A new concept for using solar photovoltaic energy in urban water supply systems

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Abstract

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Solar photovoltaic (PV) systems can be applied very well to many areas of the water sector, such as urban water supply systems. This article presents an innovative methodology for using PV energy as a practical and sustainable solution for urban water supply systems. It presents a case study of the principal technological characteristics of an integrated energy-water system. The proposed solution consists of three parts: a PV generator and inverter, a service reservoir, and a pumping station. Given current trends, the proposed solution is slightly more expensive than conventional technologies. Nevertheless, the results obtained confirm the main idea of this research, which is that photovoltaic energy is a promising technology and provides a good solution for obtaining energy, in addition to being hydraulically sustainable urban water supply systems.

Keywords: Solar photovoltaic energy, water supply, service reservoir, pumping station, sustainability, life cycle costs.

Resumen

Đurin, B., & Margeta, J. (noviembre-diciembre, 2017). Un nuevo concepto para el uso de energía solar fotovoltaica en los sistemas urbanos de abastecimiento de agua. Tecnología y Ciencias del Agua, *8(6), 47-61, DOI: 10.24850/j-tyca-2017-06-04.*

Los sistemas solares fotovoltaicos (PV) pueden aplicarse muy bien en muchas áreas del sector de agua, como en los sistemas urbanos de abastecimiento del vital líquido. Este artículo presenta una metodología innovadora para la solución práctica y sostenible por uso de energía PV en sistemas urbanos de abastecimiento de agua. Se presentan las principales características tecnológicas del sistema integrado energía-agua en un caso de estudio. La solución propuesta consiste de tres partes: PV generador e inversor, depósito de servicio y estación de bombeo. Debido a las tendencias actuales, la solución propuesta es ligeramente más cara que la convencional. A pesar de ello, los resultados obtenidos confirman la idea principal de que este trabajo de investigación es prometedor y que la energía fotovoltaica significa una buena solución para la obtención de energía, además de ser hidráulicamente sostenible para los sistemas urbanos de abastecimiento de agua.

***Palabras clave**: energía solar fotovoltaica, abastecimiento de agua, depósito de servicio, estación de bombeo, sostenibilidad, costos del ciclo de la vida.*

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Urban water system and sustainable energy supply

Urban Water Systems (UWS) are defined as natural, modified and man-made elements of the urban water cycle that can be found in towns. The systems provide water to support human life, hygiene, health, safety, recreation and amenities. A natural system includes local and regional water resources, while a built system includes water intake, water supply pipes, pump stations, service reservoirs, distribution networks, water treatment plants, sewage network, channels, drains, wastewater treatment plants, pump stations and outfalls. The built system is an integral part of the broader urban infrastructure system. Water services are functions provided by the built system of water supply what is subject of this paper (figure 1), wastewater and storm water infrastructure.

Urban water system management should contribute to the goal of sustainable urban development. Today there is a need to integrate water utility in the smart city environment. However, a smart city is much more than just efficient utilities, distribution network, and water utilities which have the opportunity to provide services that go beyond the provision of water – from aquifer to transporting and treating water, pumping, and storage. Utilities in a smart city have the chance to provide their customers with a liveable urban environment that is safer and more secure in terms of water, air, and electricity.

The biggest challenge for modern water utilities is to keep water flowing at affordable rates, and the benefits of a smart city infrastructure can help achieve that. A smart city allows utility to reduce energy consumption in two ways: (a) the first is by shifting the energy consumption as much as possible to off-peak periods, and (b) the second is by consuming renewable energy. This paper will analyze only the use of solar photovoltaic energy (PV system) that allows reduction of energy consumption in both ways.

By using green energy such as PV electric energy, cities minimize energy use from classical electric energy sources, especially daily and seasonal peak load energy, and reduce the CO_2 emission. In this way, urban areas contribute to the reduction of greenhouse gas emissions and achievement of sustainability goals.

Energy and water consumption in the cities generally more or less goes hand in hand with daily solar irradiation (see case study). This means that the use of solar electric energy generators for water supply may lead to more efficient and sustainable solution. This especially applies to peak period that occurs during the day when insolation is the highest. However, water is consumed throughout the day, while solar irradiation occurs only during the sunlight period of the day. This means that the prerequisite for achieving continuous water supply is to provide adequate water storage to balance water charge and water discharge processes in design period. However, water storage also acts as energy storage since it

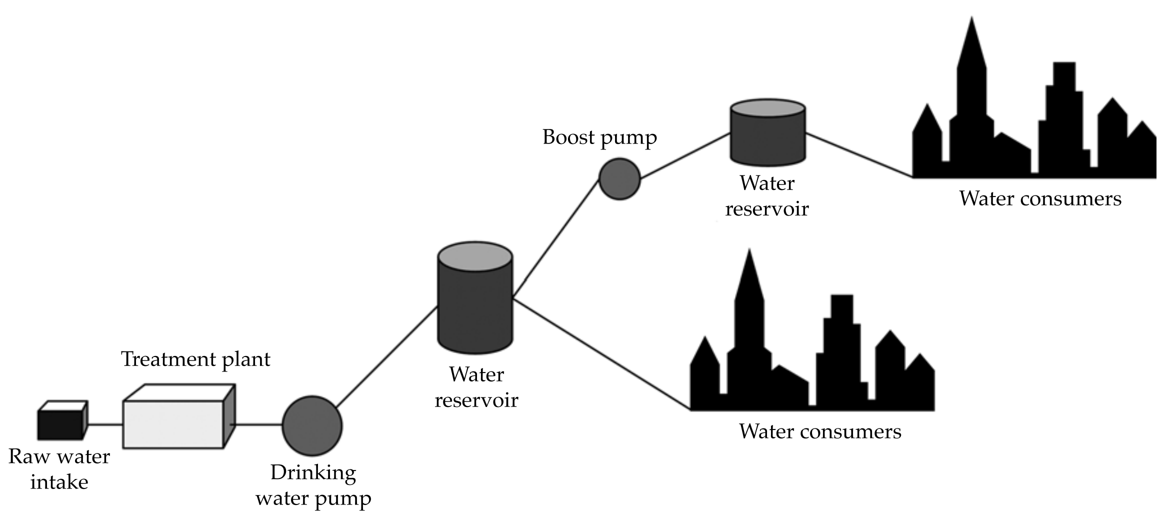

Figure 1. Typical elements of the water supply management system.

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balances energy input and output of the system at the same time.

In this paper, the PV generator has been selected as a solution for sustainable energy production for the water supply system. Input solar energy coincides with the dynamics of living in towns and hence water consumption, especially in the case of moderate and smaller size towns (figure 2). This means that energy production and water consumption could be easier to balance by using PV energy rather than other RES. PV systems use fewer technological processes and it elements in transformation of external solar energy in the system than ST systems (Green Power Technology, 2016). ST systems (especially large plants), are site specific and usually significantly distant from users, while PV systems can be located next to or within towns, as well as near water infrastructure. That is why the use of ST energy is less attractive, because it requires long distance transmission of energy with energy losses. Obviously, the most promising concept of sustainable energy production for urban water supply system is with PV system. In practice, proposed solution can hybridize with other non-renewable energy sources by connecting to the grid energy or using diesel aggregate. This paper considers the problem as a stand-alone system for electric energy supply.

The use of solar energy for water pumping has already been addressed in the literature, for example Bakelli, Hadj and Azoui (2011); Ghoneim (2006); Hamidat and Benyoucef (2009); Kenna and Gillett (1985). However, at present there are no significant publications on a more thorough consideration of possible applications of PV systems in solving the electric energy supply of urban water supply systems that comprehensively treat the integrated system "PV system-Pump Station-Service Reservoir" (PV-PS-SR), as is analyzed in this paper. None of these studies have included integration and full analysis of UWSS and its characteristics (daily and hourly consumption of water throughout the year, *i.e*. consumption profile), size of daily insolation and the role of water reservoir in the water supply system. Therefore, there is a need for sizing methodology of UWSS in accordance with the rules of the profession, which nullifies all mentioned drawbacks in relation to intermittent characteristics of the solar energy.

The paper describes the proposed solution for sustainable water supply, its basic features and methodology of sizing and selection of the size of the PV system $P_{el,PV}$ (W), volume of service reservoirs V_{op} (m^3) and total power P_{PS} (W) of the main pump station (MPS). In presented sizing methodology, each part of the system is sized separately and finally integrated into a one whole.

The proposed concept uses the PV system that operates together with water supply service reservoirs in order to provide continuous water supply to the town/consumer (figure 2). During the day, solar energy E_s is primarily used to supply electric energy $E_{el,PV}$ to main pump station (MPS) which pumps water into reservoirs. Water from the reservoirs is used according to the consumer needs. The service reservoir should be designed to have sufficient capacity to balance the pumped water and water demand. The PV system should have adequate power to supply the pump station with electric energy throughout the whole planning period. However, PV energy may at the same time be used for direct supply to the local grid and other users, when PV system has sufficient capacity and when the reservoir is full of water. The general objective of the system development is to provide continuous water supply to consumers over a long period which requires reliability with the best compromise alternative of the system elements.

H_g is geodetic head, while H_{PS} is total (manometric) head.

Theoretical postulates

System concept and sustainability of energy supply

The proposed system PV-PS-SR consists of three sub-systems:

— PV generator and inverter (PV).

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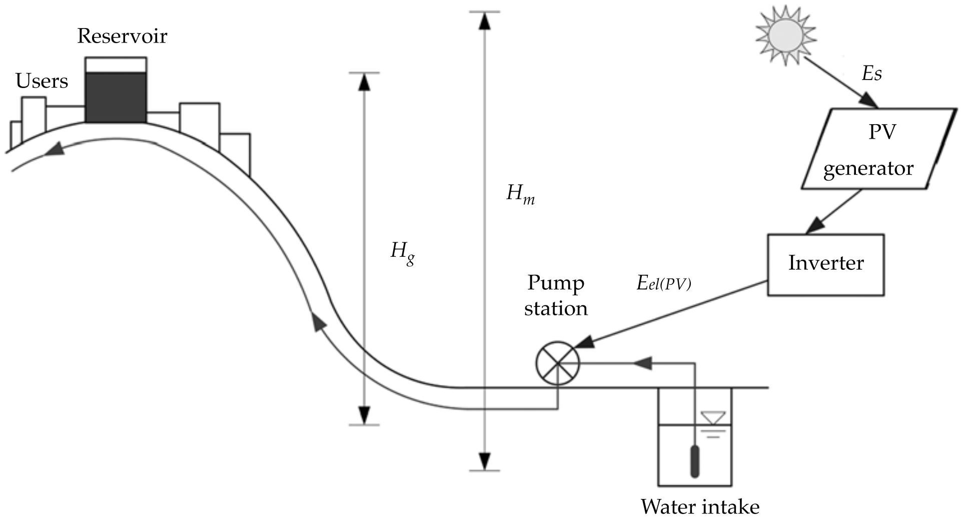

Figure 2. The concept of integrated system ''PV system-pump station-reservoir''.

— Pump station (PS) and rising main.
— Service reservoirs (SR) of water supply system.

The PV-PS-SR system essentially converts solar energy E_S from the environment into electric energy $E_{el,PV}$ (input electric energy) used for pumping water (mechanical energy E_{PS}) into service reservoir which provides sufficient water and head to the water supply network (output hydraulic energy). The total system of the proposed solution is made up of two parts: a sub-system of interest (PV-PS-SR system) and sub-system surroundings (solar energy). The energy surroundings of the system, the "Sun", are so large that they can be considered as an unlimited heat reservoir so that no matter how much is transformed to sub-system (PV-PS-SR), the temperature of the surroundings, as well as the pressure, will remain constant. It is significant for this time series that in the annual total size it more or less repeats from year to year (life cycle period) and therefore ensures continuity of the system production capacity.-The water used by the system is a part of selected water supply resources, and it is assumed that the water source has sufficient capacity throughout the entire planning period.

In this system, the main variables are daily solar energy $E_{s(i)}$, the duration of sunshine during the day $T_{s(i)}$, total daily water demand $Q_{daily(i)}$, hourly consumption of water during the day $Q_{WS(t)}$. These input parameters determine the dimensions of the system elements, the power of the PV systems $P_{el,PV(i)}$, the capacity of the pumping station $Q_{PS(i)}$ and the necessary reservoir volume $V_{op(i)}$ for balancing of water inflow by the work of the pumping station and consumption of water in the settlement, which are a set of results that define the optimal solution ($P^*_{el,PV(i)}$, $Q^*_{PS(i)}$, $V^*_{op(i)}$) in accordance with the objective function and constraints, where i = computational step in energy balance (day), i = 1,..., 366 days in planning life cycle period of N years, while t = computational step in water balance (hour) t =1,.., 24 hours in each computational day.

The way of energy $E_{s(i)}$ conversion from the environment is defined by PV and water supply system characteristics at a particular location. Each location and PV system will generate different water flow time series into the service reservoir, which results in different pump work (pumping duration $T_{S(i)}$ (h/day), pumping capacity $Q_{PS(i)}$ (m^3/h), and required operative reservoir capacity/volume $V_{op(i)}$ (m^3)), which

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has to balance water inflow $Q_{PS(t)}$ and outflow $Q_{WS(t)}$ (m³/h) for each day *(i)* in the design life cycle period.

Energy balance of the pumping system is:

$$\frac{dE_{system}}{di} = E_{el,PV} - E_{PS} - \Delta E \quad (1)$$

where i = 1,…, 366 days for each year in the planning life cycle period N, $E_{el,PV}$ is energy from the PV system, E_{system} is energy in the system, E_{PS} is energy consumption of the pump station and ΔE are energy losses from the system.

Water balance of the reservoir is:

$$\frac{dV_{reservoir}}{dt} = Q_{PS} - Q_{WS} - \Delta Q \quad (2)$$

where t = 1,…, 24 h for each i and each year in the planning life cycle period N, and $V_{reservoir}$ is water in the reservoir, Q_{PS} is the pump station flow, Q_{WS} is water consumption in the settlement and ΔQ are water losses from the system. These two equations describe operational work of the system and they are used for sizing of the analyzed system.

Power of PV generator

The nominal power $P_{el,PV}$ (W) for pumping water into the service reservoir in time step i is performed according to the characteristics of the PV power plant and local climate. The equation for electric power of a PV generator is derived from the equation used for sizing of the PV generator, presented in Kenna and Gillett (1985), and Glasnović and Margeta (2009), and which can generally be expressed as follows:

$$P_{el,PV(i)} = \frac{2.72H_{PS(i)}}{\left[1-\alpha_c\left(T_{cell}-T_0\right)\right]\eta_{MPI}E_{S(i)}} V_{PS(i)} \quad (3)$$

Where $V_{PS(i)}$ (m³/day) is daily water volume to be pumped by PV system into the service reservoir (m³), α_c is the PV generator efficiency temperature coefficient, $T_{cell(i)}$ is the average daily cell temperature and T_0 is temperature of the PV generator in Standard Test Condition (25 °C), η_{MPI} is average efficiency of motor-pump unit and inverter, $E_{S(i)}$ (kWh/m²/day) is average daily solar energy available for energy production, i is time step (days).

For a given nominal power $P_{el,PV}$ (W), possible pumping volume of water $V_{PS(i)}$ (m³) in time period i into the reservoir is:

$$V_{PS(i)} = \frac{\left[1-\alpha_c\left(T_{cell}-T_0\right)\right]\eta_{MPI}E_{S(i)}}{2.72\text{H}_{PS(i)}} P_{el,PV(i)} \quad (4)$$

The PV generator, of nominal power $P_{el,PV}$, forms a stationary field of PV collectors, interconnected serially and in parallel, in order to obtain the required voltage and current. Inverters are required in order for the PV system to provide alternating current (Rashid, 2001).

The limit in the scope of construction of the PV system, defined by local conditions generally, the PV generator area A_{PV} (m²) can be calculated by Kenna and Gillett (1985):

$$A_{PV} = \frac{P_{el,PV}}{1000\eta_{PV}} \quad (5)$$

where η_{PV} is average efficiency of the PV generator.

The power of PV generator $P_{el,PV}$ for a given daily solar radiation should pump volume of water $V_{PS(i)}$ (m³), respectively $Q_{PS(i)}$ (m³/h), which satisfies daily water demand $V_{WS,(i)}$, respectively $Q_{WS,(i)}$ in planning period (generally one year) or:

$$V_{PS(i)} \geq V_{WS(i)};\ i = 1,...,366 \text{ days} \quad (6)$$

The required power $P^*_{el,PV}$ of PV generator which satisfies the demand in critical period/day is:

$$P^*_{el,PV} = \max P_{el,PV(i)} \quad (7)$$

It is the period where the ratio between available solar radiation $E_{S(i)}$ and necessary hydraulic energy $E_{H(i)}$ for water pumping is minimal. That is why this selected power $P^*_{el,PV}$ may pump in other periods/days more water than necessary, depending on the selected capacity of the pumping station.

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Pump station capacity and power

Available insolation $E_{S(i)}$, *i.e.* electric energy $E_{el,PV(i)}$ determines the capacity and period of pumping station operation during each day of work. If all available energy is to be used for water pumping into the reservoir, average potential flow capacity of the pump station $Q_{PS,pot(i)}$ in period i is:

$$Q_{PS,pot(i)} = \frac{V_{PS(i)}}{T_{S(i)}} = \frac{P_{el,PV}}{T_{S(i)}} \frac{\left[1 - \alpha_c \left(T_{cell} - T_0\right) \eta_{MPI} E_{S(i)}\right]}{2.72\, H_{PS(i)}} \quad (8)$$

where $T_{S(i)}$ is average number of hours of daily insolation that can be used for water pumping (h/day). However, necessary average flow capacity of the pump station $Q_{PS,nec(i)}$, which satisfies water demand $V_{WS(i)}$ in period i is:

$$Q_{PS,nec(i)} = \frac{V_{WS(i)}}{T_{S(i)}} \quad (9)$$

So, the minimal required capacity of pump station Q^*_{PS} is:

$$Q^*_{PS} = \max\left(Q_{PS,pot(i)}, Q_{PS,nec(i)}\right) \quad (10)$$

Average power of the pump station P^*_{PS} is:

$$P^*_{PS} = \frac{\rho g Q^*_{PS} H_{PS}}{\eta_{PS}} \quad (11)$$

where η_{PS} is efficiency of the pump.

However, the installed capacity and operation of pumping station is determined as part of an integral solution of the PV-PS-SR system, in accordance with the characteristics and objectives of the project.

Volume of service reservoir

The required volume of water reservoir V_{op} is the result of balanced hourly inflow and outflow series, where total daily inflow is equal to total daily outfall. Volume for each day (time step i) is determined by hourly water consumption in the settlement $Q_{WS(t)}$ and the regime of water inflow into the reservoir $Q_{PS(t)}$, *i.e.* the operation of the pumping station (Margeta, 2010) in period i:

$$V_{op(i)} = \max\left[\sum_{i=1}^{366}\left(Q_{PS(i),t} - Q_{WS(i),t}\right)\right], 1 \le t \le i \quad (12)$$

where $t = 1,\ldots,24$ h and $i = 1,\ldots,366$ days.

The equation (12) is valid if in the period from $t = 1$ h to 24 h (1 day) total water inflow is equal to outfall.

The required minimal volume V^*_{op} is:

$$V^*_{op} = \max V_{op(i)};\ i = 1,\ldots,366 \text{ days} \quad (13)$$

In general, the critical day for design of volume reservoir is the day with maximum water demand, providing that that day available insolation $E_{S(i)}$ is sufficiently high.

Design procedure and characteristics of solution

The general objective of system design is finding the electric power of the PV generator that will, in the best manner possible, meet all consumer needs for water, with minimal construction and operation costs of the system RES-PS-SR. However, solar energy input is free. Broader objectives of the problem have to be taken into consideration, as well as economic aspects of green energy use, instead of classical energy. These other issues 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_2 emission, etc.

Electric energy that can be produced by the PV system directly depends on the fluctuating radiated solar energy and its size, so that for a chosen size of PV generator, in certain time periods it would pump too much, and in others too little water into the reservoir. That is why the simplest solution is the selection of the PV power plant for the most critical period of pump station work. It is necessary since the water supply system has to meet all needs constantly or at a required level of reliability in the

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whole planning period. Balancing for sizing the required volume of the service reservoir in the urban water supply system is at least one day (24 hours). However, reservoirs usually have larger volume than the required for balancing of the inflow by PS operation and the water demand in order to supply water in the system during incidental situations.

In the preliminary studies of the problem a simplified implicit approach is mainly used (figure 3). The main input data for the analysis are: climate data, including daily solar irradiation, water supply system configuration (intake, pump station, reservoir) and daily water demand needs in the planning year and fluctuation of demand during the day. At the beginning it is also necessary to determine the constraints related to the construction of the PV system, pump station and reservoir, as well as economical, legal, environmental, social and other requirements.

At the beginning of the analysis it is necessary to define the daily quantity of water in the settlement $V_{WS(i)}$, according to settlement characteristics and water consumption regime throughout the year of the planning period (i = 1,..., 366 days). After this the daily water usage pattern in a settlement $Q_{WS(t)}$ (t = 1,...,24 h) is determined.

The PV generator power $P_{el(i)}$ is calculated and the potential annual production of electrical energy is generated in accordance with the climate characteristics of the area. Based on the obtained values, the minimum required size of the PV generator $P_{el,PV}$ 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 value $P^{(1)}_{el,PV}$ and $V^{(1)}_{PS}$, which satisfy the demand, the minimum required power of $P_{el,PV}$ is determined from the established differences:

$$\Delta V_i = V_{PS,i} - V_{WS,i}\ ;\ i = 1,...,366 \text{ days} \qquad (14)$$

Due to that, critical day/period for sizing of the PV generator is $t_{tb,i,PV}$ is determined by the minimum daily difference:

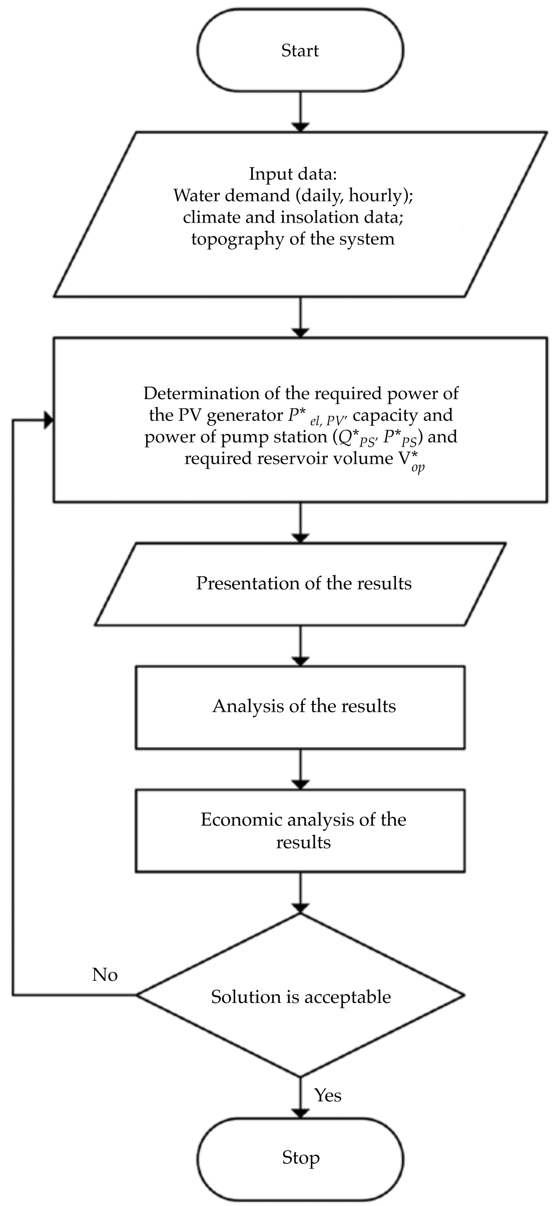

Figure 3. Flow chart of the PV-PS-SR system sizing.

$$\min \Delta V_i \Rightarrow t_{tb,i,PV} \qquad (15)$$

where ΔV_i is acceptable difference in practice application.

The selected power of the PV generator $P_{el,PV}$ will satisfy the demand throughout the whole planning period N, whereby it will generate excess electric energy in the greater period of the year. Surplus electricity can be used locally

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in the water supply system or transmitted into the regional power system and thus realize significant profits because significant incentives are given to the production of green energy in many countries. This energy can pay the costs of energy consumed from the regional power system in incidental situations (failure, insufficient sunshine, etc.).

The size of service reservoir has been calculated for each day in the year, *i*, in accordance with each balancing period t_b in the year. In general, the critical day/period $t_{tb,i,Vop}$ for the design of volume reservoir V^*_{oP} is the day with maximum water demand, providing that on day available insolation $E_{S(i)}$ is sufficiently high.

The next step selects the capacity Q^*_{PS} and power of the pumping station P^*_{PS}. Procedure for finding of the critical day $t_{tb,i,PS}$ for the design of pump station is the same as is for the volume reservoir. Since insolation is variable during the year and during the day, the pumping station work is variable both in terms of the required capacity, as well as in relation to the period of operation. It is therefore necessary to provide an energy efficient solution for different operating regimes that may occur during the year, as well as adequate reserve capacity.

The size of the system structures, and thus the cost of building the system, significantly depends on the regime of sunshine and water demand during the year. There are different situations depending on the climatic characteristics of the area and activities, *i.e.* demand in water supply system. However, the concept is very flexible and reliable, especially in cities where water consumption is greatly affected by climatic characteristics of the area, such as tourist areas of the Mediterranean. In these areas, especially in small tourist towns, the dynamics of solar radiation coincides with the dynamics of water consumption during the year. Summer insolation is higher, but water consumption is also higher in towns due to seasonal tourism.

The proposed sizing methodology of the PV system is based on critical insolation (which is usually in the winter), gives a surplus of power in the remaining period of the year, which is a certain reserve in the PV generator power during periods of high demand in the summer. This means that in the case of smaller daily insolation, due to cloudiness, the system is capable of pumping the required water quantities.

On the other hand, large reservoir volume designated for the critical period of water supply (summer period with the highest consumption of water) is a good reserve of the available water volume for possibly lower insolation in the winter when demand is many times smaller, and insulation is significantly weaker and more uncertain due to the higher cloudiness. This means that if the backup of water in the reservoir is maintained, it can meet the water demand in a period of several days when insolation is possibly lower than calculated.

The total head of the pumping station H_{PS} is variable, *i.e*. the highest when demand is the greatest. This means that in other periods the pumping station has a significant surplus of capacity.

The capacity of the pumping station in this case is still significantly higher than in the case of the use of energy from regional grid system. The same goes for the reservoir volume because water is pumped within 24 hours.

Therefore, designing a green solution for water pumping in the water supply system has a large reserve for incidental situations. Normally, it is always possible to use the energy from the grid system or other local source of energy.

Economic analyse and characteristics of the system

General sustainable objectives are related to economic, social and environmental aspects of the problem. By using green PV energy instead of classical, most of the environmental objectives are fulfilled. Social objectives are related to basic water service price as measurable criteria and sustainable green city environment as general in commensurate criteria. Fulfilment of both sustainable objectives is closely related to economical characteristics of the solution. Nowadays, the economic criteria are still dominant and

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that is the reason why good economic analyses of the problem are the basis for solution and alternative evaluation.

The economical approach, according to the concept of life cycle cost, *LCC* (€) (Bakelli *et al.*, 2011; Ghoneim, 2006) and net present value *NPV* (€) (Kenna & Gillett, 1985; Stevanović & Pucar, 2012), is developed to be the best indicator of economic profitability of the system cost analysis.

The system consists of three main parts: (1) PV generator and inverter, (2) service reservoir and (3) main pump station and associated rising main. *LCC* takes into account the initial capital cost ($C_{capital}$), the present value of replacement cost ($C_{replacement}$) and the present value of maintenance cost ($C_{maintenance}$):

$$LCC = C_{capital} + C_{replacement} + C_{maintenance} \qquad (16)$$

In the case of urban water supply system, the economic objective is to minimize possible economic losses which 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, PVX spot market price - index solar PV modules (PVX, 2015), Campoccia, Dusonchet, Telaretti and Zizzo (2009). A logical question always arises - how much is the proposed concept more expensive compared to the conventional solution and under what conditions would it also be economically acceptable. Therefore, a case study is analyzed hereinafter that will attempt to answer this question.

Initial capital/investment cost

The initial capital cost of each system component consists of the component price, the cost of construction work, installation and connection:

$$C_{capital} = C_{PV} \cdot c_{PV} + C_{SR} \cdot c_{SR} + C_{PS} \cdot c_{PS} + C_{const} \qquad (17)$$

Where C_{PV}, c_{PV} are the total power (W) and unit costs (€/W) of PV system respectively; C_{SR}, c_{SR} are the total capacity (m^3) and unit costs (€/m^3) of Service Reservoir; C_{PS}, c_{PS} are the total power (W) and unit costs (€/W) of Pump Station unit respectively; C_{const} is the total constant cost including other project related constant costs (design, land, taxes,...).

In this study c_{PV} includes total cost of PV generator and inverter; c_{PS} includes total cost of PS and rising main; c_{SR} includes total cost of SR.

The present value of replacement cost

All replacement costs occurring throughout the system lifetime have to be calculated in accordance with particular life period of each component. The present value of replacement cost ($C_{replacement}$) can be determined by Soras and Makios (1988):

$$C_{replacement} = C \cdot c \sum_{i=1}^{N_{rep}} \left[\frac{\left(1+f_0\right)}{\left(1+k_d\right)} \right]^{N_i/N_{rep}+1} \qquad (18)$$

where f_0 is inflation rate of component replacement, k_d is interest rate, C is capacity of replacement system component, c is unit component cost and N_{rep} is the number of component replacements over the system life period.

The present value of operation and maintenance cost

In this example the present value of operation and maintenance cost of the pumping system is calculated by Groumpos and Papageorgiou (1987):

$$C_{(O\&M)} = C_{(O\&M)_0} \left(\frac{1+f_1}{k_d - f_1} \right) \cdot \left[1 - \left(\frac{1+f_1}{1+k_d} \right)^{L_p} \right]; \text{ for } k_d \neq f_1$$

$$C_{(O\&M)} = C_{(O\&M)_0} \cdot L_p; \text{ for } k_d = f_1 \qquad (19)$$

Where f_1 is inflation rate for operation, k_d is annual real interest rate and L_p is the system life period in years. $C_{(O\&M)0}$ is the operation and

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maintenance cost in the first year. It can be given as a fraction k of the initial capital cost $C_{capital}$:

$$C_{(O\&M)_0} = C_{capital} \cdot k \quad (20)$$

In this study it is assumed that all prices escalate at the same rate.

Net present value (NPV) of electric energy costs

Money eventually loses its value (National Renewable Energy Laboratory, 1995), which means that it is necessary to take into account the time value of money. In other words, the net present value (*NPV*) shows how much the money will be worth at the end of a certain period. According to Kenna and Gillett (1985), Stevanović and Pucar (2012), the net present value *NPV* is defined by:

$$NPV = \sum_{i=1}^{N} \frac{F}{\left(1+d\right)^{N}} \quad (21)$$

where F is the future money value (whether positive or negative) in period N with certain discount rate d. The discount rate represents a measure of how much money is worth in a period of time in relation to its present value (National Renewable Energy Laboratory, 1995). The discount rate may be nominal and effective. In nominal discount rate inflation is taken into account, while in real discount rate inflation is not taken into account (Darling, You, Veselka, & Velosa, 2011). In this work, nominal discount rate will be considered, because it shows the real situation, as inflation is included in it.

The concept of economic energy balance is introduced, which represents the cost of electric energy in the conventional system, *i.e.* profit from the sale of surplus electricity from the PV system. The concept of the economic balance of the system is also introduced, which represents the sum of *LCC* and economic energy balance of the system.

Example and discussion

Case study

This paper presents a hypothetical example of a settlement which has a population equivalent of 8 970. The settlement is located on an island in the southern Mediterranean part of Croatia. That settlement is in hilly area of the island and has one water reservoir located at ground elevation of 259 m above sea level. Water flows into the reservoir from the wet basin of the pump station. Water in the wet basin inflows from the spring by gravity. Total head of the pump station is H_{PS} = 82.41 m. The water quality is satisfactory so that it does not need treatment. The positions of the basic facilities of the water supply system are shown in figure 4.

The analysis has been conducted according to the presented methodology. Specific water consumption per capita q_{sp} is 160 litres capita day^{-1}. Annual daily water consumption Q_{WS} is shown in figure 5 (Margeta, 2010).

Hourly consumption of water in the settlement is determined by the daily regime of consumption, as shown in figure 6 (Margeta, 2010).

For this case, the average efficiency of the inverter and motor pump unit is η_{MPI} = 0.75, η_{PV} is an average efficiency of the PV generator, cell temperature coefficient is α = 0.005 °C^{-1}, and temperature of the PV generator in Standard Test Condition is T_0 = 25 °C. The calculation is made with a 50% of average array output in relation to rated output (η_S = 0.5).

The average daily global radiation $E_{S(i)}$ and average daily insolation period $T_{S(i)}$ is shown in figure 7 (MHSC, 2007).

Results and discussion

Based on given solar power data and water demand data, by applying the presented methodology, the given data sets have been determined (table 1) for balancing period of one day (t_b = 1 day), due to the scope and purpose of this paper.

The same water supply system is sized in the conventional way by energy supply from

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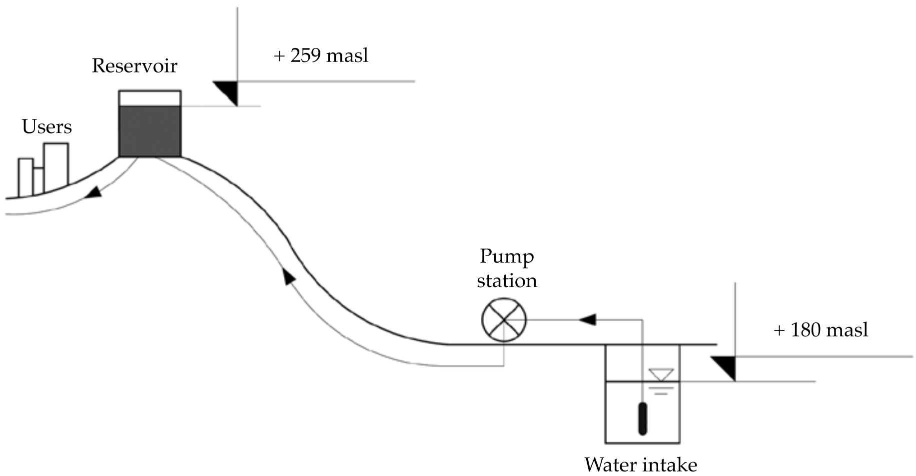

Figure 4. Case study schematic layout.

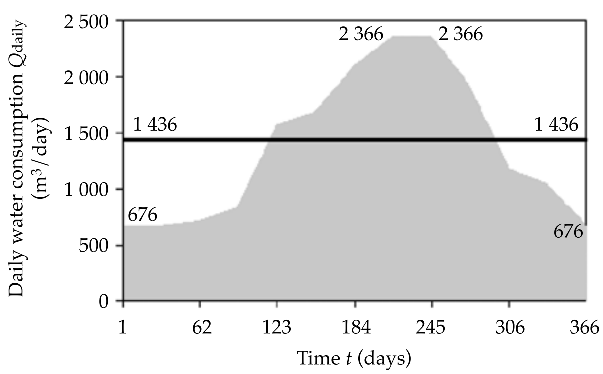

Figure 5. Daily water demand during the year.

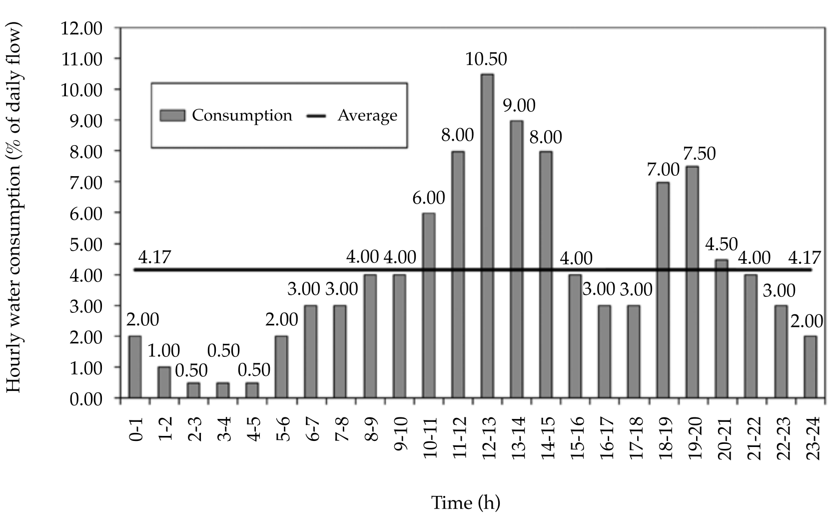

Figure 6. Hourly water demand during typical day.

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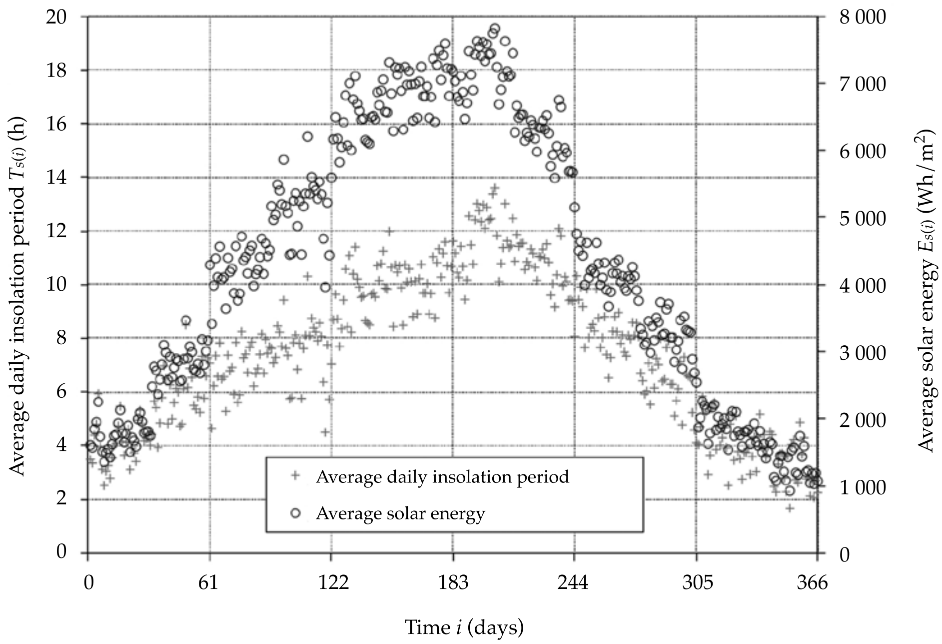

Figure 7. Average daily solar insolation and duration of sunlight.

conventional energy system. The system is dimensioned for a critical day, *i.e*. the day of peak water consumption, with constant re-pumping water into the reservoir. The characteristics of the pump station and reservoir volume are determined, and the annual electric energy consumption is calculated (table 1) by using data from Margeta (2010) and HEP Group (2017), where the value added tax is 25 %, since it is an analysis of the actual cost of electricity in the Republic of Croatia.

Based on Equation (16)-(21) and using data from literature (Bakelli *et al*., 2011; PVX, 2015; Hidroing Ltd., 2004; Hrvatske Vode PLC, 2008; Penstar Ltd., 2012; White International, 2012), Life Cycle Cost analysis (*LCC*) and also energy cost and revenue of electric energy for the PV and conventional system has been made for the period of N = 25 years and presented in tables 2, 3 and 4.

Nominal discount rate for the conventional system is 8 % (ACEEE, 2009), while for the PV system it is 10 % (US Department of Energy, 2010). It should be noted that in the PV system there are profits from the sale of surplus electricity, while in the conventional system there are expenditures due to electric energy needs. Table 3 does not include the sale or other use of all surplus electricity generated from PV systems.

Looking at the results it can be concluded that the classical system (with conventional energy sources) is better, *i.e*. about three times cheaper, compared to the system with the solar energy source.

Let's consider the sale of surplus electricity from the PV system, with the sale of all surplus electricity from the PV system (100% excess energy) (table 4).

Looking at the results for this case, we can conclude that the system with solar energy source, is more expensive compared to conventional systems (with conventional energy), but only by about 8%. The difference is not large, so it can be concluded that for cost effectiveness of application of the PV system it is very important to fully use the available energy. It is peak energy that has the highest value in the system. It can be used for various purposes, boost pump work or other daily energy needs. The annual

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Table 1. Characteristics of the PV water pumping and conventional water pumping system elements.

Concept	Solar photovoltaic (PV) system	Conventional system
Maximum daily consumption, $Q_{daily,max}$ (m³/day)	2366	2366
Critical days: $t_{tb,i,PS}$, $t_{tb,i,PS}$, $t_{tb,i,PS}$	352, 244, 244	From 212 till 243
Power of *PV* generator, $P_{el,PV}$ (kW)	512.5	-
PV generator area (m²)	3417	-
Operative reservoir volume, V_{op} (m³)	1100	584
Capacity of pumping station, Q_{PS} (l/s)	118	27
Diameter of pressure (main supply) pipe, φ (mm)	300	150
Roughness, *k* (mm); increase due to local losses (10%), *k** (mm)	*k* = 0.1; *k** = 0.11	*k* = 0.1; *k** = 0.11
Water flow velocity in pipes, *v* (m/s)	1.67	1.53
Length of pressure pipe (main supply pipe), *L* (m)	493.58	265.89
Geodetic height difference, H_g (m)	79	79
Pressure losses, Δ*H* (m)	3.41	3.41
Total head, H_{PS} (m)	82.41	82.41
Pumping station power, P_{PS} (kW)	106.05	24.25
Annual consumption of electric energy used for pumping station operation (kWh)	288 573	213 041
Annual cost of electric energy used for pumping station operation (VAT added) (€)	-	34 954 (''blue tariff'')
Annual produced electric energy from PV generator (kWh)	1 394 513	-
Annual surplus of electric energy (kWh)	1 105 939	-
Annual earnings from sales of surplus electric energy (VAT added) (€)	179 715	-

Table 2. Costs and life time aspects of the system components for the PV and conventional system.

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	10	4	4
Inverter	0.5 (€/W)	0	10	8	4	4
Service reservoir	400 (€/m³)	1	25	8	4	4
Pump station	1 (€/W)	3	15	8	4	4

hodograph of production as well as of surplus of produced energy follows the annual hodograph of water consumption (figures 5 and 7).

The analysis should be adapted to the actual characteristics of the problem. A more detailed, sensitive analysis with respect to input data and with current trends (increasing the price of electricity to drive the classic system of 2% per year in the observed period of *N* = 25 years, reducing the selling price of electricity from the PV system by 7% annually within the observed period of *N* = 25 years), the trend of price change of the generator (price reduction by the day by 4% to 7% annually within the observed period of *N* = 25 years, PVX spot market price - index solar PV modules, 2015; Campoccia *et al.*, 2009), etc., would give a more complete picture of the problem to be solved. Also, it should be noted

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Table 3. Costs of the PV and conventional system for the period of $N = 25$ years without the sale of surplus electric energy from the PV system.

Costs (€):	$C_{capital}$	C_{repl}	$C_{(O\&M)}$	Energy sale and costs	LCC
PV system	1 571 050	554 111	263 455	0	2 388 616
Conventional system	257 850	11 880	53 446	373 126	696 302

Table 4. Costs of the PV and conventional system for the period of $N = 25$ years with the sale of 100% surplus of electric energy from the PV system.

Costs (€):	$C_{capital}$	C_{repl}	$C_{(O\&M)}$	Energy sale and costs	LCC
PV system	1 571 050	554 111	263 455	1 631 280	757 336
Conventional system	257 850	11 880	53 446	373 126	696 302

that the efficiency of the PV generator increases from the current 15% (SRoeCo Solar, 2015; PVPower.com, 2015) with the expected up to 30% in the next 25 years, Goetzberger, Joachim-Luther and Willeke (2002), which has already been achieved in the laboratory, IOP - Physics World - the member magazine of the Institute of Physics (IOP, 2015). Such analysis goes beyond this work.

Conclusions

Presented concept of the use of PV systems in the electric energy supply of the main pump station of urban water supply system is feasible because of the new and innovative approach of sizing. Methodology in which each part of the system is sized separately and finally integrated into a one whole can also be practically applicable. The PV system in the presented climate conditions continuously provides sufficient electricity to operate the main pumping station throughout the whole year. It not only provides enough energy, but also provides significant surpluses that can be used in other energy consumers in the water supply system (boost pump).

Achieving the sustainability and use of green energy has its price. Although the basic energy resource is free, and so is a significant part of operating costs, the construction costs are significantly higher and predominantly relate to construction costs of the PV generator. However, total operating costs of the PV system are slightly higher in the conventional solution. Based on the presented results it can be concluded that over the oncoming 25 years the PV systems are expected to have a more significant advantage over conventional systems, due to higher efficiency and lower prices of the PV system.

It should be emphasized that the multi-criteria analysis would give a more complete picture of the analyzed problem, since in addition to economic criteria, environmental, technological, legal, political, and social-ethical criteria should be considered (Erol & Kılkıs, 2012).

The proposed concept of energy production and use has a significantly smaller impact on the environment than classical electric energy sources. In its operation it does not consume water, organic or other substances, does not create harmful residues, and therefore provides opportunities to support sustainability of the cities or green city environment (United Nations, 2012).

The proposed concept is especially acceptable for isolated water supply systems such as islands and similar areas away from the regional energy supply systems, because it provides a complete local energy supply. So it is not necessary to build long energy supply lines that create large energy losses, or at least it is not necessarily to build them in full peak capacity.

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