

Article

## Analysis of the Possible Use of Solar Photovoltaic Energy in Urban Water Supply Systems

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Received: 28 February 2014; in revised form: 13 May 2014 / Accepted: 21 May 2014 /

Published: 30 May 2014

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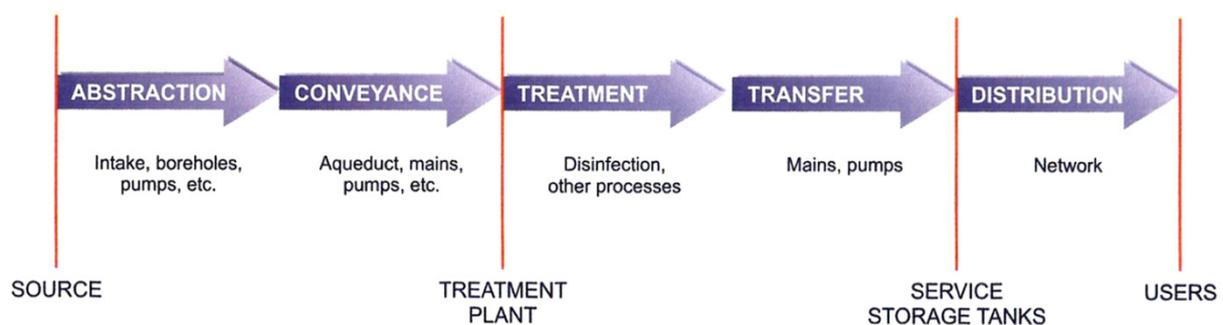
**Abstract:** Because of the importance of water supply for the sustainability of urban areas, and due to the significant consumption of energy with prices increasing every day, an alternative solution for sustainable energy supply should be sought in the field of Renewable Energy Sources (RES). An innovative solution as presented in this paper has until now not been comprehensively analyzed. This work presents the solution with the application of a (Photovoltaic) PV generator. The main technological features, in addition to the designing methodology and case study are presented in this paper. The critical period approach has been used for the first time for system sizing. The application of this sizing method provides a high reliability of the proposed system. The obtained results confirm the assumption that the PV generator is a promising energy sustainable solution for urban water supply systems. The service reservoir, which acts as water and energy storage for the proposed system, provides the basis for a sustainable solution of water and energy supply. In accordance with the proposed, the reliability of such system is high. This concept of energy supply operation does not generate any atmospheric emission of greenhouse gases, which contributes significantly to the reduction of the impacts of climate changes. The proposed solution and designing methodology are widely applicable and in accordance with the characteristics of the water supply system and climate.

**Keywords:** urban water supply; solar energy; photovoltaic pumping; sustainable water supply; life cycle cost

## 1. Urban Water Systems and Solar Energy

Urban water supply systems (UWSS) are defined as natural, modified and constructed elements of the urban water cycle, related to water supply, that can be found in towns. UWSS provide water to support human life, hygiene, health, safety, recreation and amenities. Natural elements of a system include local and regional water resources, while the modified and constructed elements include water intake, water supply pipes, pump stations, service reservoirs, and water treatment plants. The constructed water supply system is an integral part of the broader urban infrastructure system. Figure 1 shows the typical water supply management process, indicating location and transfer elements.

**Figure 1.** Typical elements of the water supply management system [1].



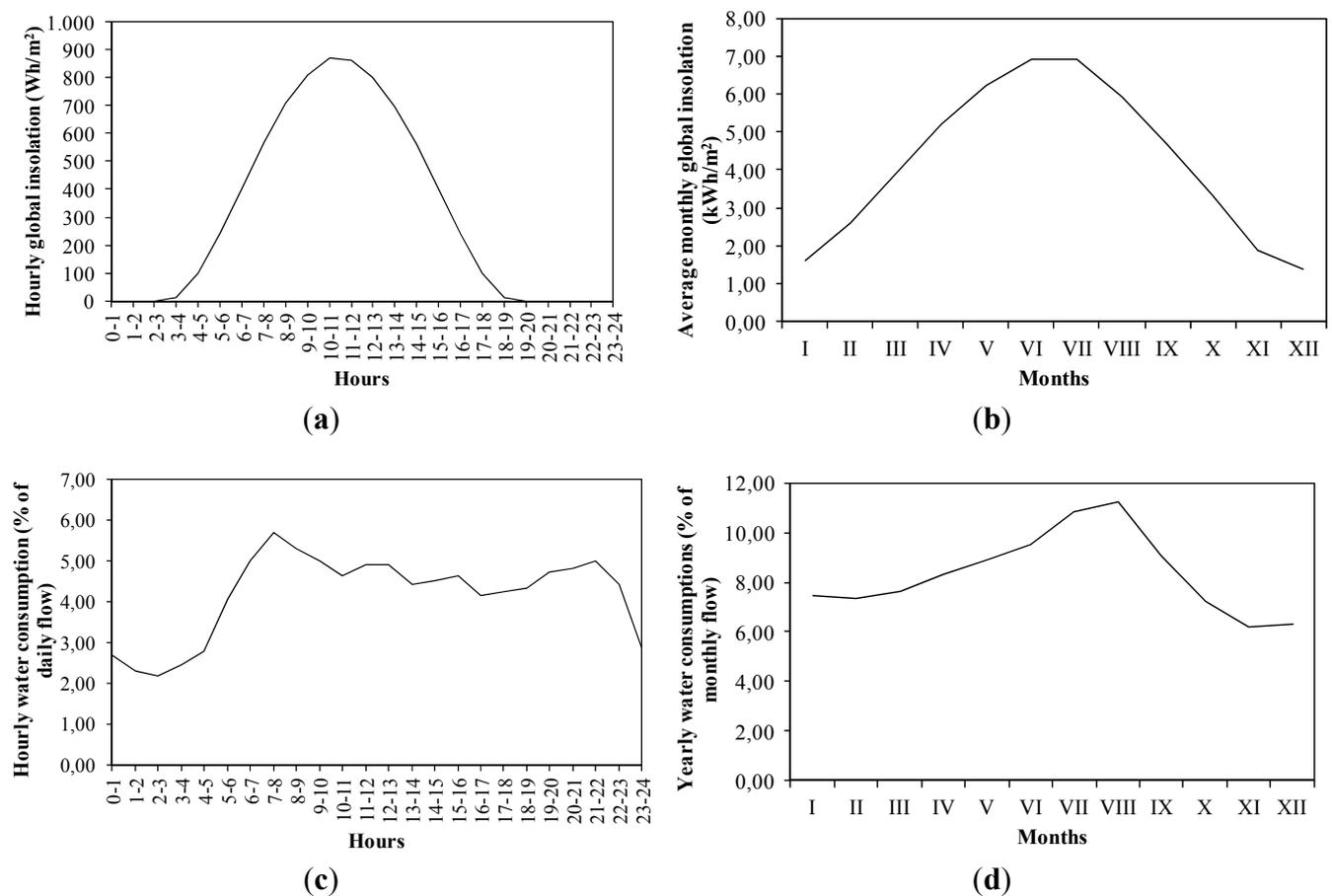
The biggest challenge for modern water utilities is to provide the required amount of water at affordable rates. UWSS activities are energy intensive and in general grow as the city and total water consumption are also expanded. Today, and especially in the future, UWSS management should contribute to the objective of sustainable urban development. A sustainable city minimizes energy use from traditional energy sources and reduces CO<sub>2</sub> emissions. Strategies to achieve sustainability include: (i) applying energy and water efficiency measures; (ii) shifting energy consumption as much as possible to off-peak periods; and (iii) the use of renewable energy. This paper will analyze the characteristics of application of PV technology for water pumping in the UWSS, or more specifically for bulk water supply. By using green energy, such as PV electric energy, cities minimize energy use from traditional electric energy sources and reduce CO<sub>2</sub> emission.

However, solar energy input is free. Broader objectives of the problem should be taken into consideration, as well as economical aspects of the use of green energy, instead of traditional energy from fossil fuels. This means that a system should be selected that will minimize the negative economical difference between the use of a green energy system and those of a traditional energy system by taking into consideration other benefits, since the supply of green energy is still more expensive than traditional energy. These other issues (benefits) which have to be taken into consideration are: energy-related environmental impacts, excessive dependence on specific energy forms, growing energy

demand and supply problems, social cost independent of the cost of oil and other fossil fuels, locally available energy sources independent of regional energy network, reduction of CO<sub>2</sub> emission, *etc.*

Water is used in various amounts throughout the whole day, while solar irradiation occurs only during the sunlight periods of the day, (Figure 2) [2–4]. The duration of daily insolation varies throughout the year according to the climatic characteristics of the area being analyzed. Therefore, PV electric energy must be used when produced or Electric Energy Storage (EES) must be used, which will provide the supply of electric energy during the night, as well as during low solar radiation (cloudy period). In this way EES has a significant role in the implementation of PV electric energy supply to UWSS. Numerous technologies of energy storage are known today (batteries, flywheel, pressure vessels, *etc.*), which differ in: size, energy storage costs, efficiency, lifetime, costs per cycle, *etc.* [5,6]. For the time being, these EES are very expensive facilities and represent a solution for smaller consumers, but not for bigger facilities such as the UWSS.

**Figure 2.** Examples of solar energy irradiation and water demand pattern in the urban areas. (a) Varaždin, Croatia, 15 July 2005; (b) Šibenik, Croatia, 1961–1980; (c) Varaždin, Croatia, 12 July 2013; (d) Šibenik, Croatia, 2013.



The Main Pump Station (MPS) that pumps water into the clean water reservoir is generally a big energy consumer. Due to the pumping systems, energy consumption represents the biggest part of energy expenses in the water sector—sometimes up to 90% [7]. Significant use of energy is required, since all water has to be brought to a higher elevation in order to produce the required pressures to

water users in the water supply area. This paper analyzes whether it is possible to use PV technology for urban water supply, whether water service reservoir can be used as EES and how the system balancing period affects its features.

The use of solar energy for water pumping has already been well addressed in literature, for example [8–10]. However, at present, there are no significant publications on a more thorough consideration of possible applications of PV generators in UWSS.

This particularly applies to the analysis of the impact of balancing period on the solution characteristics. PV energy can be used as an additional source of “green energy,” or as the only source of electric energy required for pumping water. This paper analyzes the application of the PV generator as the sole source of energy to operate the MPS.

## 2. Design Methodology

### 2.1. Critical Period Approach

Service reservoir and associated pump station, which deliver water into the reservoir when energy from the energy power system is used, are usually designed according to deterministic guidelines that specify minimal water service reservoir and optimal pump system capacity. The required capacity of the reservoir and pumping system is determined according to daily consumer demand for water in design period  $V_{WS(i)}$  and hourly demand  $Q_{WS(i)}$  in the day of maximum demand, the *critical demand period*. Design period  $t_b$  is usually the period with the highest consumption of water during the planning year. However, the design period can be longer: two or more days, up to a maximum of one week.

The size of the reservoir depends on the regime of water consumption in a settlement, and on the planned work of the pumping station. The work of pumping station, supplied with electric energy from the regional power system, can be continuous for 24 hours or more intense during the night when electricity is cheaper. Various combinations are possible that seek to optimize the operation of the pumping system, its capacity  $Q_{PS}$  and reservoir capacity  $V_{op}$ . The capacity of such a reservoir increases for fire and emergency storage, in accordance with the respective norms. Such guidelines have to accommodate a large range of possible conditions, meaning that systems are potentially overdesigned, but reliable.

In the case when PV electric energy is used, the design is more complex, because the available energy for pump system operation is variable throughout the year and during the day, depending on daily insolation. In this case, the designer must determine the PV generator power  $P_{el,PV}$  that will provide enough electricity for re-pumping water into the reservoir during the entire planning period (planning year), according to daily water consumption in a settlement  $V_{WS(i)}$ . In addition, the duration of sunshine  $T_{S(i)}$  determines the period of operation of the pumping station. In this case, the critical energy supply period, or the period for calculation of the PV generator power, is one in which the relationship between hydraulic energy required for re-pumping water  $E_{H(i)}$  and the available solar radiation  $E_{S(i)}$  is the smallest.

Consequently, the critical period for calculating the capacity of the pumping station  $Q_{PS(i)}$  is the one in which the relationship between the daily consumption of water in a settlement  $V_{WS(i)}$  and the period of active insolation  $T_{S(i)}$  is the greatest.

If the design period  $t_b$  is longer than one day, the impact of one extreme day of low insolation (usually due to cloudiness) on the capacity of the PV generator decreases, so that lower power of the PV generator is required and thereby lower costs. With a longer design period, the impact of extremely low insolation on calculation results will be smaller, so the solution will be safer and more rational. In this case they are longer critical periods.

In this paper we used the approach based on *critical design period*. This approach includes design elements of the solution: PV generator, pump station and service reservoir based on the critical period of operation of each one. It is a deterministic approach which accommodates a large range of possible conditions. It is a conservative approach, meaning that the elements of the solution are potentially oversized. However, such an approach provides a reliable solution and a required level of reliability, necessary for the functioning of water supply systems. The reliability of the bulk water supply system can be defined in terms of reliability of its storage reservoir/tank, as consumers will only notice a service interruption if the storage tank has failed (*i.e.*, run dry).

Optimization of the possible solution is based on economic and other criteria in the function of a balancing period. The balancing period of water pumping and service reservoir water balance in the urban water supply system is at least one day and may be several days, usually no more than five, ( $t_b = 1-5$  days). A longer balance period reduces the uncertainty of solar irradiation and increases the reliability of the solution. With a longer balancing period, the system is more cost-effective from the perspective of solar energy harvesting, because the sum of overall available solar radiation is greater when the balancing period is longer. This means that the required water volume can be pumped with lower installed PV generator power. Normally, with a longer balancing period, the storage capacity of the reservoir will be higher. Therefore, regardless the fact that the daily output of water from the storage does not change significantly from day to day, due to uneven influx of water into the reservoir, it will generally be higher. The relationship between  $P_{el,PV}$  and  $V_{op}$  depends on climate characteristics of the location, or on daily variability of solar radiation. With lower variability the impact on the required storage volume and the PV generator power is smaller and *vice versa*.

In the critical period approach, the estimate is mainly carried out in the following steps:

- Collecting all necessary data for estimation of water demand in the planning period,  $Q_{WS(i)}$ , and determining the daily water usage pattern;
- Collecting climate and other necessary data for the design of PV generator;
- Selecting the number of days for system water usage balance, *i.e.*, balancing (design) period,  $t_b = 1, 2, 3, 4$  and 5 days;
- Selecting the most critical periods for the determination of the required power of the PV generator  $P_{el,PV}$  from available time series of solar radiation  $E_{S(i)}$  and water demand  $V_{WS(i)}$  in accordance with the selected balancing period  $t_b$ ;
- Determining the required power of PV generator  $P_{el,PV}$ , according to the selected critical daily balancing period  $t_b$  [10,11];
- Determining the capacity  $Q_{PS}$  and power  $P_{PS}$  of the main pumping station (MPS) for each balancing period  $t_b$  for every day  $i$  of the year [12]. The largest obtained capacity  $Q_{PS(i)}$  and power  $P_{PS(i)}$  is selected;

- For the selected balancing period  $t_b$ , determining the required operative reservoir volume  $V_{op}$  for the selected PV generator power  $P_{el,PV}$  and the period of its work during the day (inflow), according to the foreseen regime of hourly water consumption in a settlement (outflow) for each balancing period  $t_b$ , for every day  $i$  of the year. The largest obtained volume  $V_{op(i)}$  is selected;
- Determining the cell area  $A_{PV}$  ( $m^2$ ), for each balancing period  $t_b$  [10];
- Analysis and ranking of obtained solutions of PV generator power  $P_{el,PV}$ , operative reservoir volume  $V_{op}$  and total power  $P_{PS}$  of MPS of different balancing period  $t_b$ .

The input data for the analysis are: climate data (daily average air temperature, daily average solar irradiation, average number of hours of daily insolation), water supply system configuration (water intake, pump station, service reservoir), daily and hourly water demand and fluctuation during the day. It is also necessary to determine the constraints related to the construction of a PV generator, pump station and service reservoir, as well as legal, environmental, social and other requirements.

At the beginning of the analysis it is necessary to define the daily quantity of water in a settlement  $V_{WS}$  ( $m^3/day$ ), according to settlement characteristics and water consumption regime throughout the years of the planning period.

After this, the daily water usage pattern in a settlement  $V_{WS,t}$  ( $m^3/h$ ) in the period of  $t = 1, \dots, 24$  hours is determined (diurnal pattern). The same pattern is used for each day  $i$ .

Based on the obtained values, the minimum required size of the PV generator is determined, which provides the necessary inflow of water in the critical period. This procedure is simple, because the relation between  $P_{el,PV}$  and  $V_{PS}$  is linear.

Based on the selected/calculated initial values,  $P_{el,PV}$  and  $V_{PS}$ , which satisfy water demand  $V_{WS}$  in the planning period, the minimum required  $P_{el,PV}$  is determined from established differences  $\Delta V_{tb,i}$ :

$$\Delta V_{tb,i} = V_{PS,tb,i} - V_{WS,tb,i}, \quad i = 1, 2, \dots, 365 \quad (1)$$

The critical day/period  $t_{Pel,PV,tb,i}^*$  for PV generator design is determined by the minimum daily difference:

$$\min \Delta V_{tb,i} \Rightarrow t_{Pel,PV,tb,i}^* \quad (2)$$

where  $\Delta V_{tb,i}$  is an acceptable difference in practice application.

When the balancing period  $t_b > 1$  day, calculation series of  $t_b$  days are performed, where series are formed with calculation step always  $\Delta i = 1$  day,  $i = 1, 2, \dots, 365$ . If the sum does not end with the last member of the observed series, the process ends with the next member of the same series.

Available insolation  $E_S$ , *i.e.*, electric energy  $P_{el,PV}$  determines the period of the pumping station operation  $T_S$  with uniform rate during daily work period.

The required operation volume of service reservoir  $V_{op}$  is obtained by standard procedure, using a mass diagram with cumulative pumping curve plotted on it [12], by using of Excel ©2007 (Microsoft). Time step for calculation is one hour,  $t = 1, \dots, 24$  hours. The size of service reservoir has been calculated for each day  $i$  in accordance with each balancing period  $t_b$  in the year. In general, the critical day/period for the design of volume reservoir  $t_{V,tb,i}^*$  is the day with maximum water demand, providing that on day available insolation  $E_{S(i)}$  is sufficiently high. It should be noted that the fire and emergency volumes are not taken into account for this case. These volumes are more or less constant, while the

operation volume is variable during the day. In accordance with the respective norms and particular situations, influence of fire and emergency volumes on operation volume analysis may be neglected [12]. However, the total required volume of service reservoir is the sum of operation, fire and emergency volumes.

The required volume  $V_{op}^*$  for each alternative  $t_b$  is:

$$V_{op}^* \geq \max V_{op,i} \quad (3)$$

## 2.2. The Choice of a Compromise Solution

The general objective of the system design is finding the power of the PV power plant that will, in the best manner possible, meet all consumer needs for water, with minimal construction and operation costs of the system. The requested result of the optimization process is the best compromise solution between the pairs of  $P_{el,PV}$  and  $V_{op}$  and also the pump station power  $P_{PS}$  that best meets the set objectives. The optimal combination  $x$  of PV generator power  $P_{el,PV}^*$  ( $f_1$ ), operating service reservoir volume  $V_{op}^*$  ( $f_2$ ) and power  $P_{PS}^*$  ( $f_3$ ) of MPS is sought for the selected alternatives  $X$ :

$$DR[f_1(x), f_2(x), f_3(x)], x \in X \quad (4)$$

$DR$  means to apply the appropriate decision rule(s) and to find the best-compromise solution  $x^*$  from the set of alternatives  $X$ . The standard trade-off method could, among other, be used for the selection of a compromise solution [13]. In this case, the economic criterion is dominant. However, the problem can be analyzed by extending the number of criteria, of which the reliability of water supply is the most important one.

General sustainable objectives are related to economic, social and environmental aspects of the problem. Most of the environmental objectives are fulfilled by using green energy instead of traditional. Social objectives relate to basic water service price as measurable criteria and sustainable green city environment as general commensurate criteria. The fulfillment of both sustainable objectives is closely related to economical characteristics of the solution. Nowadays, the economic criteria are still dominant and for this reason good economic analysis of the problem is the basis for the solution and alternative evaluation.

The economical approach, according to the concept of Life Cycle Cost  $LCC$  (€) [8,9], is developed to be the best indicator of economic profitability of the system cost analysis.  $LCC$  takes into account the initial capital cost  $C_{capital}$ , present value of replacement cost  $C_{replacement}$  and present value of maintenance cost  $C_{maintenance}$ :

$$LCC = C_{capital} + C_{replacement} + C_{maintenance} \quad (5)$$

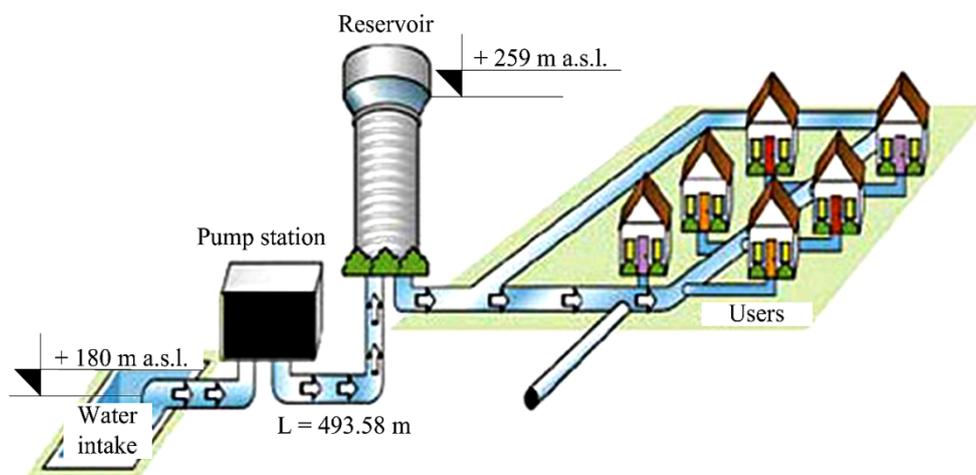
In the case of urban water supply systems, the economic objective is to minimize possible economic losses that occur due to not using conventional energy sources which are still cheaper than green sources. These losses are expected to decrease over the time, because PV generators are becoming cheaper and conventional energy more expensive [14,15].

In this paper we will simplify the economic analysis, providing sufficient information for understanding the problem characteristics.

### 3. Example

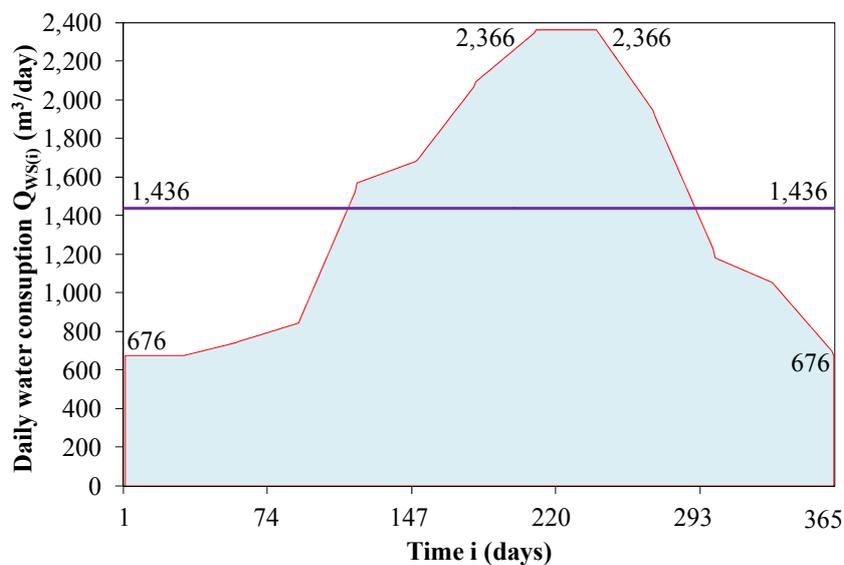
This paper presents a hypothetical example of a settlement with a population equivalent of 8970. The settlement is located on an island in the southern Mediterranean part of Croatia. It is in a hilly area of the island and has one water reservoir located at a ground elevation of 259 m above sea level. Water flows into the reservoir from the wet basin of the pump station. Water flows into the wet basin of the pump station by gravity from the spring. Total head of the pump station is 82.41 m. The water quality is satisfactory and does not need treatment. The positions of the basic facilities of the water supply system are shown in Figure 3 [16].

**Figure 3.** Case study schematic layout.



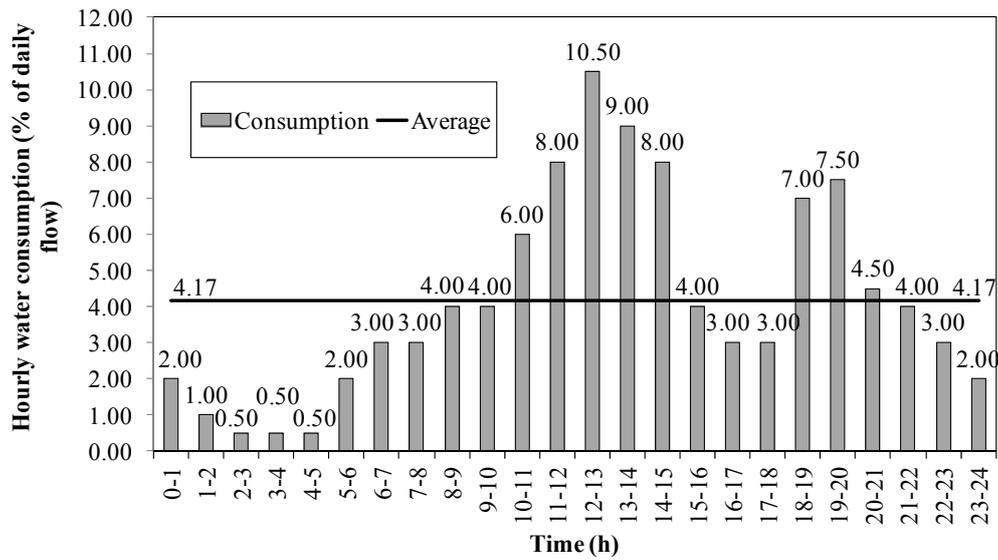
The analysis is conducted according to the presented methodology. Specific water consumption per capita  $q_{sp}$  is 160 L per day. The daily water consumption pattern through the year is shown in Figure 4 [12].

**Figure 4.** Daily water demand during the year.



Hourly water consumption pattern [12] in the settlement is determined by the daily regime of consumption, as shown in Figure 5.

Figure 5. Hourly water demand during typical day.

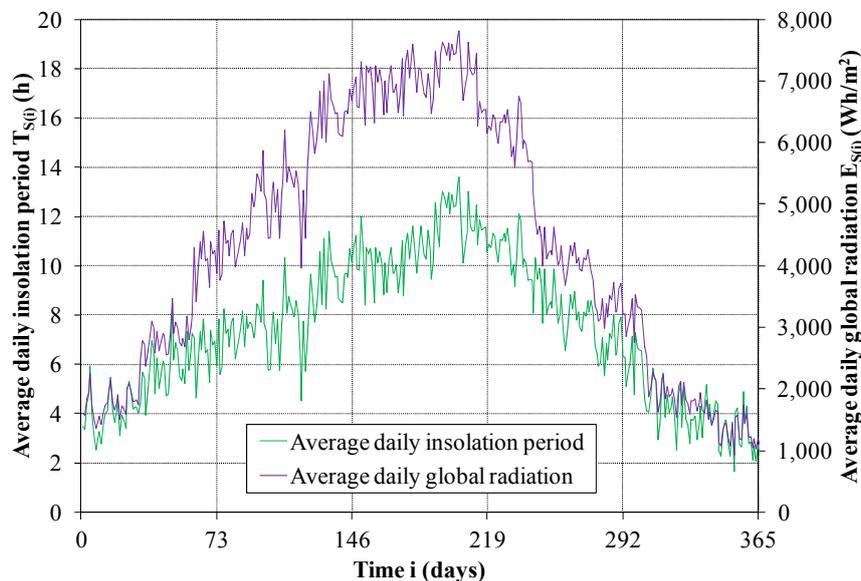


For the considered location, the average pump head is  $H_{PS} = 82.41$  m, average efficiency of the inverter and motor pump unit is  $\eta_{MPI} = 0.75$ , cell temperature coefficient is  $\alpha_C = 0.005$  °C<sup>-1</sup> and temperature of the PV generator in Standard Test Condition is  $T_0 = 25$  °C.

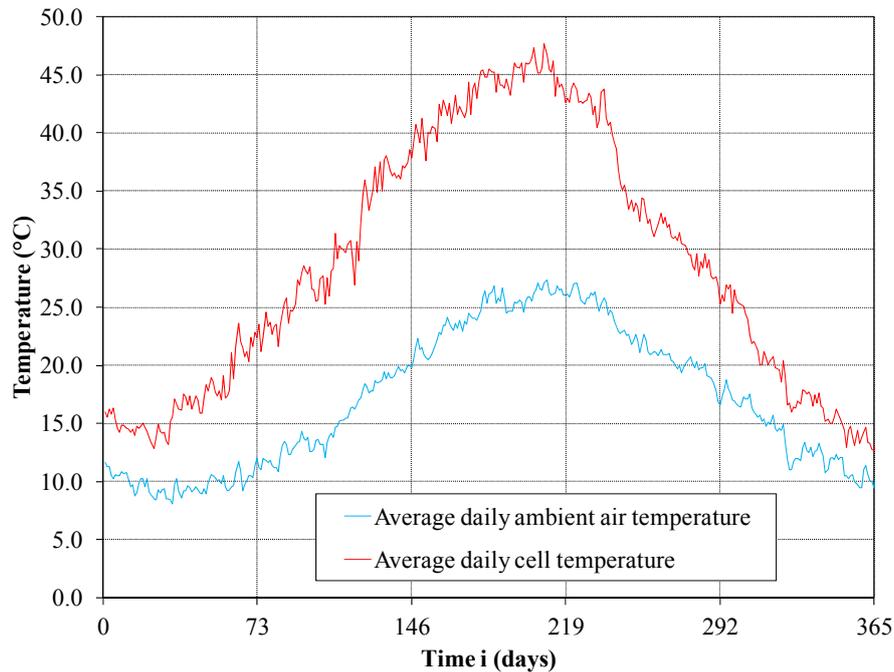
The calculation is made with 50% of an average array output in relation to rated output ( $\eta_S = 0.5$ ). This approximation is taken because the calculation from data in [3] shows that for the southern Mediterranean part of Croatia, the ratio of surface size of the daily profile of  $E_S$  during  $T_S$  and surface size of the daily profile of  $E_S$  during daily duration of solar radiation is about 50% in the winter period of the year. In the summer period this ratio is even up to 75%. However, the relevant value is 50%, because the critical day/period  $t_{Pel,PV,tb,i}^*$  for the PV generator is in winter.

The average daily global radiation  $E_{S(i)}$  and average daily insolation period  $T_{S(i)}$  are shown in Figure 6, while the average daily cell temperature  $T_{cell(i)}$  and average daily ambient air temperature  $T_{a(i)}$  are shown in Figure 7 [17].

Figure 6. Average daily solar insolation and duration of sunlight.



**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).

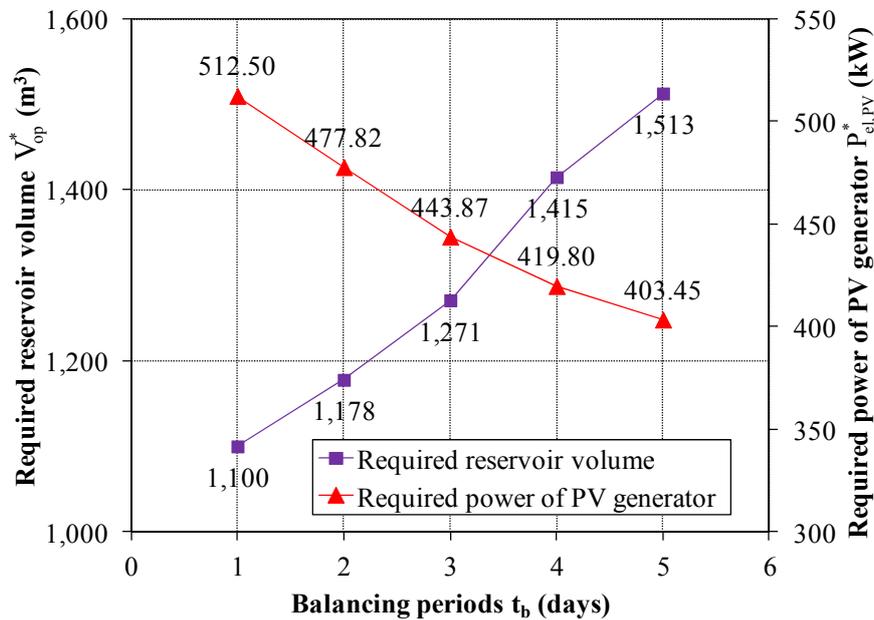
The required capacities of pump station  $Q_{PS}^*$  and power of pump station  $P_{PS}^*$  are calculated by using the value of  $\eta_{PS} = 0.90$  [12] (Table 2).

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.

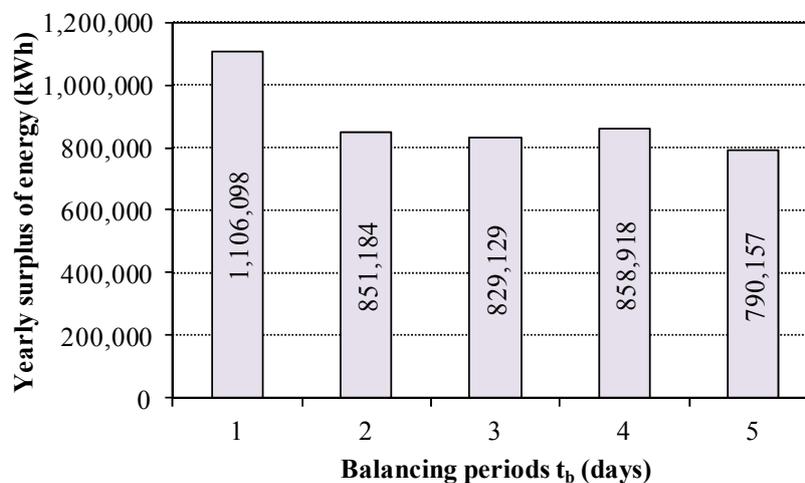
Bal. periods $t_b$ (days)	Power $P_{el,PV}^*$ (kW) of PV	Volume $V_{op}^*$ (m <sup>3</sup> ) of SR	Power $P_{PS}^*$ (kW) of PS	$C_{capital}$ Total (€)	$C_{repl}$ Total (€)	$C_{(O\&M)}$ Total (€)	$LCC$ (€)
1	512.50	1,100	106.00	1,570,996	554,084	263,418	2,388,498
2	477.82	1,178	119.47	1,546,310	526,705	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].

## Acknowledgements

We would like to thank Ms Marina Culic for reviewing of English language and style in this manuscript.

## 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.

## References

1. The Priority Actions Programme Regional Activity Centre (PAP/RAC): Integrated Coastal Urban Water System Planning in Coastal Areas of the Mediterranean—Volume I, Principles and Planning; PAP/RAC: Split, Croatia, 2007.
2. Matić, Z. *Solar Radiation on Area of the Republic Croatia*; Energetic Institute Hrvoje Požar: Zagreb, Croatia, 2007. (In Croatian)
3. SODA—Solar Radiation Data—Solar Energy Services for Professionals. Available online: [http://www.soda-is.com/eng/services/services\\_radiation\\_free\\_eng.php](http://www.soda-is.com/eng/services/services_radiation_free_eng.php) (accessed on 9 January 2013).
4. Varkom PLC. *Water Consumption Data*; Varkom PLC: Varaždin, Croatia, 2013. (In Croatian)
5. Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y. Progress in electrical energy storage system: A critical review. *Progr. Nat. Sci.* **2009**, *19*, 291–312.
6. Electricity Storage Association (ESA)—Technology Comparisons. Available online: [http://www.electricitystorage.org/technology/tech\\_archive/technology\\_comparisons](http://www.electricitystorage.org/technology/tech_archive/technology_comparisons) (accessed on 4 December 2013).
7. Moreira, D.F.; Ramos, H.M. Energy Cost Optimization in a Water Supply System Case Study. *J. Energy* **2013**, *2013*, 1–9.
8. Bakelli, Y.; Hadj, A.A.; Azoui, B. Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept. *Sol. Energy* **2011**, *85*, 288–294.
9. Ghoneim, A.A. Design optimization of photovoltaic powered water pumping system. *Energy Convers. Manag.* **2006**, *47*, 1449–1463.
10. Kenna, J.; Gillett, B. *Solar Water Pumping: A Handbook*; Intermediate Technology Publications: London, UK, 1985.
11. Margeta, J.; Glasnović, Z. Exploitation of temporary water flow by hybrid PV-hydroelectric plant. *Renew. Energy* **2011**, *36*, 2268–2277.
12. Margeta, J. *Water Supply: Planning, Design, Management and Water Purification*; Faculty of Civil Engineering and Architecture, University of Split: Split, Croatia, 2010. (In Croatian)
13. Chankong, V.; Haimes, Y. *Multiobjective Decision Making: Theory and Methodology*; Elsevier-North Holland: Washington, DC, USA, 1983.
14. Campoccia, A.; Dusonchet, L.; Telaretti, E.; Zizzo, G. Comparative analysis of different supporting measures for the production of electrical energy by solar PV and Wind systems: Four representative European cases. *Sol. Energy* **2009**, *83*, 287–297.
15. SolarServer—PVX spot market price index solar PV modules. Available online: <http://www.solarserver.com/service/pvx-spot-market-price-index-solar-pv-modules.html> (accessed on 8 January 2014).
16. District of Columbia Water and Sewer Authority—About Drinking Water Quality in Washington, DC, USA. Available online: [http://www.dcwater.com/drinking\\_water/about.cfm](http://www.dcwater.com/drinking_water/about.cfm) (accessed on 10 December 2013).

17. Meteorological and Hydrological Service (MHSC). *Climatic data for Palagruža and Komiža — From 1995. till 2006*; MHSC: Zagreb, Croatia, 2007. (In Croatian)
18. Four Peaks Technologies, Inc.—Solar electricity costs. Available online: [http://solarcellcentral.com/cost\\_page.html](http://solarcellcentral.com/cost_page.html) (accessed on 2 January 2014).
19. Hidroing Ltd. *The Regional Water Supply System: Neretva, Pelješac, Korčula, Lastovo, Mljet—Novelation of Pre-Investment Programe*; Hidroing Ltd.: Split, Croatia, 2004. (In Croatian)
20. Hrvatske Vode PLC. *Water Supply Plan of Split and Dalmatia County*; Hrvatske Vode PLC: Split, Croatia, 2008. (In Croatian)
21. Penstar Ltd. *Price Book*; Penstar Ltd.: Cardigan, UK, 2012.
22. White International. *CNP Industrial Pumps—Price List 2011*; White International: Mippera, Australia, 2012.
23. Croatian Energy Regulatory Agency (HERA). *Methodology for Determining the Amount of Tariff Items for Electricity within the Universal Service*; HERA: Zagreb, Croatia, 2013. (In Croatian)
24. U.S. Department of Energy. *The Prospect for \$1/Watt Electricity from Solar. \$1/W Workshop*; U.S. Department of Energy: Washington, DC, USA, 2010.
25. European Commission. *Energy Roadmap 2050*; 2012. Available online: [http://ec.europa.eu/energy/publications/doc/2012\\_energy\\_roadmap\\_2050\\_en.pdf](http://ec.europa.eu/energy/publications/doc/2012_energy_roadmap_2050_en.pdf) (accessed on 19 December 2013).
26. Goetzberger, A.; Luther, J.; Willeke, G. Solar cells: Past, present, future. *Sol. Energy Mater. Sol. Cells* **2002**, *74*, 1–11.
27. The National Center for Photovoltaics (NCPV). Research Cell Efficiency Records. Available online: [http://www.nrel.gov/ncpv/images/efficiency\\_chart.jpg](http://www.nrel.gov/ncpv/images/efficiency_chart.jpg) (accessed on 16 April 2014).
28. United Nations. Report of the United Nations Conference on Sustainable Development. In Proceedings of the United Nations Conference on Sustainable Development, Rio de Janeiro, Brazil, 20–22 June 2012.

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