













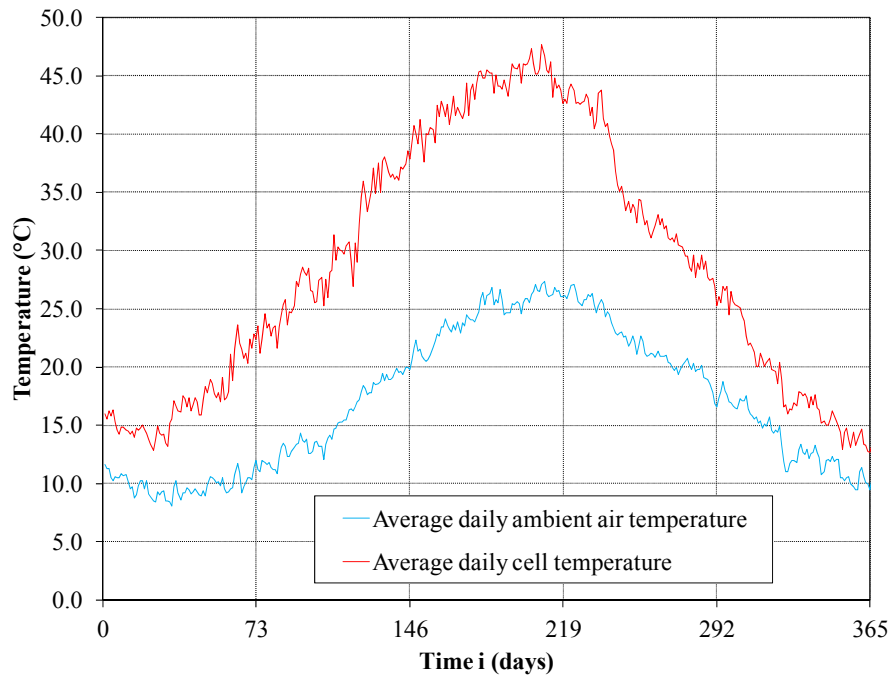








**Figure 7.** Average daily cell temperature and average daily ambient air temperature.



**4. Results and Discussion**

Based on the given data, by applying Equation (2), critical days  $t_{Pel,PV,ib,i}^*$  and  $t_{V,ib,i}^*$  in the given data sets have been determined (Table 1). Also, by applying the previously presented methodology, the required PV generator power  $P_{el,PV}^*$ , required area of the PV generator  $A_{PV}$  (using the value of  $\eta_{PV} = 0.15$ ) and required reservoir volume  $V_{op}^*$  (by applying Equation (3)) are calculated (Table 1 and Figure 8).

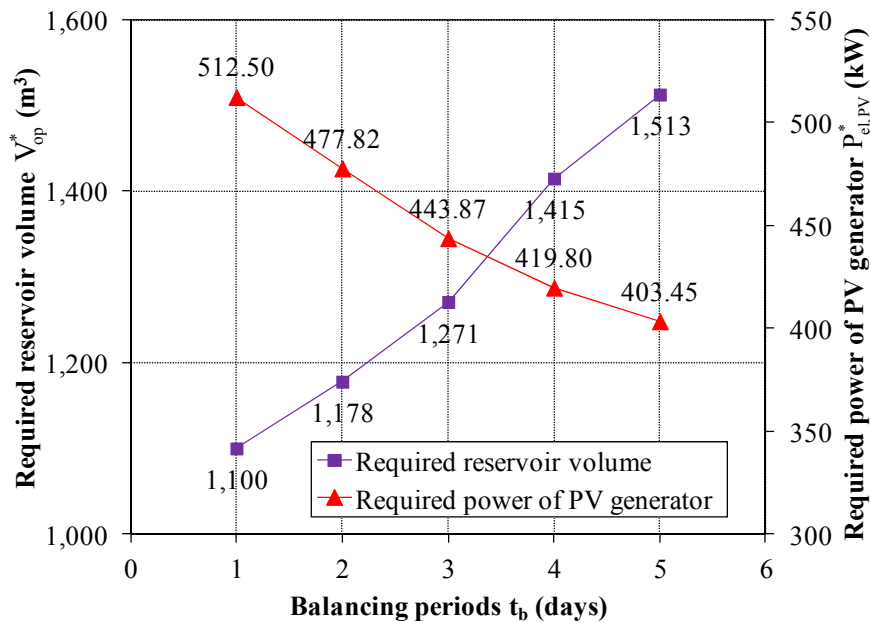
The required capacities of pump station  $Q_{PS}^*$  and power of pump station  $P_{PS}^*$  are calculated by using the value of  $\eta_{PS} = 0.90$  [12] (Table 2).

By using data from literature [15,18–22] and Equation (5), Life Cycle Cost analysis *LCC* has been made and presented in Table 3 and Table 4.

**Table 1.** The length of balance period in accordance with critical days and required area for a PV generator.

Balancing periods $t_b$ (days)	1	2	3	4	5
Critical days $t_{Pel,PV,ib,i}^*$ (days in year) for the $P_{el,PV}^*$	352	344–345	344–346	349–352	348–352
Critical days $t_{V,ib,i}^*$ (days in year) for the $V_{op}^*$	244	244–245	243–245	243–246	242–246
Required area for PV generator $A_{PV}$ (m <sup>2</sup> )	3417	3185	2959	2799	2690

**Figure 8.** The length of the balance period in accordance with the required power of a PV generator and required reservoir volume.



**Table 2.** Capacity  $Q_{PS}^*$  and power  $P_{PS}^*$  of pump station for different balancing periods  $t_b$ .

Balancing periods $t_b$ (days)	1	2	3	4	5
Capacity of pump station $Q_{PS}^*$ (L/s)	118	133	124	117	111
Power of pump station $P_{PS}^*$ (kW)	106.00	119.47	111.39	105.10	99.71

**Table 3.** Costs and lifetime aspects of the system components.

Component	Unit cost, $c$ (mean value of literature data)	Maintenance costs in the first year, $k$ (%)	Lifetime, $L_P$ (years)	Real interest rate, $k_d$ (%)	Inflation rate (%)	
					$f_0$	$f_1$
PV generator	1.5 (€/W)	1	25	8	4	4
Invertor	0.5 (€/W)	0	10	8	4	4
Service reservoir	400 (€/m <sup>3</sup> )	1	25	8	4	4
Pump station	1 (€/W)	3	15	8	4	4

**Table 4.** Costs of obtained solution variants.

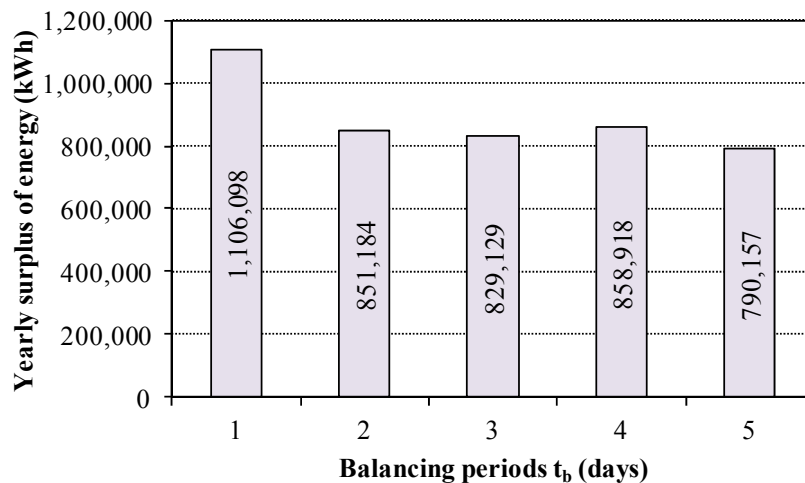
Bal. periods $t_b$ (days)	Power $P_{el,PV}^*$ (kW) of PV	Volume $V_{op}^*$ (m <sup>3</sup> ) of SR	Power $P_{PS}^*$ (kW) of PS	$C_{capital}$ Total (€)	$C_{repl}$ Total (€)	$C_{(O\&M)}$ Total (€)	$LCC$ (€)
1	512.50	1,100	106.00	1,570,996	554,084	263,418	2,388,498
2	477.82	1,178	119.47	1,546,310	526,705	269,198	2,342,213
3	443.87	1,271	111.39	1,507,525	489,479	261,567	2,258,572
4	419.80	1,415	105.10	1,510,697	462,815	260,740	2,234,252
5	403.45	1,513	99.71	1,511,808	444,154	259,436	2,215,398

It is evident that the fifth alternative is the most cost-effective. As a matter of fact, the difference in the maximum and minimum value of  $LCC$  is less than 8%, so a suitable compromise solution can be selected among them. We should not forget that the downward trend in prices of a PV generator (price reduction by the day by 4% to 7% annually within the observed period of  $N = 25$  years) is very significant [15]. This means that construction costs of the reservoir will have a decisive role.

The service reservoir, which has the function of balancing the inflow and supply of water to towns also acts as energy storage and thus determines the size of the required power of the PV generator. Theoretically assumed dependence of the size of conjugate pairs of  $P_{el,PV}$  and  $V_{op}$  as the basis for solution optimization was confirmed by the obtained results. It can thus be seen that, by using a longer balancing period  $t_b$ , the power of the PV generator is becoming smaller and the volume of service reservoir is becoming bigger. This functional dependence, in function of the length of the balancing period and electric/water energy storage, is the basis for the optimization of the system. Longer balance periods would probably yield more favorable solutions, considering that the PV generator is the most expensive element, although not significantly.

The system produces a surplus of electric energy during the sunshine period in the year, since it is designed to satisfy the needs in the critical period (Figure 9). With greater power of the PV generator, the available surplus is also higher. If there is a connection with the local grid (system), the aforementioned surplus of electric energy could be distributed to other consumers or can be sold.

**Figure 9.** Yearly surplus of energy from a PV generator in relation to the pump station needs.



The obtained profit from the sale of the produced electric energy surplus profit (€) and net cost (€) over the observed period of  $N = 25$  years are obtained by using the net present value ( $NPV$ ) [10] (Table 5). In this calculation, the sale price of electric energy from the PV generator in Croatia is 0.07 €/kWh [23] and the nominal discount rate for PV electric energy is 10% [24]. Net cost is the difference between  $LCC$  and profit. It can be seen that  $LCC$  is decreasing from 28% for  $t_b = 5$  days, up to 37% for  $t_b = 1$  day. This can significantly contribute to the economic benefits of the proposed solution if there is a market for green energy. Potential revenue from the sale of green electrical energy surplus changes the selection of obtained solution alternatives, considering only the economic criterion. In this case, alternative 1 is the most economical.

**Table 5.** Profit and net cost of the system over the observed period of  $N = 25$  years.

Balancing periods $t_b$ (days)	1	2	3	4	5
Profit (€)	878,512	676,049	658,530	682,185	627,578
Net cost (€)	1,509,986	1,666,164	1,600,042	1,552,067	1,587,820

In the presented climate area daily surpluses are higher in the summer than in the winter period. Such behavior of the system is particularly beneficial in tourist areas of the Mediterranean which are characterized by a significant increase in water consumption during the summer because of the tourists.

The biggest problem for operation of the proposed system is uncertainty of daily solar irradiation due to possible cloudiness. However, by using the critical period approach, significant system capacity reserves are achieved and, consequently, the reliability of the system work is increased. The selected power of the PV generator is able to cover uncertainty in water demand in the summer period, since the critical period for design is the winter low irradiation period (maximum PV generator power), while the selected volume of service reservoir is able to cover uncertainty in winter solar irradiation, since the critical period for volume design is the summer peak water demand (maximum reservoir volume). By using longer balancing period  $t_b$  the system reliability will be higher.

The advantage for having the system in combination with a network of other energy sources is the opportunity to provide redundancy in the system. Also, the advantage of the use of the solar energy system is that it provides energy into the grid and itself provides some measure of overall redundancy.

This concept of energy supply operation does not generate any atmospheric emission of greenhouse gases, which contributes significantly to reduction of the impacts of climate changes, as well as to meeting the requirements arising from relevant strategies [25]. A photovoltaic installation makes no noise, making it suitable for construction close to people.

Long-term goals of the water sector include continuous adaptation to climate change and reducing the industry carbon footprint. With greater power of a PV generator, the reduction of greenhouse gas emissions is also greater. If it is assumed that all electric energy is produced in a coal-fired power plant, which typically emits 0.95 kg of CO<sub>2</sub>/kWh [11], a PV generator would then reduce CO<sub>2</sub> emission over the observed period of  $N = 25$  years (Table 6).

**Table 6.** Amount of reduced CO<sub>2</sub> emission over the observed period of  $N = 25$  years.

Balancing periods $t_b$ (days)	1	2	3	4	5
Amount of reduced CO <sub>2</sub> emission (t)	33,120	30,879	28,685	27,129	26,072

This type of solution for electric energy supply of water supply systems also has other environmental benefits, as it reduces the need for central power station capacity and the need to reinforce transmission and distribution systems. It also provides electricity at the point of use so that energy losses should be much lower than when power is transmitted over a distance of several kilometers.

The weakness of the obtained solution can be seen due to the large surface area required for installing solar panels, which is not always easy to find in urban areas. In line with the expected increase of the PV cell efficiency (from the present 15% up to the expected 30% in the next 30 years [26], where in laboratory conditions 44% of the PV cell efficiency has already been achieved [27]), the required area

for installing of solar panels will be reduced proportionally to the increasing of their efficiency. Therefore, this concept will be more suitable for the use in urban areas.

The adoption of this concept may contribute to the EU 20-20-20 target by 2020 [25] and also may increase revenue through the Renewable Obligation Certificates, ROCs. It is obvious that the proposed solution is promising, but its use will greatly depend on the characteristics of local climate, PV systems, water supply systems and also of the community commitment to water and energy supply sustainability. The biggest threats in using the presented concept could be mistrust and skepticism from managers and engineers of water supply companies. Despite the fact that the presented concept is technologically very simple and straightforward for application, it is different from the usual concept of water supply. It is therefore necessary to continue with researching and developing the proposed solutions, as well as with publishing the new obtained results.

## 5. Conclusions

It has been shown that the proposed concept of the use of a PV generator for electric energy supply of the main pump station in a bulk water supply system is feasible. By using PV electric energy for water pumping in urban water supply system, as has been presented, this system becomes a “green water system.” Given that the primary energy source (the Sun) is inexhaustible and free of charge, energy supply, essential for the operation of water supply system, is sustainable.

The obtained results show that the proposed solution can reliably and continuously supply the main pump station with green electricity, providing a reliable and continuous water supply to meet the needs of consumers. In accordance with the proposed, the reliability of such a system is high.

The proposed solution can be used as a stand-alone power system or in combination with electric energy from the regional network (fossil fuels fired power plant). It can be concluded that the solution analyzed in this study would be very useful in all situations where the supply of electricity from energy power system is limited or when it is necessary to increase the capacity of a long transmission system (*i.e.*, isolated locations like islands). The proposed solution is also convenient to apply for peak power generation.

It is obvious that there is a whole range of possible applications, and the solution itself will depend on the characteristics of the location and the problem addressed. In any case, the proposed concept of energy production and use provides opportunities to support the sustainability of cities or a smart city environment [28].

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## Author Contributions

First author has expanded and elaborated the concept and the idea of the second author about the manuscript content. Both authors were involved in preparing of the manuscript.

## Conflicts of Interest

The authors declare no conflict of interest.

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