Modeling and design of a PV system for irrigation

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Tehno-economic Analysis of the Use of Solar System for Agricultural Land
Dr. D. Topic, University of Osijek, Electrical Engineering Faculty in Osijek, Croatia, Prof. dr. D. Sljivac, University of Osijek, Electrical Engineering Faculty in Osijek, Croatia, Prof. dr. M. Stojkov, University of Osijek, Faculty of Mechanical Engineering in Slavonski Brod, Croatia, J. Perko MEE, Regional Energy Agency North, Koprivnica, Croatia, Domagoj Gasparovic, HEP-ODS, Elektra Sisak
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Abstract—Paper deals with the use of solar energy for irrigation of agricultural land. Due to the extensive damage caused by drought, it is necessary to irrigate the agricultural land. Authors have made a description and technical calculation of the solar system to power electric pump used for irrigation of agricultural land. In general, not-existence of power supply on wide agriculture area located away from urban or rural settlement is very important problem. Further on, the working principle of irrigation system using solar energy is described. The paper also discusses the economic analysis of the solar system.
Key words: Battery, Electrical energy, DC/AC inverter, Irrigation, Pump, Photovoltaic modules, Photovoltaic system, Solar power

I. Introduction

Irrigation is a cultivation measure used to add amounts of water to the soil necessary for plants to reach optimal growth and development. To function properly, irrigation systems, in most cases, require electricity for their drive. The electricity used to power the pumps is most easily obtained from diesel engines or the electrical distribution grid, but for both cases it is necessary to pay either the electricity or the fuel for the diesel engines. Since in most cases of agricultural area is away from the electrical distribution grid resulting in unprofitable grid connection charges but also in order to reduce fuel expenses, possible solution for acquiring electricity is the use of renewable energy sources. Such energy, gained from renewable energy sources, is free and what is also very important ecologically acceptable.

II. Solar radiation energy

The Sun is an inexhaustible energy source. Because of the Earths axial rotation, its elliptical orbit and shape and its tilt towards the orbital plane, there are daily and yearly changes of the power of the solar rays that reach the Earth's surface [1, 2]. The radiation power that reaches a surface perpendicular to the radiation, located between the Earth in relation to the Sun equals from 1365 W/m^2 to 1372 W/m^2 depending on the position of the Earth in relation to the Sun because of its elliptical orbit [1].

Solar radiation's potential energy is several times greater than the one gained from other renewable energy sources like biomass, wind energy and water energy which are already, like all sources of energy, just different transformations and forms of solar radiation energy [3, 4]. These facts confirm that an unsubstantial part of solar energy causes the waves and water-currents in the seas and oceans and causes the wind and wind-currents. Also, a small part of the solar radiation energy is involved in photosynthesis which allows the production of biomass.

Fig. 1 shows a comparison of the yearly sun radiation on the Earth's surface (1) and applied solar energy till now (2), with the yearly energy consummation in the world (7), the overall known fossil reserves (oil (3), gas (4) and coal (5)) and nuclear fuel (uranium) reserves (6), [5].

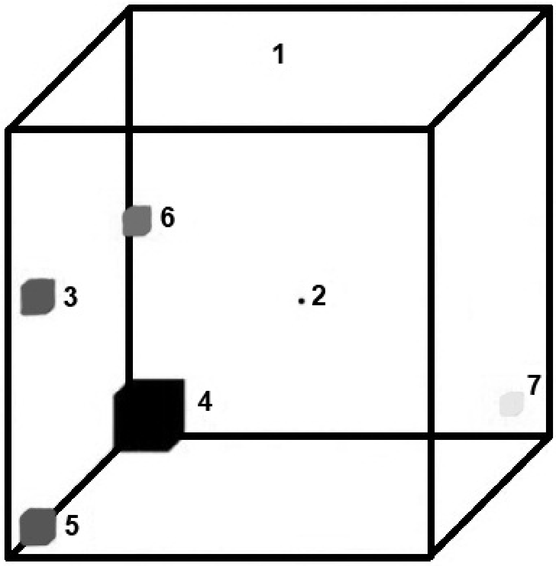

Fig. 1. Comparison of the yearly sun radiation on the Earth's surface with the yearly energy consummation in the world

III. Solar photovoltaic systems

Photovoltaic systems represent an integrated set of photovoltaic modules and other components planned to transform the primary Solar energy directly into the final electricity with which is ensured the functioning of a certain number of DC and AC loads, independently or together with a backup source. There are two types of solar photovoltaic systems: photovoltaic systems that are not connected to the grid (stand-alone systems) and photovoltaic systems connected to an electricity grid (on-grid systems). The basic classifications of photovoltaic systems are shown in Fig. 2 [1].

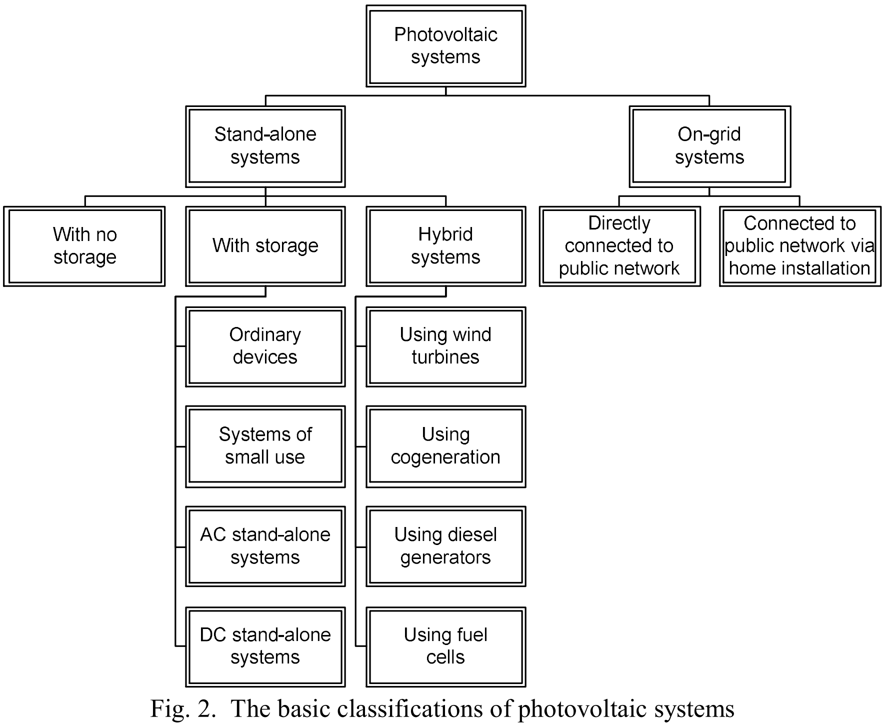

Fig. 2. The basic classifications of photovoltaic systems

A. Stand-alone photovoltaic systems

Stand-alone photovoltaic systems or photovoltaic systems that are not connected to the grid can be with or without energy storage and hybrid systems which can be with a wind turbine, cogeneration or diesel generators. The basic components of a stand-alone photovoltaic system are:

1) photovoltaic modules (PV modules)
2) charge controller
3) battery
4) DC or AC load
5) inverter (if loads works on AC current)

Stand-alone photovoltaic system is shown in Fig. 3. A PV module consists of multiple solar cells which are connected in a specific series-parallel combination to gain the adequate voltage or power. PV modules are manufactured in different dimension sizes and rated powers. It is ideal to place them on the south side of the roof at a 45° angle and it is important to avoid shadows because in that case the energy production is gravely decreased. PV modules function as extremely eco-friendly because they produce electricity directly from the sunlight, [1]. Charge controllers, controlled by a microprocessor, efficiently control energy and therefore ensure better use, greater autonomy, a longer lifetime and optimal battery usage.

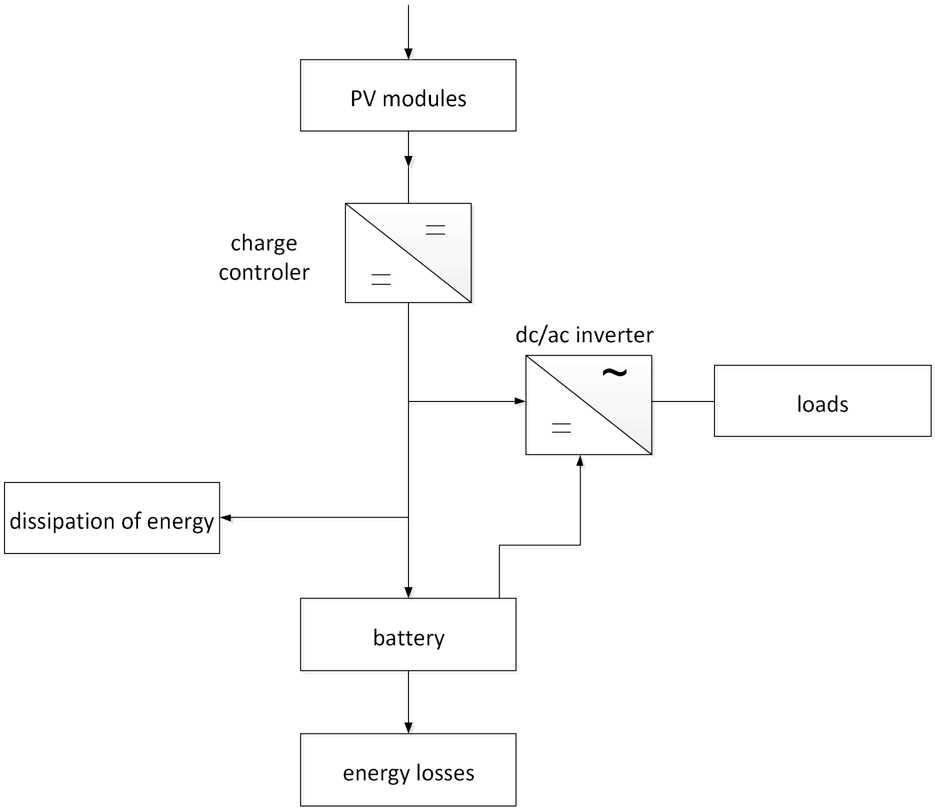

Fig. 3. Model of stand-alone photovoltaic system

Battery is energy storage in which the processes of charge and discharge are reversible which means that when the battery empties, it can be recharged by using an outer source of DC current whose voltage is greater than the electromotive force of the battery. With solar systems, lead batteries are most frequently used. Inverters convert DC voltage of a battery into AC voltage of the same amount, frequency and wave form as is the open public electricity grids. Inverters ensure a safe and reliable work of all loads foreseen to be powered by the grids voltage.

The loads of stand-alone photovoltaic systems should, considering having energy storage, be energy efficient which means having the least amount of energy usage.

IV. Irrigation systems

If the basic vegetation factors are maintained in optimal boundaries, it is possible to achieve high and quality transmission of agricultural cultures. Therefore, water is one of the basic vegetation factors. In case of drought, adverse soil humidity occurs at which the plants can difficultly ensure the necessary water. Because of that, it is necessary to irrigate agricultural land. Irrigation is hydro-engineering measure for the improvement of the soils physical properties by adding water to achieve optimal humidity for the vegetation period and to achieve optimal crops with [5, 6, 7 and 8]. There are four methods for agricultural irrigation:

1) surface irrigation
2) underground irrigation
3) rain irrigation
4) localized irrigation

V. The principle of irrigation with utilization of solar energy

A pump that is used like the engine of this system is powered by the photovoltaic modules. Photovoltaic (PV) modules use solar energy that is converted directly into electrical energy which is stored in rechargeable battery and is used to pump when needed. They are indirectly powering pump that draws water from another water source and filling water tank from where water continues to drop what is used for irrigation of agricultural land (Fig. 4.).

A. Calculation of pump and water storage volume for irrigation system

To determine the required storage volume V_s, it is necessary to calculate the volume of irrigation V_i and the amount of water that is pumped from water source V_p. Water storage volume is equal to the difference of volume of water that is pumped from water source and the required volume for irrigation function:

$$V_s = V_p - V_i \qquad (1)$$

where:
V_s – water storage volume (m^3)
V_i – required volume for irrigation (m^3) during the time t_i (h)
V_p – volume of water that is pumped from the water source (m^3) during the time t_p (h) with flow q_p (dm^3/h)

The required daily volume of irrigation water to the required water flow $q_{i,s}$ per square meter of irrigated land during the time of irrigation t_i for agricultural surface S is:

$$V_i = q_{i,S} \cdot t_i \cdot S \cdot 10^{-3} \qquad (2)$$

where:
$q_{i,s}$ – required water flow per square meter of land during one hour (dm^3/h, m^2)
t_i – daily time of irrigation (h)
S – irrigated agricultural area (m^2)

Pump rated power depends on the altitude difference between the water level of water source and water level in water storage. If there is a feasible flow q_p from the water source (river, lake), and if the water needs to draw on the total height H_p, then the required pump rated power is:

$$P_p = \frac{\rho \cdot g \cdot q_p \cdot 10^{-3} \cdot (H_2 + H_{2v})}{3600} \qquad (3)$$

where:
P_p – pump rated power (W)
ρ – density of water (kg/m^3)
g – acceleration of gravity (m/s^2)
q_p – flow which may be provided from sources (dm^3/h)
H_2 – difference of the level to which water must be pumped to the water level of the pump (m)
H_{2v} – difference of the level of the pump to the level of water source (m)
H_p – total difference of the level to which water must be pumped to the level of power source

If the water is pumped with pump power P_p on height H_p with flow q_p during the time t_p, then the amount of water that is pumped into the tank is:

$$V_p = q_p \cdot t_p \cdot 10^{-3} \qquad (4)$$

where:
t_p – time of pumping the water during the day (h).

Tank volume is finally obtained:

$$\begin{aligned} V_S &= V_p - V_i = \\ V_S &= (q_p \cdot t_p - q_{i,S} \cdot t_i \cdot S) \cdot 10^{-3} \end{aligned} \qquad (5)$$

Fig. 4. Irrigation system utilization of solar energy

Fig. 5 shows cylindrical water tank. If the height h of the cylindrical water tank is given, the diameter of its base d_v can be calculated:

$$d_v = \sqrt{\frac{4V}{h\pi}} \qquad (6)$$

where:
d_v – base diameter of cylindrical water tank (m)
h – height of cylindrical water tank (m)

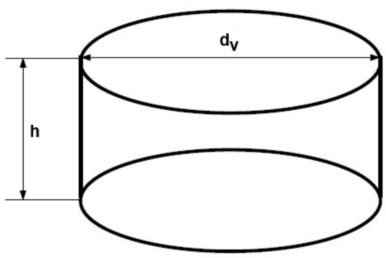

Fig. 5. Cylindrical water tank

B. Calculation of photovoltaic system

It is necessary to size the stand-alone PV system to run the pump for irrigation of agricultural area around Osijek on latitude [N]: 45°32′ and longitude [E]: 18°38′, according to daily consumption of the pump given in Table I.

Load	Power P (W)	Pieces	Running time Δt (h)	Average daily consumption W_d (Wh/day)	Required daily capacity L_d' (Ah/day)
Pump	1250	1	2	2500	57,9

Table I Daily Consumption of the pump

The system provides a DC voltage of 48 V and pump is running on AC 230 V / 50 Hz. Monocrystalline PV modules with the following characteristics were selected: rated power 75 W, short-circuit current I_{KS} = 5 A, open circuit voltage U_{OK} = 20 V and maximum power point P_m (U_m = 16.9 V and I_m = 4.5 A). Efficiency of the battery is η = 0.85. Considering the battery losses of 15 %, the total average daily consumption is obtained:

$$L_d = \frac{L'_d}{\eta} = \frac{57.9}{0.85} = 68.12 Ah/day \tag{7}$$

where:
L_d – total average daily consumption with losses (Ah/day)
L_d' – required daily load capacity (Ah/day)
η – efficiency of the battery

Because of assumption of equal mean daily consumption in any month, most appropriate slope of PV modules from May to October of PV modules exposure is selected for the best electricity generation. Thus, photovoltaic modules are set at an angle β = 30° for which the average daily value of irradiation $H_β$ south sloping pad of Osijek are presented in Table II during analyzed months.

Month	May	June	July	August	September	October
$H_β$ (β=30°)(kWh/m^2)	5.25	5.38	5.67	5.29	4.22	3.39

Table II Average daily value of irradiation south sloping pad of Osijek

To obtain a DC voltage of 48 V, the number of modules to be connected in series will depend on the operating voltage of module. At the other hand, instantaneous battery voltage does not exceed 14.2 V, so the minimum number of series connected modules can be determined by the relation:

$$n_s = \frac{U_s}{U_i} = \frac{48}{14.2} = 3.38 \tag{8}$$

where:
n_s – number of series connected modules
U_s – DC voltage of system (V)
U_i – upper limit of instantaneous battery voltage (V)

Thus, the minimum required number of modules connected in series is n_s = 4. To obtain the required current with considering assumed consumption, more parallel branches should be connected. Each branch is a string of n_s series-connected modules. The minimum required number of parallel-connected branches will depend on the current which is given by one branch. This is 5 % lower current than the short-circuit current which is I_R = 4.75 A. This amount is calculated for unit radiation of 1 kWh/m^2, and for other values of radiation, the mean daily values of output current contribution D of one branch are obtained:

$$D = I_R \cdot H_\beta \tag{9}$$

where:
D – mean daily value of output current contribution (Ah/day)
I_R – current of one branch (A)
$H_β$ – mean daily value of radiation (kWh/m^2)

The average daily values of output current contribution of one branch of photovoltaic modules D per month for angle $\beta = 30^{\circ}$ is shown by Table III.

Month	May	June	July	August	September	October
D (Ah/day)	24.94	25.56	26.93	25.13	20.05	16.1

Table III Average daily values of output current contribution of one branch

The average annual value of the daily output current contribution for a single branch is D_g = 23.12 Ah/day. The required minimum number of parallel-connected branches of the module is obtained:

$$n_p = \frac{L_d}{D_g} = \frac{68.12}{23.12} = 2.95 \qquad (10)$$

where:
n_p – minimum number of parallel-connected branches of the modules
D_g – average annual value of daily output current contribution for a single branch (Ah/day)

Thus, the minimum required number of parallel branches is $n_p = 3$. Comparison of monthly electricity needs of the pump and a monthly contribution from the output of PV system that consists of 12 modules is shown by Table IV (rated voltage of PV system is 48 V). The monthly amount of current contribution from photovoltaic system is:

$$D_F = D \cdot n_p \cdot N \qquad (11)$$

where:
D_F – monthly value of current contribution from PV system (Ah/day)
N – number of days in month

Consumption for each month is:

$$L_p = L_d \cdot N \qquad (12)$$

where:
L_p – consumption for each month (Ah)

The surplus or deficit of contribution from the output of PV system ΔD per month is obtained from:

$$\Delta D = D_F - L_P \qquad (13)$$

where:
ΔD – surplus or deficit of contribution from the output of PV system (Ah)

Month	L_p (Ah)	D_F (Ah)	ΔD (Ah)
May	2111.72	2319.42	207.7
June	2043.6	2300.4	256.8
July	2111.72	2504.49	392.77
August	2111.72	2337.09	225.37
September	2043.6	1804.5	-239.1
November	2111.72	1497.3	-614.42
		Total deficit:	-853.52
		Total surplus:	1082.64

Table IV Comparison of monthly electricity needs of the pump and monthly electricity contribution from the output of photovoltaic system

Deficit of 853.52 Ah in September and October must be provided by batteries. Capacity of battery must be of such capacity to not be discharged more than 80 % considering the temperature factor of approximately 0.95.

So, the capacity of the battery is:

$$C = \frac{\Delta D_m}{0.8 \cdot 0.95} = \frac{853.52}{0.8 \cdot 0.95} = 1123.05 Ah \qquad (14)$$

where:
C – capacity of battery (Ah)
ΔD_m – total deficit (Ah)

If the batteries of 24 V / 1200 Ah were used, than their number for one parallel branch is:

$$n_{p2} = \frac{C}{C_B} = \frac{1123.05}{1200} = 0.935875 \qquad (15)$$

where:
C_B – rated capacity of battery (Ah)
n_{p2} – minimal number of parallel-connected batteries

Each branch has two batteries connected in series (48 V / 24 V = 2), which means that a total of 2 batteries is required. One string of two series-connected batteries of 24 V / 1200 Ah is enough to satisfy energy needs of electric pump. The number of consecutive cloudy days during which the loads are supplied from battery can be also obtained:

$$n_0 = \frac{0.8 \cdot 0.95 \cdot 1123.05}{L_d} = \frac{912}{68.12} = 12.53 \qquad (16)$$

where:
n_0 – number of consecutive days without sunshine (day)

Thus, the system can operate 12 days without sunshine powered only by battery energy storage. Overall, the PV system consists of 12 individual modules of 75 W making the total power of photovoltaic system of 900 W and two batteries.

VI. Economic analysis of PV system

Cost of installation of this PV system is 3500 euros per kW of installed power without battery storage. Total costs of the power system including the cost of battery are 30 % more than PV system cost. Rated power of this system is 0.9 kW, so investment costs including the cost of battery are 4095 euros. Total annual electricity consumption (Table 4) for this system is 541.47 kWh . Electricity price in Croatia is 0.122 €/kWh [9] which means that the annual savings of this system is 64.98 € per year. It is also necessary to consider that the electricity from the distribution electric network is hardly accessible on agricultural land. Power supply to agricultural land is much more expensive in investment considering the fact that for most agriculture areas transformer substation, 10 kV underground power line and low voltage connection with measurement need to be built. Also, PV system prices are decreasing all the time, so repayment period of this system will also be greatly reduced.

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