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A SIMPLE METHOD ESTIMATES AND ECONOMIC INDICATORS OF PHOTOVOLTAIC SYSTEMS FOR DRIP IRRIGATION

Boško Gajić¹, Zorica Tomić², Zorica Sredojević³

Summary

Renewable, environment friendly, photovoltaic (PV) solar energy have been one of the most attractive means for pumping the water needed to irrigate crops. However, since at the present time PV systems still suffer from high investment costs it is necessary to accurately dimension the installations. This study presents a simple but accurate a process to estimate the required dimension of a photovoltaic installation designed to power a pumping system for the drip irrigation of a raspberry plantation in W Serbia. The methodology is based on systematic approach to the problem, taking into account all relevant elements, from PV pumping system, local climate, soil properties, depth of well, characteristics of the crop, to irrigation system. With an array of 579 Wp it was found that the system is able to irrigate, without deficit of water, 1.0 ha raspberry plantation. The methodology presented here is applicable for a range of crop areas, and a variety of crop types in regions of similar climate, soil and latitude. Besides the advantages for the environment, since it uses a renewable energy, a study on the economic viability of a photovoltaic system shows that it is similar to conventional systems which use a generator unit. Moreover, the high price of fossil fuels guarantees a progressive advantage of photovoltaic systems.

Key words: *PV-pumping, Irrigation, Raspberry, Investments, Economic Indicators.*

JEL: *Q24, Q25, D42*

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Introduction

Photovoltaic technology can be used for different purposes, from PV cells in watches and calculators, to solar modules in telecommunications equipment and emergency traffic applications, to PV arrays for water pumping and generation of electricity in agricultural and rural areas. Water pumping applications include, but are not limited to domestic water, irrigation, livestock watering, and village water supplies. In combining irrigation and solar energy, a small PV system can be used to power a water pump for small-scale irrigation. The use of such a system is first appropriate since there is a natural relationship between the availability of solar energy and the water requirement. That is, the water requirement increases with increasing solar radiation level. Solar water pumping systems have some distinct advantages in electrical power production such as, being environmentally friendly, requiring no fuel cost, operating with no noise and wear due to absence of moving parts, and also requiring little maintenance. Using PV array to drive water pumping units for irrigation and drinking water in remote areas, where other sources of power not available, are found to be the most feasible and economically viable design configuration (Posorski, 1996).

The major barriers of using PV systems, in general, are the high market prices of photon capture devices, and installation costs and low energy conversion efficiency of PV cells available in the market (Cuadros et al., 2004; van Campen et al., 2000, Firatoglu and Yesilata, 2004; Sredojević et al., 2008, Golusin et al., 2010). Significant cost penalties therefore result from oversizing a PV system since the cost is mostly dependent on the PV array area (Landridge et al., 1996). Therefore it is necessary to correctly dimension PV solar power installations before initiating any subsequent study of their performance in a given application. i.e., one must determine the power requirements for a specific application accurately in order to make the cost of the installation profitable in as short a time scale as possible (Cuadros et al., 2004). The previous optimizing of PV water pumping systems, which have been the subject of numerous papers, mainly dealt with improvement of effectiveness of various system components, as well as their better mutual adjustment, with the aim of total cost reduction of the PV pumping system (EC, 1997; Ghoneim, 2006).

On the other hand, optimal sizing of the PV pumping system is basically reduced to calculation of the required hydraulic energy at the output of the system and its relation to monthly average daily solar irradiation. Hydraulic energy for PV pumping systems for irrigation is estimated based on required water quantity data, calculated by agronomist, and total head of water rise (Kenna and Gillett, 1985; Hamidat et al., 2003). There is a dearth of research information on studies connecting both technologies. Cuadros et al., (2004) reported a procedure to estimate the required dimension of a PV installation designed to power a pumping system for drip irrigation of an olive orchard in semi-arid climate (SW Spain). Hence, in this study we present simple procedure to estimate the design requirements of a PV system to power the drip irrigation of a raspberry plantation in a hilly-mountainous area, in W Serbia. This is based on the separate existing knowledge on PV pumping and on the water requirements of the crop. We have specifically addressed the requirements of raspberry plantations in the region of Arilja.

This study was developed taking as a basis the climatic and soil properties of raspberry plantations in the Arilje raspberry producing area. The Arilje raspberry producing area (349 km²) is located in the W Serbia (Photo 1). This is a hilly-mountainous area at an altitude of 330 to 1382 meters. Raspberry production plays a major role in the wealth of the Arilje region not only in the farming sector, but also socially, environmentally, etc. The area of the region devoted to raspberry is around 4000 ha. Serbia is one of the largest raspberry producing and exporting countries in the world. With annual production of 76 991 tons Serbia occupies second place in the world raspberry production (FAOSTAT, 2007).

Raspberry producing areas are in general socially and environmentally very sensitive. Raspberry plantations represent one of the few viable options for generating wealth in Serbia and reducing rural depopulation. Raspberry is grown mostly under rain-fed conditions in the Arilje region. However, global climate change is the cause of increasingly frequent and long-standing draughts, reduction in precipitation amounts, soil moisture and water resources capacity, prolonged vegetative growth, increased solar radiation, temperature and evaporation and gravely intensifying problems in waterpower engineering and food production. Due to above mentioned, Arilje raspberry growing region that yields 20,000 tons of raspberry crop accounting for 1/3 of national and 1/20 of the world fresh raspberry crop production, 40-50 million Euros worth, has undergone the decline in yields from a record of 33–28 t/ha to an average of 7–8 t/ha, tending to a further drop.

The owners of raspberry plantations are increasingly facing a challenging question: How to cope with a draught and maintain the level of production with limited water resources and electrical energy to power a pumping system? In solving the problem, the option of utilizing solar energy seems to be especially attractive. Evaluated through photovoltaic potential, depending on geographical latitude and the season, it is the largest natural renewable source of energy available to each individual plantation.

The mentioned option is attractive for at least three reasons more: (i) Increasingly limited, costly and difficult of access at any place non-renewable conventional energy sources (oil, natural gas, coal, water-electrical energy). (ii) Sufficiently high solar potential of Arilje raspberry growing area to power a pumping system for the drip irrigation of raspberry plants. Energy requirements of this type of system are lesser by 3–12 times, simultaneously saving water requirements by 40-60% compared to other irrigation methods (gravitation, sprinkler systems), but still constitute a little-known technical option, especially in the agricultural sector. (iii) Maintenance of profitability and achievements of “Arilje-Serbian” raspberry, which has become synonymous in the world with being good quality, developed by highly-disciplined technology of growing in an “Arilje way” by hand harvest on small-sized plantations (average size 0.36 ha), suited to the capacity of a rural patriarchal family engaging 2-3 seasonal workers for raspberry harvest campaign.

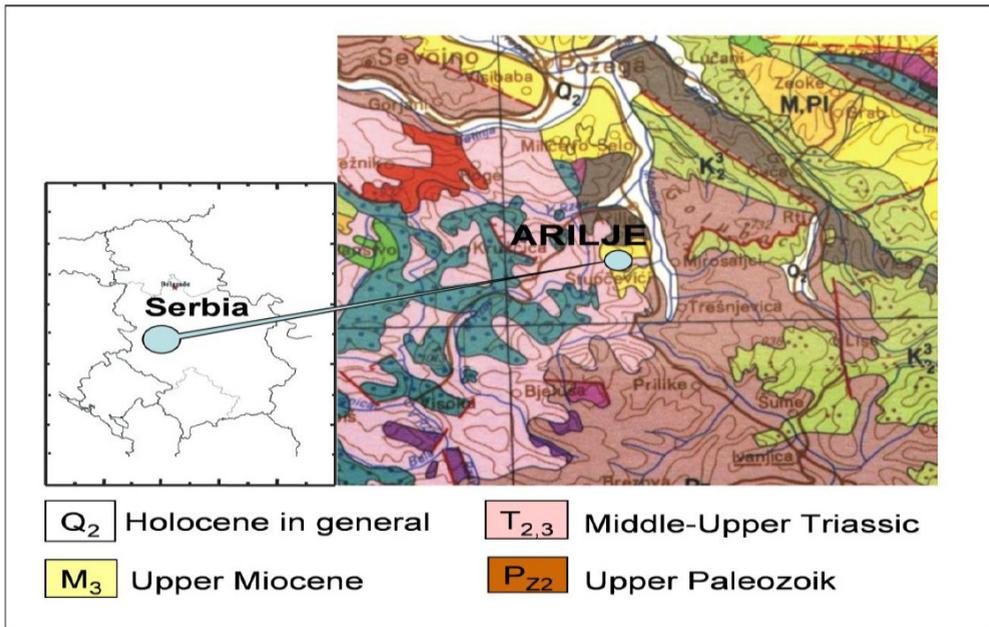
Several experiments have shown that raspberry plantations irrigation, even at rates which are relatively small compared to those used for other crops, may enhance the productivity of the raspberry \approx 2.5–3 times, compared to that under rain-fed situations (farmer’s statements). There is, therefore, a tendency to bring raspberry cultivation under irrigation during the dry

season (May – July). The aim of introducing irrigation with PV water pumping system into raspberry plantations of the Arilje raspberry producing area is to increase their productivity, and hence to allow the economic development of extensive rural areas of this Region, avoiding migration from these territory to the cities. Also, the FAO and EU vigorously encourage and support the use of renewable, non-contaminating energy resources in achieving sustainable agriculture and rural development (van Campen et al., 2000, Commission of the European Communities, 2006, Milić et al., 2008). The use of drip irrigation powered by solar energy could contribute to the necessary long-term reduction of energy and water consumption in the agricultural sector. The procedure presented here is likely being applicable to other berry-like fruits (blackberry, blueberry, etc.) and crops and other regions of the world.

Material and methods

Site description. The study was conducted on noncarbonate silt loam soils classified as Fluvisols (FAO, 2006), at the experimental farm of Specialized Agricultural Cooperative of raspberry producers, berry-like fruits and other fruits “RUBUS ARILJE”, located in the village of Stupčević, 6 km south of the city of Arilje (43°45’ N, 20°05’ E, 354 m a.s.l.) in W Serbia (Picture 1).

Picture 1. Locations of analyzed areas

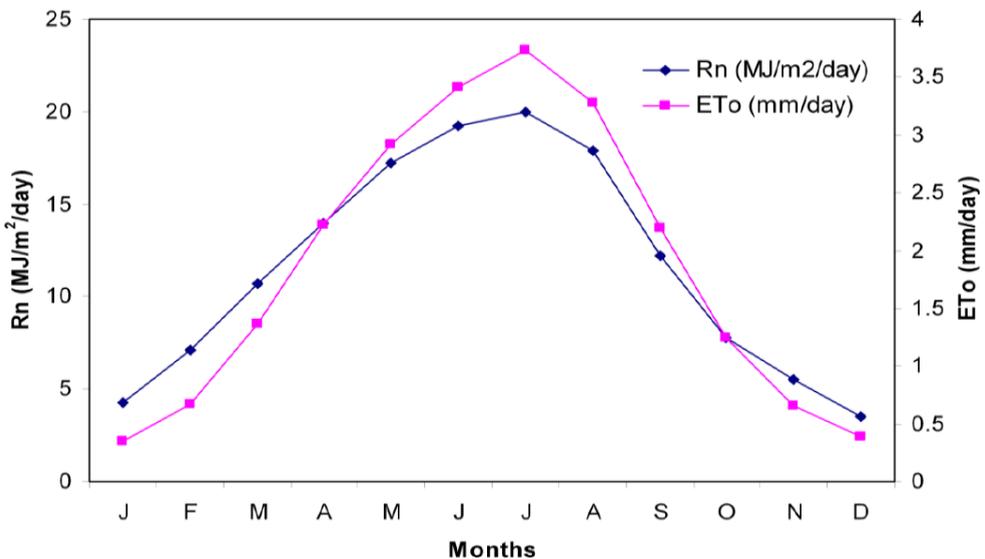


The Fluvisols were formed over a poorly carbonated alluvium of the Moravica River and are one of the most fertile soils found in Serbia and large areas of south eastern Europe. The soil has the water retention ($\text{cm}^3 \text{cm}^{-3}$) 0.31 at -33 kPa (field capacity, *FC*), 0.10 at -1500 kPa (permanent wilting point, *PWP*) and a plant-available water capacity (*PAWC*) of 147

mm in the top 0.7 m. Infiltration rates are very high when the soil is dry and cracked. Such soils are well suited for raspberry growing, since they are deep, clayey, with no coarse elements on the surface, and well drained.

Climatological characteristics. Climate of the region is continental. Rainfall in the region is highly variable with an annual coefficient of variation of 50%. Over the 20-year period (1988–2008) annual rainfall varied between 538 and 975 mm with a mean of 740 mm, 60% falling in September–April. Summer rainfall is characterised by intense convective storms and long dry periods with high temperatures and evaporative demand. The mean annual daily temperature is around 10°C, with maximum and minimum temperatures in August (28.2°C) and in January (−4.7°C), respectively. Average annual evaporation (Class A pan) is 685 mm (1971–2000) with maximum daily values commonly reaching 3.7 mm. A summary of the recorded mean monthly solar radiation and reference evapotranspiration is presented in Figure 1.

Figure 1. Recorded mean daily net radiation (R_n) at the surface of the crop and reference evapotranspiration (ET_o) at the site of Arilje



Field measurements were taken during the productive cycle of a 3 years old raspberry (*Rubus idaeus* L.), variety “Willamette” on a 0.5 hectares. This variety is perfectly adapted to the climate and the quality of the soils. The raspberry plants had an average height of 1.7 m, spaced of 2.5 m between rows by 0.2 m between plants.

Results and discussion

Estimation of crop water requirements. The soil and its properties determine water retention capacity and conditions/processes of water flow from surface into deeper layers (infiltration) and from soil into the atmosphere (evapotranspiration). Soil moisture is the key decision variable that determines the conditions within the system and water requirements. If the

soil water content is insufficient to compensate the transpiration losses from the plants, the crop will be subjected to a water deficit that will alter a series of processes with negative repercussions on production. Similarly, there is a main water loss by evaporation from the surface of the soil, depending mostly on meteorological factors and soil properties. The sum of the water consumed by the plant in transpiration and evaporated from the soil is called the evapotranspiration of the crop, ET , and it must be wholly satisfied by rainfall and/or irrigation for the crop production potential not to be affected. ET constitutes the most important variable to be considered when designing an irrigation strategy for a particular crop in a specific soil and under a climatic regime (Allen et al., 1998, Gajić and Sredojević, 2006b). The calculation of ET is the first step in order to estimate the annual crop water requirement, $ACWR$. Estimation of ET is essential for computing the soil water balance and irrigation scheduling. ET is governed by weather and crop condition. According to Doorenbos and Pruitt (2007), mathematically, ET in i period can be expressed as:

$$ET = ET_0 \cdot K_c \quad (1)$$

where ET_0 is the reference crop evapotranspiration and K_c is the crop coefficient. Real evapotranspiration (ET) is actual water consumption of a crop per area unit. Reference evapotranspiration represents the potential evaporation of a well-watered grass crop. The water needs of other crops are directly linked to this climatic parameter. The reference crop evapotranspiration, which depends on meteorological parameters and soil characteristics, is calculated by the FAO–Penman–Monteith equation (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET_0 = reference evapotranspiration (mm day^{-1}), Rn = net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$), G = soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$), T = mean daily air temperature at 2 m height ($^{\circ}\text{C}$), u_2 = wind speed at 2 m height (m s^{-1}), e_s = saturation vapour pressure (kPa), e_a = actual vapour pressure (kPa), $e_s - e_a$ = saturation vapour pressure deficit (kPa), Δ = slope of vapour pressure curve slope vapour pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$) and γ = psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

Meteorological parameters were obtained from an automated weather station, located in the vicinity of the experimental area (≈ 1 km). The second step is to account the coefficients, K_c . The value of the K_c varies with the development stages of the crop, and depends on degree of water supply of crops during vegetation period and on climate conditions of the area. For the values of K_c , we use those obtained from experiments carried out in the Arilje raspberry producing area (Kljajić, 2012).

Table 1 The irrigation schedule for the raspberry plantations of the Arilje raspberry producing area

Months	Decade (d)	P_e (mmd ⁻¹)	ET _o (mm d ⁻¹)	K_c	ET (mm d ⁻¹)	ET - P_e (mm d ⁻¹)	$W_{(i-1)}$ (mm)	$W_{(i)}$ (mm)	Q_{NIR} (m ³ ha ⁻¹ d ⁻¹)	Q_{GIR} (m ³ ha ⁻¹ d ⁻¹)
May	V1	11.1	28.0	0.86	24.1	13.0	147.0	146.8	128	142
	V2	14.5	31.0	0.96	29.8	15.3	146.8	144.3	128	142
	V3	14.6	32.0	1.00	32.0	17.4	144.3	139.7	128	142
June	VI1	13.6	33.0	1.03	34.0	20.4	139.7	132.1	128	142
	VI2	16.1	35.0	1.04	36.4	20.3	132.1	124.6	128	142
	VI3	13.0	38.0	1.05	39.9	26.9	124.6	110.5	128	142
July	VII1	12.4	38.0	1.04	39.5	27.1	110.5	96.2	128	142
	VII2	14.2	38.0	1.03	39.1	24.9	96.2	84.1	128	142
	VII3	14.7	38.0	1.00	38.0	23.3	84.1	73.6	128	142
Total	-	124.2	311.0	-	312.8	188.6	-	-	-	-

Note: P_e , effective rainfall; ET_o , reference evapotranspiration; K_c , crop coefficient; ET , crop's evapotranspiration; $W_{(i-1)}$, soil moisture values at the beginning of certain decades (e.g. $W_{(i-1)}$ is soil moisture at the beginning of stage i); W_i , soil moisture at the end of stage i ; Q_{NIR} , net decadal irrigation (e.g. decadal required water amount for irrigation)

The accurate determination of K_c for different crops is an important task, for which in-depth research is required (Cuadros et al., 2004, Gajić et al., 2006a), given the importance of these parameter in the irrigation schedule and the size of the PV installations, and therefore, the cost. During the rainy season, the effective precipitation, P_e , is higher than the ET and, therefore, water reserves are important. The P_e is the water quantity that could be used by the plant. The decadal reserve of soil water, R_d (mm decade⁻¹), is determined by means of the water balance equation:

$$R_d = P_e - ET \quad (3)$$

The water reserves accumulated during the rainy season determines the quantity of water at the beginning of the dry season. The initial value of soil moisture, $W_{(i=0)}$, at the beginning of the dry season can be expressed:

$$W_{(i=0)} = FC \quad (4)$$

Only a portion, R_e , of this water content is available to the plants, and it cannot exceed a threshold level, the so-called allowable water depletion, AWD . The AWD is a portion of the $PAWC$ which constitutes the difference between the FC , and the PWP . In other words, AWD is the amount of water stored in the plant's root zone that is readily available to the plant. To prevent plant water stress an allowable depletion factor is used to calculate the manageable allowable depletion. This factor varies but is usually around 50%. In the case of raspberry, AWD is estimated by the following expression:

$$AWD = 0.50 \cdot PAWC = 0.50 \cdot D_r \cdot (FC - PWP) \quad (5)$$

where D_r , effective rooting depth of crops, for raspberry estimated at 700 mm. In this

case, the $AWD = 73.5 \text{ mm} = 735 \text{ m}^3 \text{ ha}^{-1}$. In order to avoid the plant water stress and optimal crop yield is achieved, the minimum amount of water stored in the soil can be set within the values:

$$AWD \leq R_e \leq FC \quad (6)$$

One approach followed in many irrigation schedules is to apply a quantity of water equivalent to the difference $ET - P_e$ during dry periods, when $ET > P_e$ (Hamidat et al., 2003; Vilela et al., 2007). This procedure does not consider the water stored in the soil during the wet months of water surplus. It has the advantage of exceeding any underestimate of $ET - P_e$ but disadvantages are greater, such as wasting water and the need for higher water flows. Another, a more reasonable approach consists of using water reserves accumulated during the wet season to complement the water provided by irrigation, which will minimize the irrigation water flow per hectare, with the corresponding decrease in power requirements (Cuadros et al., 2004). This will allow the irrigation of a larger surface area for the available water supply. Thus, the annual (vegetative) crop water requirement, $ACWR$ would be:

$$ACWR = \Sigma (ET - P_e) - AWD \quad (7)$$

where $\Sigma (ET - P_e)$ is the difference between ET and P_e during the vegetative cycle, and AWD is the amount of water at the beginning of the dry season, i.e. readily available water. The $ACWR$ is obtained as mm decade^{-1} , but may also be expressed in $\text{m}^3 \text{ ha}^{-1} \text{ decade}^{-1}$ ($1 \text{ mm} = 10 \text{ m}^3 \text{ ha}^{-1}$). If these requirements are divided between the numbers of decades in which irrigation is necessary (for example, from the first decade in May until the third decade in July in hilly-mountainous region of W Serbia), the net irrigation requirement is obtained, Q_{NIR} . Taking into account the efficiency of a drip irrigation system, $\eta_s = 90\%$, the gross irrigation requirement, Q_{GIR} , will be:

$$Q_{GIR} = \frac{Q_{NIR}}{\eta_s} \quad (8)$$

Table 1 show the values of $\Sigma (ET - P_e) = 188.6 \text{ mm}$, and of $AWD = 73.5 \text{ mm}$. Thus $ACWR = 115.1 \text{ mm}$. The irrigation requirements for the raspberry plantations in the Arilje region are therefore $1151 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$. If we divide these $ACWR$ by the number of decades in which irrigation is necessary (May to July, as seen from Table 1), we find that the Q_{NIR} , are $\approx 12.8 \text{ mm decade}^{-1} = 128 \text{ m}^3 \text{ ha}^{-1} \text{ decade}^{-1}$. For the active root zone, the soil moisture content ($W_{(i)}$, mm) at the end of any decade (i) was obtained by the decadal soil water balance equation for this layer given by:

$$W_{(i)} = W_{i-1} + P_{e(i)} + Q_{NIR(i)} - ET_{(i)} \quad (9)$$

where W_{i-1} soil moisture in time stage $i-1$ (mm) and $Q_{NIR(i)}$ is water from PV pumping system which is, by irrigation, added to soil in time stage i (m^3). From the summary of the results for the scheduling of the raspberry plantations in Arilje region in Table 1, the soil moisture content, $W_{(i)}$, at the end of any decade (i), is higher than the AWD .

Design of the photovoltaic pumping irrigation system. Solar photovoltaic water pumping system for irrigation in remote locations consists of at least three basic components: a PV panels (array), a motor, and a pump. Depending on the design, a system may use storage batteries and a charge regulator. Water can be stored into an elevated tank and then gravity-fed irrigation systems. The tank serves as an energy store and supplies the pressure needed for the irrigation system. The stored water can bridge periods of low insolation and supplies the pressure needed for the irrigation system. Pilot plants equipped with a water tank operate at considerably low system pressures, compared to conventional diesel or petrol pumps.

This presumes, of course, that all components of the irrigation system have been designed for such low pressures. The motor must be chosen according to the power requirements and the type of current to operate. If the motor needs, alternating current inverter will need to be installed. The selection of pump in a solar water pumping is solely application dependent, such as water requirement, water height, and water quality.

A pumping system demand is defined as the product of the mean depth from which the water must be raised and the daily flow that is needed. The unit of measurement is $m^4 day^{-1}$. Considering that solar radiation fluctuates during the day, the efficiency of the PV pumping system components in exploitation are lower than would be in optimal operating conditions. Taking into account: (i) energy losses caused by the water friction in the pipes irrigation system (local and linear losses), R ; (ii) the fraction of the day when the solar radiation is below the threshold at which the pump starts to work $G_d (> G_{threshold})$; (iii) the efficiency of the photovoltaic generator, η_G ; (iv) the efficiency of the inverter, η_I ; and (v) the efficiency of the motor in exploitation, η_{MB} ; the maximum energy required from the PV generator, E_{PG} , will be:

$$E_{PG} = \frac{E_H + R}{G_d (> G_{Threshold}) \eta_G \eta_I \eta_{MB}} \quad (10)$$

where the hydraulic energy, E_H ($kW h day^{-1}$), required for lifting a volume of water Q (mean daily water flow) to a height H , is:

$$E_H = 2.725 \cdot 10^{-3} QH \quad (11)$$

H is the total height to which the water is pumped, being the sum of the depth of the well and the necessary height to establish the pressure at the irrigation heads. The energy losses (or head loss) R in pipes due to water flow (friction) are around 10% of E_H . With respect to the efficiencies, Lorenzo, according to Cuadros *et al.*, (2004), suggested $Gd (> G_{threshold}) = 0.95$; $\eta_G = 0.85$; $\eta_I = 0.90$; $\eta_{MB} = 0.43$.

Therefore, the overall efficiency of the generator-pump connection is approximately 31%. The power of the PV generator, P_{el} , is calculated according to the method of the peak sun hours (Cuadros *et al.*, 2004). It is the most used methodology and all field and laboratory experiments on PV panels are usually carried out considering one peak Sun

intensity (1 kW m^{-2}). Consequently, the nominal power of a panel is expressed as kW or peak W. Thus:

$$P_{PG} = \frac{E_{PG}}{h_s} \quad (12)$$

where h_s is the number of effective hours of sun per day (the number of hours per day above the standard level of radiation of 1 kW m^{-2}). The value of h_s coincides numerically with the data for solar radiation expressed in kWh m^{-2} .

At least, the power loss produced when the solar cells are operating at temperatures above 25°C must be considered. These losses are approximately 10% of the P_{PG} (Cuadros *et al.*, 2004). Therefore, the peak PV power, P (kWp), will need to be:

$$P = P_{PG}(1 + 0.1) \quad (13)$$

Table 2 shows the values of all the variables that are involved in the connection between the pumping and PV systems. The results show that the optimal nominal electric power, for reference parameters in the Arilje area, that would satisfy the consumer demands throughout the entire observed period, is $P_{PG} = 579 \text{ W}$.

Table 2. Design characteristics of the drip irrigation and photovoltaic system

Months	Decades	h (h day^{-1})	H (m)	Q ($\text{m}^3 \text{ day}^{-1}$)	E_H (kWh day^{-1})	R (kWh h day^{-1})	E_{PG} (kWh day^{-1})	P_{PG} (W)	P (W)
May	V1	4.9	19	14.2	0.735	0.074	2.587	526	579
	V2	5.2	19	14.2	0.735	0.074	2.587	498	547
	V3	5.5	19	14.2	0.735	0.074	2.587	470	517
June	VI1	5.0	19	14.2	0.735	0.074	2.587	517	569
	VI2	5.1	19	14.2	0.735	0.074	2.587	507	558
	VI3	6.2	19	14.2	0.735	0.074	2.587	417	459
July	VII1	5.9	19	14.2	0.735	0.074	2.587	438	482
	VII2	5.5	19	14.2	0.735	0.074	2.587	470	517
	VII3	6.4	19	14.2	0.735	0.074	2.587	404	445

Note: h , daily effective hours of sun during the irrigation months; H , total pumping elevation; Q , gross daily irrigation rate; E_H , hydraulic energy; R , friction losses in the conduit system; E_{PG} , electrical energy required in pumping; P_{PG} , electrical power required in pumping; P , peak required photovoltaic power.

Analysis of economic viability. To ascertain what would be the most profitable installation, two options are proposed to be compared: a) electric energy supplied by a generator unit; b) electric energy supplied by a photovoltaic installation. Thus, if a generator unit is used, its power should be 1.5 kW at least, taking into account the requirements to start the pump. However, it should be taken into account that, as well as the purchase of the unit and the fuel costs, there are other costs of lubricating oil and equipment maintenance. Furthermore,

these motors suffer breakdowns, which contribute to increase the price of water unit that is pumped. In Table 3 are shown the economic variables for an average project life of 25 years, as the time period without efficiency losses and 6% annual interest rate.

Table 3. Economic and power variables assumed in the study for the electric and photovoltaic generators

Variables	Electric generator	Photovoltaic generator
Total capital investment (€)	4,500	14,500
Average diesel consumption (Lh ⁻¹)	0.80	-
Diesel oil price (€L ⁻¹)	1.40	-
Maintenance cost (€)	450	-
Pump power (kW)	0.80	0.80
System power (kW)	4.2	1.8

Table 4 shows the economic indices, for the electric generator or the alternative photovoltaic generator, calculated from the variables of Table 3.

Table 4. Economic indicators for the electric and photovoltaic generators

Economic indicators		A m o u n t	
		Electric generator	Photovoltaic generator
CI ₀	Total capital investment (€)	4,500	14,500
NPV ₀	Net present value (€)	20,800	42,000
IRR	International rate of return (%)	38	28
PBT	Payback time (year)	3.00	3.40

According to Table 4, the net present value, *NPV*, is higher, and the internal rate of return, *IRR*, is lower for the photovoltaic generator, being similar the payback time, *PBT*, for both alternatives, which determines that the photovoltaic installation is more profitable than the electric generator. The profitability achieved through the integration of irrigation technology and photovoltaic pumping, optimizing the efficiency of both systems, is finally demonstrated.

Conclusions

We here present a multi-step optimization methodology to sizing photovoltaic water pumping irrigation system. The method developed here includes a systematic approach to the problem, taking into account all relevant elements, from PV pumping system, local climate, soil properties, depth of well, characteristics of the crop, to irrigation system. The result of such approach is a new a simple, fast, and reasonably accurate mathematical model for defining optimal nominal electric power of the PV generator. The procedures reported above have shown that the optimal nominal electric power of the PV generator, for reference parameters in the Arilje region, with decade average daily water requirements of 12.8 m³ ha⁻¹ day⁻¹, that would satisfy the raspberry demands throughout the entire irrigation observed period, is $P_{PG} = 579$ W.

The methodology described here could be of greatest use in scheduling irrigation strategies

and in improving the production of raspberry in the hilly-mountainous continental region of the W Serbia. The main aim will be the creation of wealth in economically poor regions, reducing rural depopulation, the avoidance of erosion and use of fossil fuels, etc. Besides the advantages for the environment, since it uses a renewable energy, a study on the economic viability of a photovoltaic system shows that it is similar to conventional systems which use a generator unit (twice the net present value for the photovoltaic system). Moreover, the high price of fossil fuels guarantees a progressive advantage of photovoltaic systems.

The procedure presented in this paper for raspberry can be applicable to any other berry-like fruits (blackberry, blueberry, etc.) and site in the world with similar environment conditions.

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Appendix

FC	field capacity	D_r	effective rooting depth of crops
PWP	permanent wilting point	R_e	portion of water content is available to plants
$PAWC$	plant-available water capacity	Q_{NIR}	net irrigation requirement is obtained
ET	evapotranspiration	Q_{GIR}	gross irrigation requirement
$ACWR$	annual crop water requirement	η_s	irrigation efficiency
ET_o	reference crop evapotranspiration	$W_{(i)}$	soil moisture in time stage i
K_c	crop coefficient	W_{i-1}	soil moisture in time stage $i-1$
Rn	net radiation at the crop surface	R	energy linear losses
G	soil heat flux density	η_G	efficiency of PV generator
T	mean daily air temperature	η_I	efficiency of inverter
u_2	wind speed	η_{MB}	efficiency of motor
e_s	saturation vapour pressure	E_{PG}	max energy required from the PV generator
e_a	actual vapour pressure	E_H	hydraulic energy
$e_s - e_a$	saturation vapour pressure deficit	H	total head
Δ	slope of vapour pressure curve	Q	mean daily water flow
γ	psychrometric constant	P_{PG}	nominal power of a panel
P_e	effective precipitation	h_s	number of effective hours of sun per day
R_d	decadal reserve of soil water		
$W_{(i=0)}$	initial soil moistures		
AWD	allowable water depletion		

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JEDNOSTAVNI METOD PROCENE I EKONOMSKI POKAZATELJI FOTONAPONSKIH SISTEMA ZA NAVODNJAVANJE KAP PO KAP

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Rezime

Obnovljiva, ekološka, fotonaponska (FN) solarna energija je jedan od najatraktivnijih načina za pumpanje vode potrebne za navodnjavanje useva. Međutim, pošto su u ovom trenutku FN sistemi još uvek iziskuju visoka investicionim ulaganjima, neophodna je precizna procena veličine odgovarajuće instalacije. U ovom radu je predstavljen jednostavan, ali precizan metod za procenu potrebne fotonaponske instalacije za pumpanje sistema za navodnjavanje kap po kap na porodičnoj plantaži maline u zapadnom delu Srbije. Metodologija se zasniva na sistematskom pristupu problemu, uzimajući u obzir sve relevantne elemente FN pumpnog sistema, lokalnih klimatskih osobina zemljišta, karakteristike useva, kao i potrebe za sistemom za navodnjavanje. Uz niz od 579 Wp utvrđeno je da je ovakav sistem sposoban za navodnjavanje, bez deficita vode, za 1 hektar maline. Ovaj način je primenljiv i za druge useve u regionima slične klime, zemljišta i geografske širine. Pored prednosti za životnu sredinu, jer koristi obnovljivu energiju, analiza o ekonomskoj opravdanosti pokazuje da je fotonaponski sistem sličan konvencionalnim sistemima koji koriste druge generatore. Štaviše, visoka cena fosilnih goriva garantuje progresivnu prednost fotonaponskih sistema.

Ključne reči: *FN-pumpanje, navodnjavanje, malina, investicije, ekonomski pokazatelji*

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CONTENT

1. Gajić Boško, Tomić Zorica, Sredojević Zorica
**A SIMPLE METHOD ESTIMATES AND ECONOMIC INDICATORS
OF PHOTOVOLTAIC SYSTEMS FOR DRIP IRRIGATION 223**
2. Milojević Ivan, Vukoje Aleksandra, Mihajlović Milan
**ACCOUNTING CONSOLIDATION OF THE BALANCE BY
THE ACQUISITION METHOD 237**
3. Pejanović Radovan, Glavaš-Trbić Danica, Tomaš-Simin Mirela
**ABOUT THE CAUSES OF AGRICULTURE CRISIS IN
THE REPUBLIC OF SERBIA 253**
4. Vukoje Veljko, Psodorov Đorđe, Živković Jasmina
**PROFITABILITY OF PRODUCTION OF PASTA
FROM SPELT FLOUR 265**
5. Borec Andreja, Prišenk Jernej
**MODELS OF PARTNERSHIPS AND ORGANISATIONAL FORMS IN
SHORT FOOD SUPPLY CHAINS IN THE SLOVENIAN MOUNTAINS . 277**
6. Ene Corina
THE RELEVANCE OF TRACEABILITY IN THE FOOD CHAIN 287
7. Erokhin Vasily, Ivolga Anna
**NEW DEVELOPMENTS IN RUSSIA-EU TRADE
WITH AGRICULTURAL GOODS:
INFLUENCES OF TRADE INTEGRATION 299**
8. Grujić Biljana, Roljević Svetlana, Kljajić Nataša
**CATEGORIZATION OF POVERTY IN
THE REPUBLIC OF SERBIA IN THE PERIOD 2006-2010 309**

9.	Jovanić Tatjana AGRI-ENVIRONMENTAL LEGISLATIVE FRAMEWORK IN SERBIA IN LIGHT OF THE HARMONISATION WITH EU LAW . . .	321
10.	Looijen Arnold, Heijman Wim EUROPEAN AGRICULTURAL CLUSTERS: HOW CAN EUROPEAN AGRICULTURAL CLUSTERS BE MEASURED AND IDENTIFIED? . . .	337
11.	Majstorović Aleksandar, Dukić Dragan, Zogović Mihajlo AN AGRICULTURAL LAND VALUE ASSESSMENT MODEL.	355
12.	Papić Brankov Tatjana, Tanjević Nataša CORRUPTION IN THE LAND SECTOR	365
13.	Pejovic Igor, Jovanović Vladimir NEW FISCAL ROLE OF THE GOVERNMENT IN THE TRANSITION OF THE AGRICULTURE IN SERBIA	379
14.	Sudarević Tomislav, Vlahović Branislav, Šurjanović Ivan THE ATTITUDES TOWARD APPLICATION OF VIRAL MARKETING IN THE FOOD INDUSTRY IN SERBIA	389
15.	Tešić Aleksandra, Ilić Dragan, Tepavac Rajko SOURCES OF INVESTMENT FINANCING AND THEIR IMPACT ON ECONOMIC GROWTH OF THE REPUBLIC OF SERBIA	403
16.	Živković Dragić, Rajić Zoran, Jelić Sreten, Jandrić Mersida ORGANIZATIONAL AND ECONOMIC CHARACTERISTICS OF PRODUCTION AND MEAT PROCESSING COMPANY	419
17.	List of reviewers in 2012	427