excess solar energy sales are used.

Figure 3 shows the main flows of the system. Using gutters on the roof, rainwater can be accumulated from the rooftop to a water reservoir. The stormwater reservoir is referred to as the upper reservoir to emphasize the system function. The upper reservoir is the energy reservoir, while the lower reservoir consists of a nearby waterway (river). Here, water can be collected and released while the pump or turbine is running. Assumptions for the simulation model are summarized in Figure 4.

The optimization algorithm simulates using the model function for approximate values representing the realities. A random sunny day data in its simulation is shown in Figure 5.

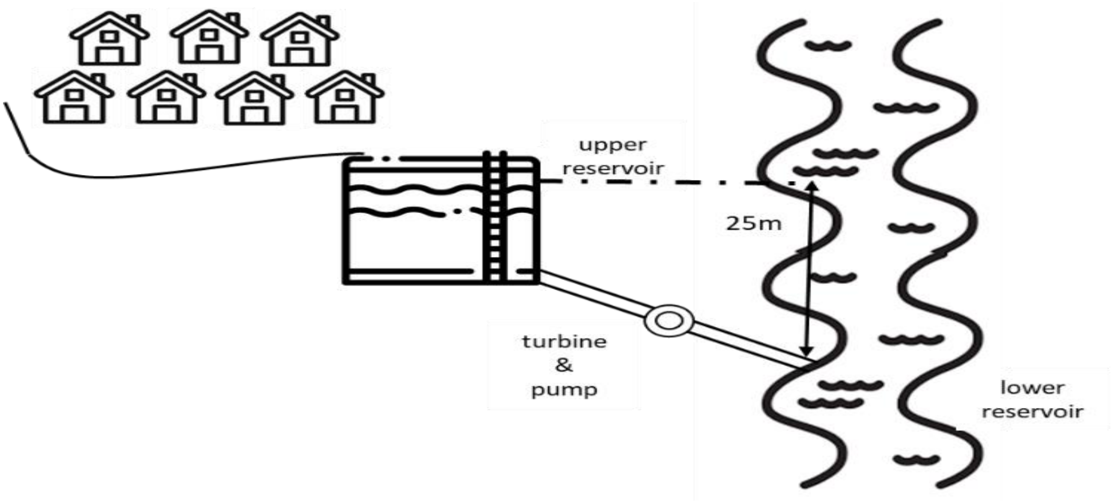
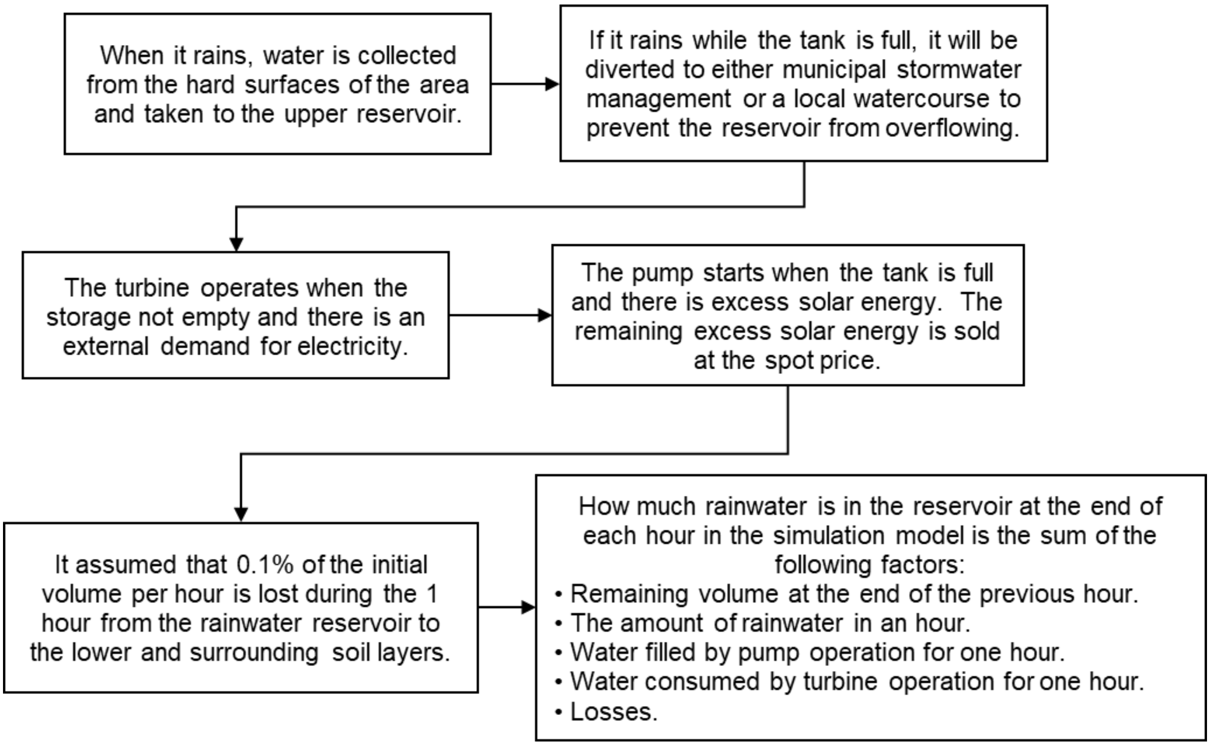


Figure 3. The operating conditions of the simulation.



When it rains, water is collected from the hard surfaces of the area and taken to the upper reservoir.

If it rains while the tank is full, it will be diverted to either municipal stormwater management or a local watercourse to prevent the reservoir from overflowing.

The turbine operates when the storage not empty and there is an external demand for electricity.

The pump starts when the tank is full and there is excess solar energy. The remaining excess solar energy is sold at the spot price.

It assumed that 0.1% of the initial volume per hour is lost during the 1 hour from the rainwater reservoir to the lower and surrounding soil layers.

How much rainwater is in the reservoir at the end of each hour in the simulation model is the sum of the following factors:
- Remaining volume at the end of the previous hour.
- The amount of rainwater in an hour.
- Water filled by pump operation for one hour.
- Water consumed by turbine operation for one hour.
- Losses.

Figure 4. Assumptions for the simulation model.

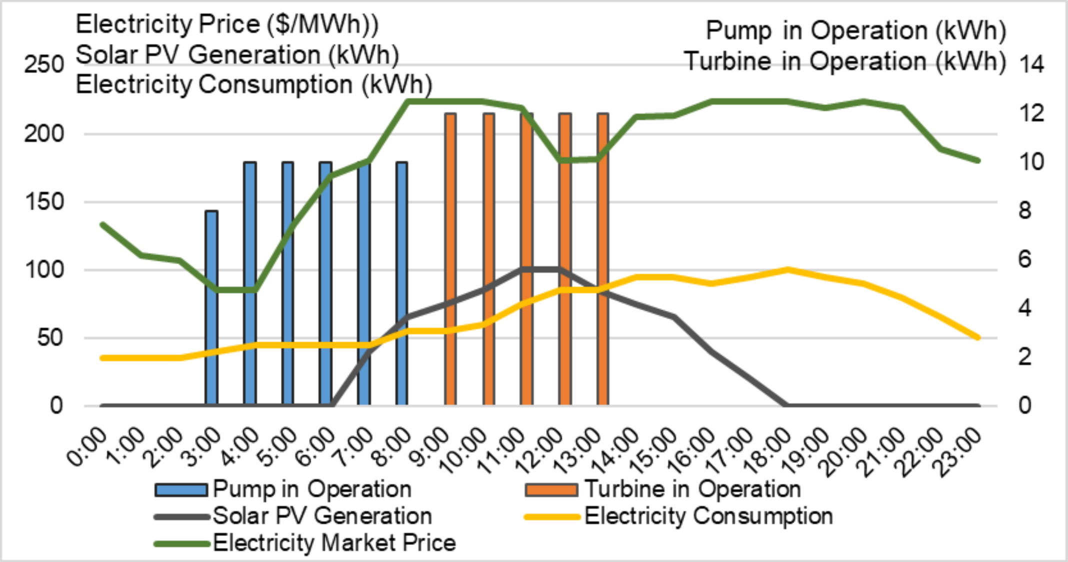


Figure 5. Results of the optimization model.

The price of electricity must be high during operation in turbine mode, the demand and price for electricity are high when the sun starts to set, and people come home in the afternoon. In the hours before and after 12 o'clock when the sun is at its highest, it can be operated in turbine mode, unused energy is sold to the spot market. Well-chosen turbine operating hours have the potential to benefit the electricity grid by generating during times when bottlenecks may occur. This, in turn, may lead to increased efficiency in water storage as a precaution against increased social benefits and fluctuating rations in the electricity market (intermittent nature of renewable energy sources).

Hourly precipitation data were obtained from the Kaman meteorological station (Latitude: 39° 21' 27.00" N Longitude: 33° 43' 26.00" E) and downloaded from the article[28]. The total hourly precipitation per square meter is multiplied by the reduced area to be drained and included in the model. The maximum hourly precipitation measured in 2014 for the 20-ha area is 7.72 $m^3 s^{-1}$, corresponding to 1.9 kWh in potential energy. In the calculations, the average temperature of the area is 11 °C, the density is 999.7 kg m^{-3}, the gravitational acceleration is 9.81 m s^{-2}, and the height is 25 m.

The role of stormwater supplementation as an energy source, 72-hour results are shown in Figure 6. This range is presented as it clarifies a rainy period for the first 25 hours followed by a sunny period. As seen in Figure 6, the addition of rainwater causes turbine operation.

3.2 Simulation Model

A mathematical simulation method has been established to evaluate the pumping power-stormwater reservoir system in the electricity market. The simulation is performed in the MATLAB calculation program and is based on an iterative algorithm on the most profitable operating strategy for the pumped hydroelectric power plant. This simulation assumes that the electricity purchase and selling prices follow the electricity spot prices. The results should be interpreted according to these data, and it is the evaluation for energy storage that corresponds to the reservoir capacity and discharge or fills time scenario in the electricity market.

The results of the simulation model are shown in Figure 7 (pump and turbine operation in parallel with electricity price changes) and reservoir level (energy storage). Electricity market prices are seen in the simulation model of high and low events.

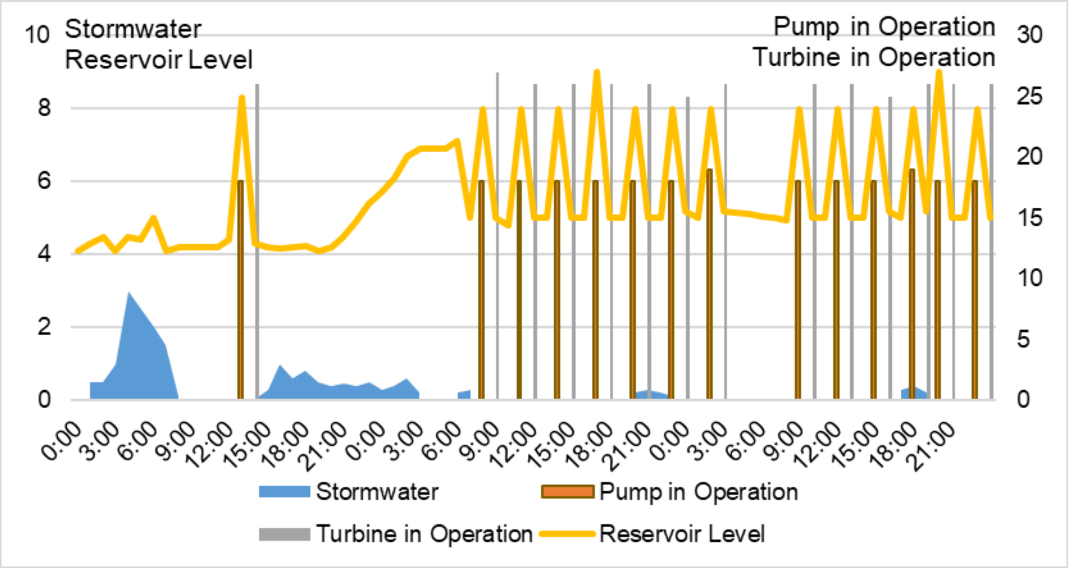


Figure 6. Energy generation from stormwater.

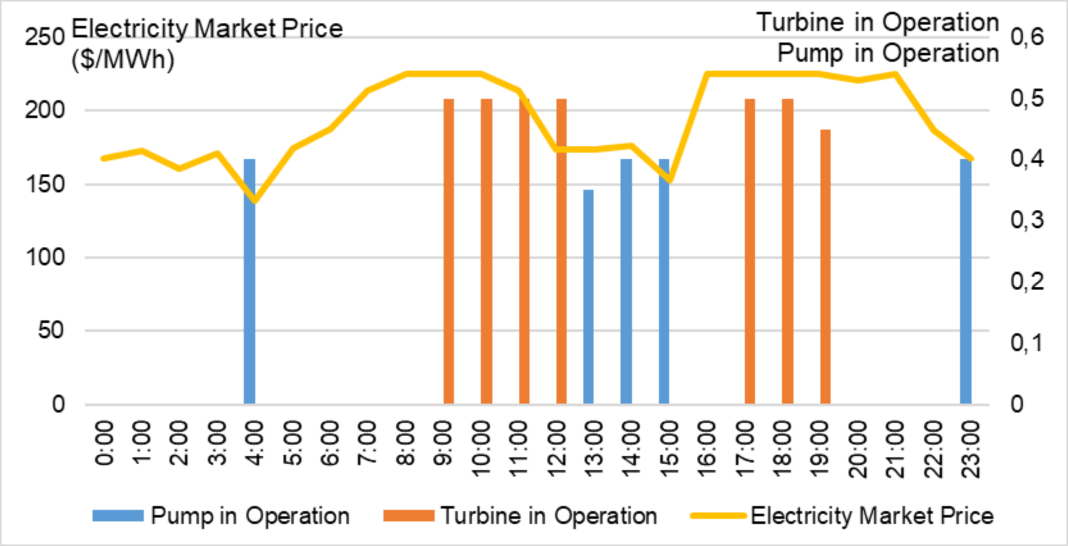


Figure 7. Pump and turbine operation according to energy market prices (3 January 2023).

4 Results and Analysis

In this section, the conditions in the simulation model are analysed. The results obtained for the pumping power-stormwater reservoir dimensions, optimum conditions, and simulation model are evaluated. The reliability of the study is explained as clearly as possible with figures showing how the simulation works, and it was aimed to keep the reliability high. The economic benefit of pumping power-stormwater systems has relatively low potential under operating conditions. The simulation model provided small-scale economic benefit; this shows that for a water (energy) reservoir to be a more profitable concept, it must be realized on a large scale.

Figure 8 shows what the result would be if the pumping power of the stormwater system was different from the installed peak power of the solar cell system. The pumping stormwater system provides more savings when combined with a larger solar cell system. Savings continue to rise even as individual use declines, meaning an inverse relationship between them. As the solar cell system gets smaller, the energy use increases almost exponentially because the solar energy produced is insufficient for pumping.

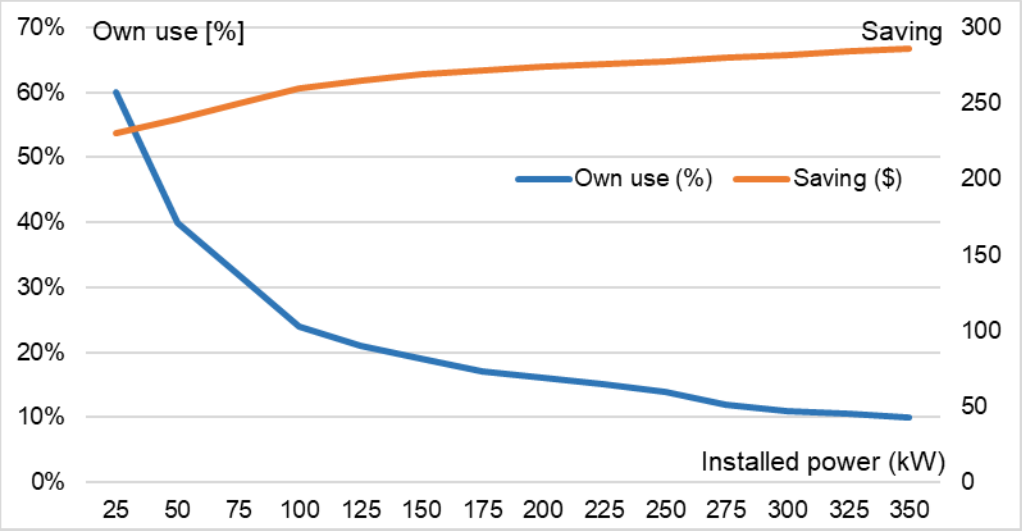


Figure 8. Sensitivity analysis of the installed power in the solar cell system.

Figure 9 shows the impact of storage capacity on economic benefit as a percentage. As the reservoir capacity changes, the pump and turbine output, design, and filling time change accordingly. It can be interpreted that the most significant increase in economic benefit occurs with small changes.

The economic potential when dimensioning reservoir fill times is illustrated in Figure 10. As mentioned in Section 3.1, the pump is dimensioned for filling time, while the turbine is sized for 25% higher flow and therefore, shorter discharge time. The best economic benefit is a short fill time. Still, any fill time less than one hour is less than the frequency at which electricity price data is collected, so it is uncertain in representing reality. It is clear from the figure that shorter unloading times, down to an hour, yield greater financial benefits. The economic benefit with a fill time of one hour corresponds to approximately 50% more economic benefit compared to a fill time of six hours.

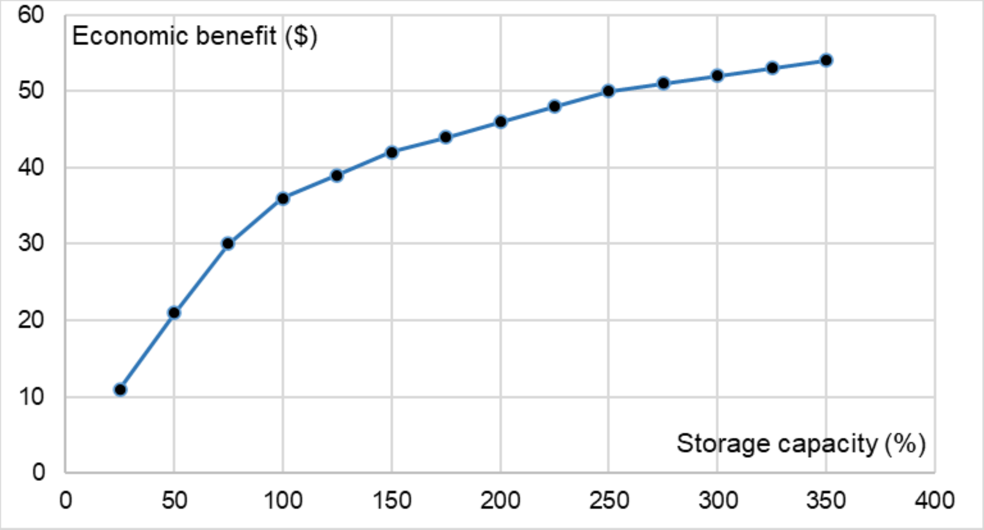


Figure 9. Sensitivity analysis of reservoir storage capacity.

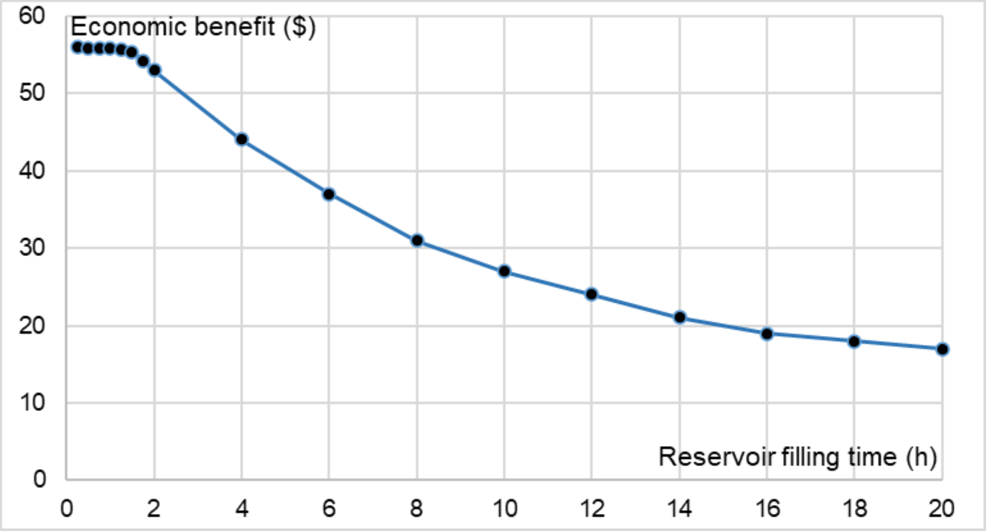


Figure 10. Sensitivity analysis of reservoir filling times.

Whether there is a huge impact on the nearby watercourse (river) and therefore, whether it is more appropriate to have a lower reservoir is not examined in this study. Also, whether a pumping-powered stormwater system affects sedimentation and thus, the treatment capacity of the stormwater reservoir is not included in this study. The establishment of a battery system for the storage of excess solar energy has not been examined in this study as it can be examined in future studies.

5 Conclusions and Future Directions

The aim of this study is to provide electricity from rainwater in regions with heavy rainfall but minimal electricity. In terms of power generated, raindrops will probably never be able to compete with a hydroelectric power station. However, they have one big advantage - they are free. With the increasing energy prices and developing new technology, the commercial use of rain energy does not seem far away.

Energy generated from solar cells in a pump power stormwater system reduced variable electricity costs by $ 572. The PV system can achieve savings, but the installed capacity of the PV system is critical to the system configuration. Utilizing the reservoir area to its maximum capacity will result in the lowest operational costs. In the energy storage dimension represented by a pumped stormwater reservoir in the study, the economic benefit potential is not very high. However, these results showed that; if the region with heavy rainfall and the large reservoir area is selected, the income rate increases exponentially. Minimizing operating costs, maximizing storage capacity and efficiencies, as well as filling and unloading times of approximately one hour are recommended.

In addition to the limited economic viability of pumped stormwater systems, potential barriers are mainly the need for more financial incentives and reduced treatment capacity of stormwater management.

In terms of economic sustainability and flexibility, it is thought that the operator can participate in frequency control and reactive power support by making various cooperation agreements. One more feasibility study can be developed in future studies.

Conflict of Interest

The author declares that there is no conflict of interest.

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Author Contribution

Conceptualization: Coban, H.H.
Data curation: Coban, H.H.
Methodology: Coban, H.H.
Formal analysis: Coban, H.H.
Visualisation: Coban, H.H.
Software: Coban, H.H.
Writing (original draft): Coban, H.H.
Writing (review and editing): Coban, H.H.
Validation: Coban, H.H.
Supervision: Coban, H.H.
Funding acquisition: Not applicable
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