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ELABORATION OF AUTONOMOUS IRRIGATION SYSTEMS INTEGRATED WITH PHOTOVOLTAIC

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Abstract: *The autonomous irrigation systems integrated with PV, a method of PV pump system calculation for small irrigation and control of agricultural processes are presented. The solar radiation calculation was performed with PVGIS software. The numerical example contains pump flow rates, pumped water volumes (daily, monthly and for all irrigation period)*

Keywords*: Photovoltaic installation, water, solar radiation, solar pump*

1. Introduction

According to the long-term meteorological data during the active vegetation period, the average precipitation amounts of 235 mm in the southern region and of 330 mm in the northern region [1]. Natural moisture is insufficient to obtain expected crops, especially vegetables, even in the years with average climatological characteristics. Often the territories of Moldova, Romania and Ukraine are subject to long-term droughts. Long-term observations indicate that this region is under the influence of a relatively dry 12-year climate cycle and the drought rate is increasing. Figure 1 shows the dynamics of the dry years of the X-XX centuries. The analysis of the drought development data of the 20th century reveals that in the following years the drought will repeat every 2-nd, 3-rd or 4-th year [2]. At the same time, there is a drastic decrease of the irrigated land, figure 1 [1]. The difficulty of this problem varies from country to country, being more striking in those countries that lack fossil energy sources and sufficient sources of potable water for irrigation. RM is a part of this category of countries, which covers from the import about 86% of the needed energy resources and produces only 18,4 % of the electricity consumption.
The main causes of the decrease of irrigated surfaces after 2010 are:

1. Because of privatization, about one million farmers possessing agricultural land with an area not exceeding 2,5 ha have appeared.

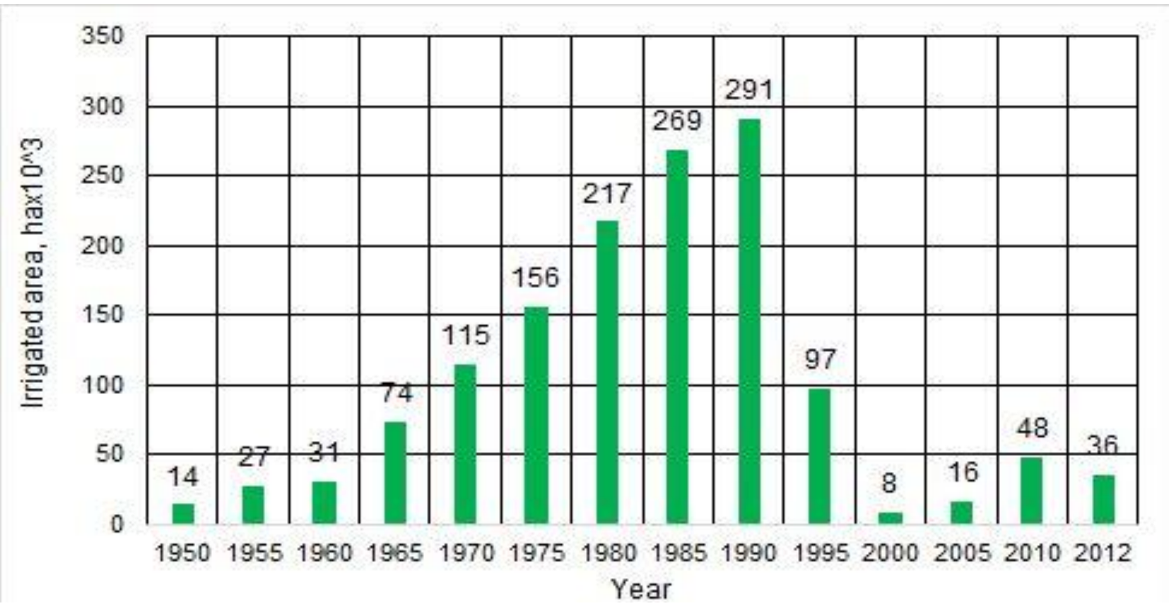

Fig. 1. Variation of irrigated surfaces during 1950-2012

2. Increasing the cost of electricity tenfold.

Existing systems designed to irrigate large areas and with excessive energy consumption have become uncompetitive.

Therefore, taking into account the provisions of the strategy, the development of automation tools in the agri-food sector is an activity meant to facilitate these provisions. In the following compartments we will present the automation facilities for irrigation installations, realized within the UNDP project "*Autonomous integrated irrigation systems based on wind turbines, small hydro and photovoltaic installations*".

2. The photovoltaic pumping

A modern and energy-efficient solution that meets new market conditions is the photovoltaic pumping system, known since 1980s of the last century. In the last five years the cost of solar modules has significantly decreased and photovoltaic irrigation becomes competitive within traditional systems. A growing number of countries launch programs to accelerate the solar technology development. Republic of Moldova is taking the first steps in this field, only a few experimental photovoltaic pumps have been implemented and there is no program to support this technology. The paper presents a PV pump system sizing method for farmers intending to implement low-power photovoltaic systems for small irrigation.

Regardless of the irrigated land particularities the sizing procedure of the PV pumping system comprises several necessary steps to be taken.

2.1 Water requirement

The first step in designing a solar-powered water pump system is to determine the overall water requirement for the operation. In other words, we need to know the required water volume or irrigation norm, the water volume distribution during irrigation, and the daily water requirement etc. These data are available in the literature [1,3] or by consulting agricultural specialists.

2.2. Determining the solar radiation for your location

Appropriate data should be used to determine the amount of solar radiation available at the site. These data are available in the archive of the State Hydro Meteorological Service (SHMS) or in [2,3]. With them, the global solar radiation, G_β in W/m^2, on tilted surface or PV pane can be calculated l. The used formula is the following [3]

$$G_\beta = R_b B + \frac{1}{2}(1 + Cos\beta)D + \frac{1}{2}(1 - Cos\beta)\rho G, \quad (1)$$

where R_β is the ratio of total radiation on the tilted surface at angle β to that on the horizontal surface; B – direct or beam radiation; D - diffuse radiation; G – global radiation on the horizontal surface; ρ – reflectance coefficient. The B, D and G values can be found in [4]. All data are for a horizontal surface as a possessing result of SHMS measurements for the period of 1954-1980.

In [4] are presented numerical values of the ratio R_b for the difference of latitude ϕ and inclination angle β (every 5^0) and the latitude of the place (every 5^0). Based on these data the values of the report R_b for Moldova were interpolated. The territory was divided into three areas - south (latitude 46^0), center - (47^0 latitude) and north - (latitude 48^0). Linear interpolation was used, the difference ϕ - β ranges from 0 to ± 20^0 with a step of 5^0. Numerical data of R_b can be found in [5,6].

Using (1) we can calculate the daily global solar radiation, G_β for a different month for each 3 hour: 6^{30}, 9^{30}, 12^{30}, 15^{30} and 18^{30}. In this case we should use data about B, D and G published in [4].

EU countries have developed a free online software for calculation of diurnal and monthly solar radiation. The diurnal radiation is calculated every 15 minutes. For the calculation a new database Climate-SAF PVGIS [7] is used. These data are based on satellite images performed by CM-SAF (Geostationary Meteosat and Polar EUMetSat). The database represents a total of 12 years of data. From the first generation of Meteosat satellites, known as MFG, there are data from 1998 to

2005 and from the second-generation Meteosat satellites, known as MSG, there are data from June 2006 to May 2010. The coverage extends from 0° N (equator) to 58° N and from 15° W to 35° E. These data are more representative of the last climate years, and show often higher irradiations than the classic PVGIS data.
Using this software [7], we calculated the diurnal radiation at Chisinau meteorological station on horizontal surface and we compared them with the ones from the 1954-1980 period. The results are included in Table 1.

Table 1: Diurnal radiation, kW/m^2

Month / hour	April			May			June			July			August			September		
	[4]	PVGIS	Diff., %	[4]	PVGIS	Diff., %	[4]	PVGIS	Diff., %	[4]	PVGIS	Diff., %	[4]	PVGIS	Diff., %	[4]	PVGIS	Diff., %
6^{30}	0.10	0.14	+40	0.19	0.23	+15	0.24	0.26	+8.3	0.21	0.25	+19	0.14	0.19	+36	0.07	0.08	+14
9^{30}	0.44	0.46	+4.5	0.55	0.57	+3.6	0.62	0.59	-4.8	0.60	0.60	+0.0	0.55	0.55	+0.0	0.45	0.41	-8.9
12^{30}	0.53	0.55	+2.8	0.62	0.67	+8	0.72	0.68	-5.5	0.70	0.70	+0.0	0.66	0.66	+0.0	0.55	0.49	-11
15^{30}	0.31	0.37	+19	0.39	0.48	+23	0.46	0.50	+8.7	0.47	0.50	+6.4	0.41	0.45	+9.8	0,29	0.31	+6.9
18^{30}	0.01	0.03	+200	0.05	0.11	+120	0.09	0.14	+55.5	0.09	0.12	+33	0.04	0.06	+50	n/a	n/a	n/a

We note the following:

1. The average error from April to September in the period 9^{30} - 15^{30} does not exceed + 3.0%.
2. Early in the morning (6^{30}) and evening (18^{30}) the errors are high and may exceed 100 %. But this does not affect the calculations because at the respective hours the PV pump does not work.
3. The calculated diurnal radiation values based on the new Climate-SAF PVGIS database are higher compared to those from 1954-1980. In our view, these are the consequences of global climate change.

In the present paper, we used the new Climate-SAF PVGIS database and free online software for calculation of diurnal radiation [7].

2.3. Total dynamic head

The total dynamic head (H) for a pump is the sum of the vertical lift, pressure head, and friction loss. The friction losses apply only to the piping and appurtenances between the point of inlet and the point of water distribution in the irrigation pipeline. Therefore, friction losses between the water basin or storage tank and the point of use are independent from the pump and do not need to be accounted for when sizing the pump. So, the H is equal:

$$H = H_G + H_L + H_P, \tag{2}$$

where H_G – is vertical lift or the geodetic height measured from the water level and the highest point of water lifting; H_L - friction losses; H_P – pressure head or the pressure required for the proper functioning of sprinklers or drippers expressed in m.

2.4. Selecting the pump and solar array

Depending on the water source we can select a surface pump or a submersible pump. For PV systems, special pumps, called solar pumps, are also produced. It is characterized by higher efficiency and stable operation under conditions of variation of solar radiation [8,9]. As an example, in fig. 2 are presented the variations of solar pump flow over the course of days for different months.
Depending on the required flow Q and TDH, we can find the power and then select the PV panel with adequate peak power.

2.5. PV panel mounting

As a rule, the PV panel is mounted on special frames and directed to the south. To increase efficiency, we recommend adjusting the inclination angle to the horizon. As the irrigation period in

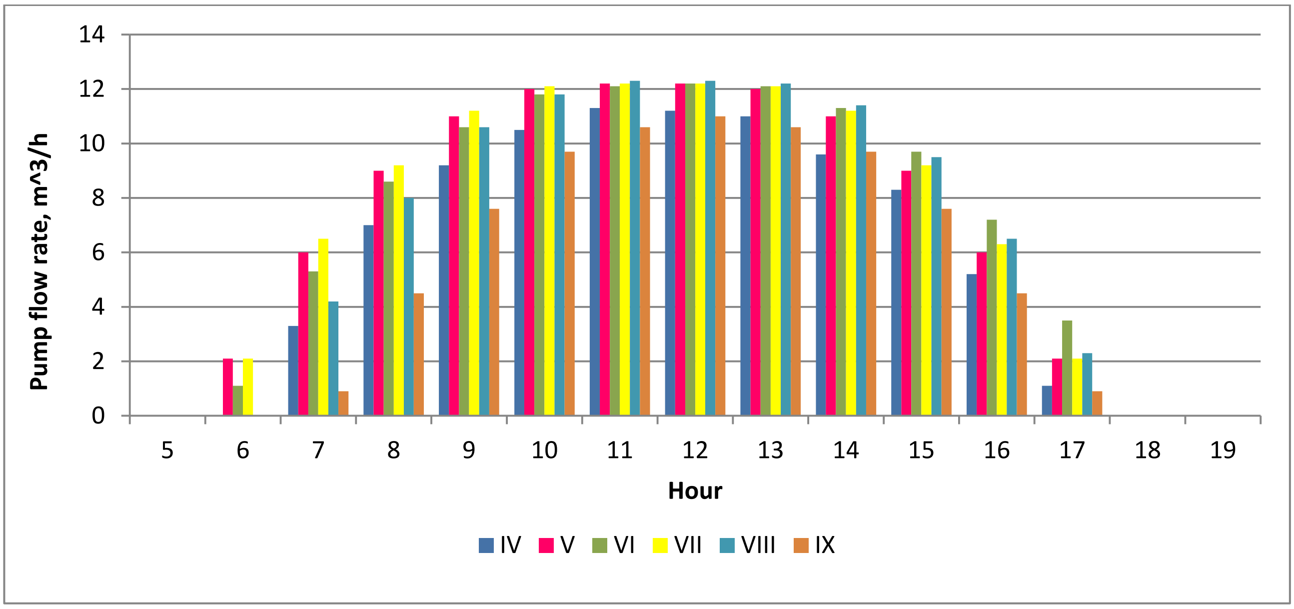

Fig. 2. Variation of solar pump flow over the course of days for different months

the Republic of Moldova is about 6 months (April - September), it is rational to change this angle once in a month. In the table 2 are included the optimal inclination angle for April – September, valid for the central region (latitude $\phi = 47^0$).
If a panel is to be mounted on an existing structure, that structure must first be analyzed to ensure that it has the necessary structural integrity to withstand all local wind, snow, and ice conditions.

Table 2: Optimal inclination angle

Month	April	May	June	July	August	Sept.
Angle, grade	33	20	13	17	28	43

Daly, monthly and total delivery rates. For this purpose, we calculate daily solar radiation using PVGIS software, the power generated by the PV panel and the effective operating time of the pump per day. From the *Q (P, H)* characteristics the pump flow rate and daily water volume are determined.

3. The automatization, informatization and monitoring of the irrigation processes

3.1. Design of the control system

The design of the automated control system for monitoring and optimization to ensure the irrigation processes will be carried out taking into account the following factors: acquisition of climatic data from plantations, application of nutrients and pesticides, herbicides, information processing and automatic control of the irrigation system, such as the monitoring of renewable energy sources. On the other hand, the design of the automated system must take into account the location of renewable plants and resources. In other words, the system has to be territorially distributed and it is reasonable to be hierarchized, considering the various issues that need to be solved.
Taking into account the experience of the most advanced companies in this field as well as their own experience, a three- layer hierarchical system has been proposed. The bottom layer is the most sophisticated, inhomogeneous and dependent and specific of agricultural enterprises. At this level are placed the means of acquiring the climatic data on the plantation field, the means of controlling the valves and pumps with remote control, the means of accelerating the fertilization equipment, as well as the means of monitoring and control of the renewable resources.
The second layer of the system has preponderant communication functions with minimal computing capabilities, decision-making, in other words, a kind of gateway between the lower level and the upper level. The mission of this level is to provide communication coverage with all subsystems at the bottom level and to provide communications to the top level server (server).

Finally, the superior layer of the automation, monitoring and control system for irrigation systems is seen as a typical Internet solution, which will store all information on irrigated plantations as well as the state of the equipment and auxiliary subsystems. On the other hand, it must provide authorized access to users of this system. At the third level (server) will be first remote monitoring of several irrigation systems, groups of stations, including homing. If server monitoring and control node is connected to the Internet, then monitoring stations can be done from any point on the earth.

For any control and monitoring system, including for irrigation installations, data acquisition plays a primary role. For these reasons, it has been decided to build an acquisition subsystem based on an integrated sensor network. It was decided, taking into account the relief and climatic conditions of Rep. Moldova, that the control must be performed by an average performance microcontroller, which will operate autonomously and is monitored and guided by the two most powerful controllers by radio communication at short distances (up to 4-5 km). It was designed and realized the functional schema and real equipment of integrated sensors and valve control modules for irrigation system. The most important sides both of this modules are the autonomous electrical power subsystem with 20W photovoltaic panel and accumulator and remote data acquisition and control by means of radio communication. The integrated sensor includes a set of sensors: air humidity and temperature, soil humidity and temperature at 2 levels; rain sensor, luminosity; photovoltaic panel and accumulator voltage.

As the main goal represents creating architecture of the control unit with the greatest possible reliability (for a duration of 5-7 years of activity) based on small processors it is necessary to analyze all families of microcontrollers from Atmel, Motorola, Renesas, Texas Instruments to select the proper microcontroller for this task. Making a comparative analysis, we outline that three different solutions are required by several parameters simultaneously such as productivity, memory capacity, energy consumption, cost, accessibility and reliability:

a) uC MSP430F155 part of the MSP430 from Texas Instruments;
b) uC MC68HC912DT128A part of the Motorola HC12 family;
c) uC ATMega part of the Atmel family.

Given the specialization of microcontroller core functions of low layer for controlling data acquisition, control, regulation and distribution of electricity, telemetry control the thermal station control and a microcontroller auxiliary functions of quality analysis of electricity generated, it is necessary to analyze low consumption devices, which typically are designed for wind generators and irrigation systems. For the integrated sensor module, it has been decided to use the uC ATMega controller, with performance comparable to other controllers, a very low consumption and a lower price.

In the similar mode the valve control module can open/close 2 valve with DC electro-motors and communicate the states of the valves. One important performance is high velocity of data acquisition (all data may be received by 1-2 sec) and the low cost – about 150 dollars per unit.

The territorial location of the integrated sensors and the control modules with the valves is done depending on the specifics of the plantation land and the configuration of the irrigation installations. For this project it was performed the maps of integrated sensors and valve control modules for irrigation system for the concrete destinations: the farm Tri Dienal (from Criuleni) (fig. 3) and real view emplacement (fig. 4).

Fig. 3. Emplacement map of the integrated sensors module and the valve control module for irrigation system on Tri Denal (Criuleni) farm

It was decided to use one valve control module and one integrated sensor for 2 parcels (total 6 integrated sensor and 12 valve control modules) on the Fortuna Lapis farm and (total 4 integrated sensor and 14 valve control modules) for the Tri Dienal farm with the goal to minimize the cost of these equipment.

Fig. 4. Irrigation system for the farm Tri Dienal (from Criuleni): real view emplacement

3.2. The medium layer of irrigation control system

It is proposed a farm plantation medium layer control module for irrigation system, that coordinate all the processes for irrigation installation and for communication with high level (servers). For this case it is proposed the Rasberry controller with a higher computing performance and low cost. It was developed the software for this controller, which include more components for the coordinating the communication between low level modules and the servers.
Interaction between the turbine station controllers, integrated sensors and the monitoring system was proposed to be performed according to a model, for example, as shown in fig. 5, which implies the access of the users of the stations practically from an unlimited distance, which is reasonable by the use of communications and computers, including the Internet. The problem is simplified if the station controller connects to the network through units with a range greater than the previous one, sufficient to intercept the communications network. For such a case, high- speed and medium-to-high-speed radio communications, there is at the moment a whole range of possibilities and means. These means must meet the following requirements for this channel type: relatively low emission power, but high sensitivity; the possibility to modify the emission frequencies in a scheduled manner; GSM/GPRS communication modes; possibilities to maintain various communication protocols.

Applying this model, the medium-level controller architecture is proposed, which includes two different communication channels: one for low level interaction in the 435-450 MHz frequency band - the low-band radio amateur band and the second channel based on GSM / GPRS mode for connection to the Internet server. This is a farm plantation control module for irrigation system, that coordinate all the processes for irrigation installation and for communication with high level.

3.3. Monitoring and reports of the plantations irrigation process

Any system for monitoring various processes, including plantation irrigation, requires totalizing means / tools, reporting on current and cumulative outcomes. Therefore, a series of applications have been developed for the irrigation monitoring system, which allows the final user to make the necessary sums and conclusions. We present a series of such reports: the user can visualize the irrigation water consumption on the selected parcel during certain stages of planting development or throughout the season as compared to the irrigation rules and the precipitations (fig. 5), report about portions of irrigation norms about portions of irrigation norms, precipitations and irrigation volumes for the some phase of plant development (fig. 6).

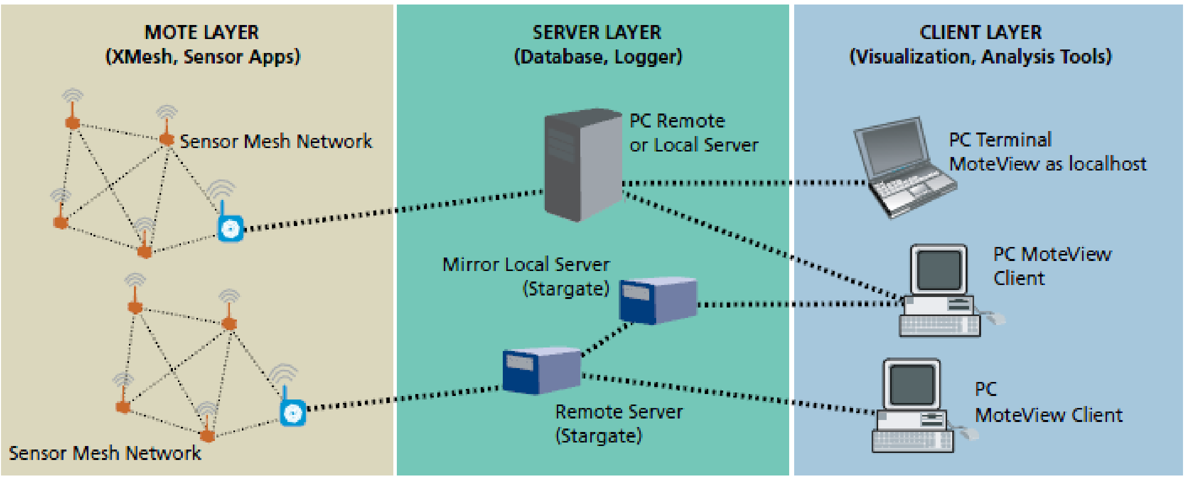

Fig. 5. The model of interaction between components of the irrigation system through various networks, including the Internet

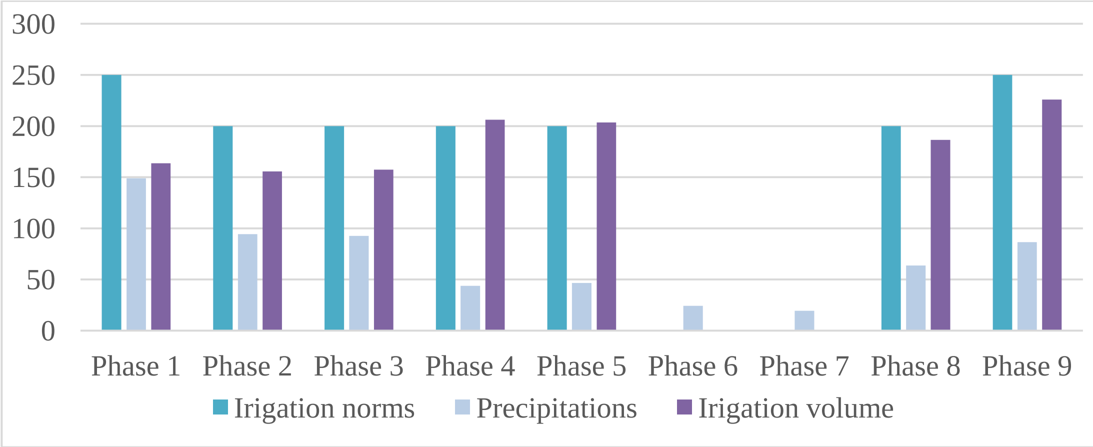

Fig. 6. Example of report diagram about irrigation norms, precipitations and irrigation volumes for the each phase of plant development

3. Results

The proposed land for irrigation presents a superintensive cherry orchard with a 7-ha area and is located in the west of the Criuleni town (central region), figure 3. The water for irrigation is pumped from a 9000 m^3 basin. The basin is part of a large irrigation system that uses water from the Dniester River. Thus, the basin is permanently filled. The solar pump drives water from the basin to the existing irrigation system.

The existing irrigation system is equipped with the SUPERNET™ UD Micro Sprinkler, the operating pressure of which must be 1,5-4,0 Bar [10].

Water Requirement. According to [11] the required irrigation water volume for superintensive orchard is about 5000 m^3/ ha. So, for the April - September irrigation period the required water volume is equal to $V_R = 5000 \cdot 7 = 35\ 000\ m^3$. For pump selection, we calculate the flow by dividing the required water volume to the number of pump operating hours during the irrigation period

$$Q = V_R /(N_D \cdot N_{hd}) = 35\ 000/(170 \cdot 8) = 25{,}7\ m^3/h, \qquad (3)$$

where N_D – number of days; N_{hd} - pump operating hours per day.

The total dynamic head. H_G = 5 m, H_L = 1,4 m (according to [12] for PVC pipe length-200 m, diameter-100 mm), H_P = 39 m (according to [11] the sprinkler operating pressure that will not exceed 4 Bar or 39 m of the water column). Thus, H = 45 m.

Pump selection. The most suitable pump for the calculated flow rate Q=26 m^3/h and H= 45 m is the Solar Surface Pump System PS7k2 CS-F20-5 [10], rated flow 27 m^3/h at H = 45 m The flow characteristics as a function of input power, *Q(P, H)* are shown in fig. 7.

As shown in fig. 7, based on a calculated flow rate of 26 m^3/h (rounded) and a H of 45 m a minimum input of 5,8 kW of peak power is required. With daytime variation of solar radiation, the pump's operating point will slip on the *Q (P, H)* characteristic.

PV panel selection. The PV panel selected for this system must be able to provide the minimum energy requirement to run the pump. In our case about 5,8 kW. However, the panels must have additional capacity to account for any potential reduction in power due to radiation data incertitude, high module temperature, dust, etc. Many PV manufacturers recommend increasing the minimum peak power value by 25 - 30 % to account for these environmental factors. To increase the pump's running diurnal time with a maximum flow, it is rational to increase power by another 50%. Therefore, the PV panel will be sized to provide a minimum output of $1{,}8 \cdot 5{,}8 = 10{,}44$ kW. We accept 11 kW.

Daly, monthly and total delivery rates. First, we calculate diurnal solar radiation using PVGIS software. The selected point coordinate Latitude: 47,200768, Longitude: 29,128662, the optimal tilted angle is 13^0, the panel is facing the south – Orientation: 0^0. The results are displayed every 15 minutes. In the same way, we did for all 6 months of the irrigation period. Diurnal radiation over each hour is shown in fig. 4 on the left. With hour solar radiation, the power generated by the PV panel is calculated using formula

$$P_{PV} = (R_{Daily}/1000)\cdot P_p\,, \qquad (4)$$

where R_{Daily} – average hourly solar radiation as result of PVGIS calculation; P_p–PV panel peak power, 11 kW.
Using the pump characteristic $Q\ (P,H)$ for H = 45 m (fig. 7, red color) we determine the pump average hourly flow. The calculations are repeated for all pump operating hours. As a result, we get the daily pump flow variation, the daily and monthly volume of pumped water, fig.8, on the right.

During the irrigation period, the volume of pumped water is equal to the sum of the months volumes from April till September: V_{Total} = 40300 m^3 and is higher than the required by 15 %. We find a relative constancy of maximum solar radiation on the PV panel and the maximum flow rate of the pump, thus:

1. The maximum solar radiation on the PV panel is equal to 784 W/m^2 and corresponds to July. In April, the maximum radiation is lower by 15,3% and in September - by 21,2%.

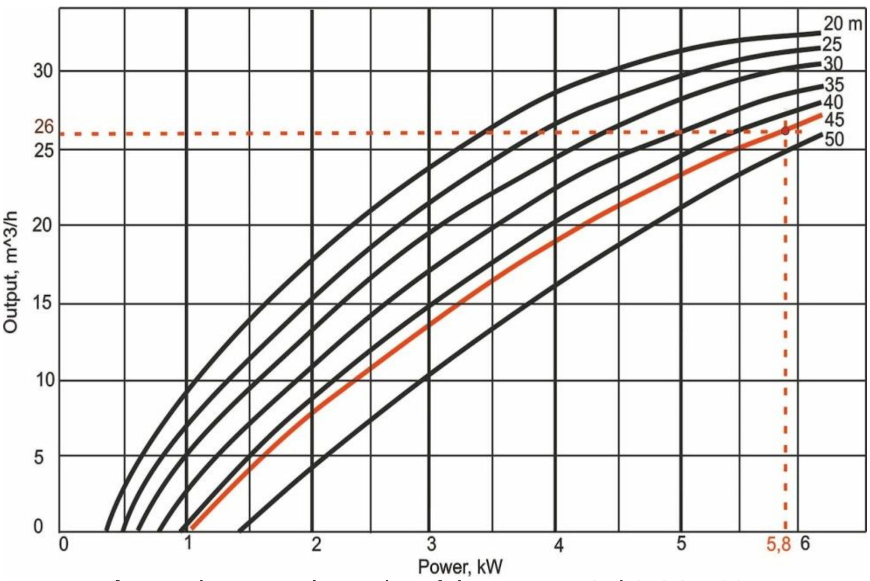

Fig. 7. The operating point of the pump PS7k2 CS-F20-5

2. In May-August over 4 hours a day, the system ensures a maximum flow rate of 27 m^3/h. In April, the maximum flow rate is lower only by 3,7 % and in September - by 4,4 %.

This relative solar radiation and pump flow constancy is due to the selection of a PV panel with higher power and the optimum inclination angle in April – September period.

5. Conclusions

During the irrigation period, the volume of pumped water is equal to the sum of the months volumes from April till September: V_{Total} = 40 300 m^3 and is higher than the required by 15 %. We find a relative constancy of maximum solar radiation on the PV panel and the maximum flow rate of the pump, thus:

- The maximum solar radiation on the PV panel is equal to 784 W/m^2 and corresponds to July. In April, the maximum radiation is lower by 15,3% and in September - by 21,2%.
- In May-August over 4 hours a day, the system ensures a maximum flow rate of 27 m^3/h. In April, the maximum flow rate is lower only by 3,7 % and in September - by 4,4 %.

The developed the hardware of acquisition, processing and communication for the remote control and management of irrigation installation and the realized software of the low and medium layers provide the remote control. The proposed architecture, software structure for the background and public servers can store all the data about irrigation processes.
It have been carried out on the automation of plantation's irrigation process: three irrigation planning and control modalities have been proposed and software testing has been carried out to ensure the high reliability of the information and command system and efficiency.

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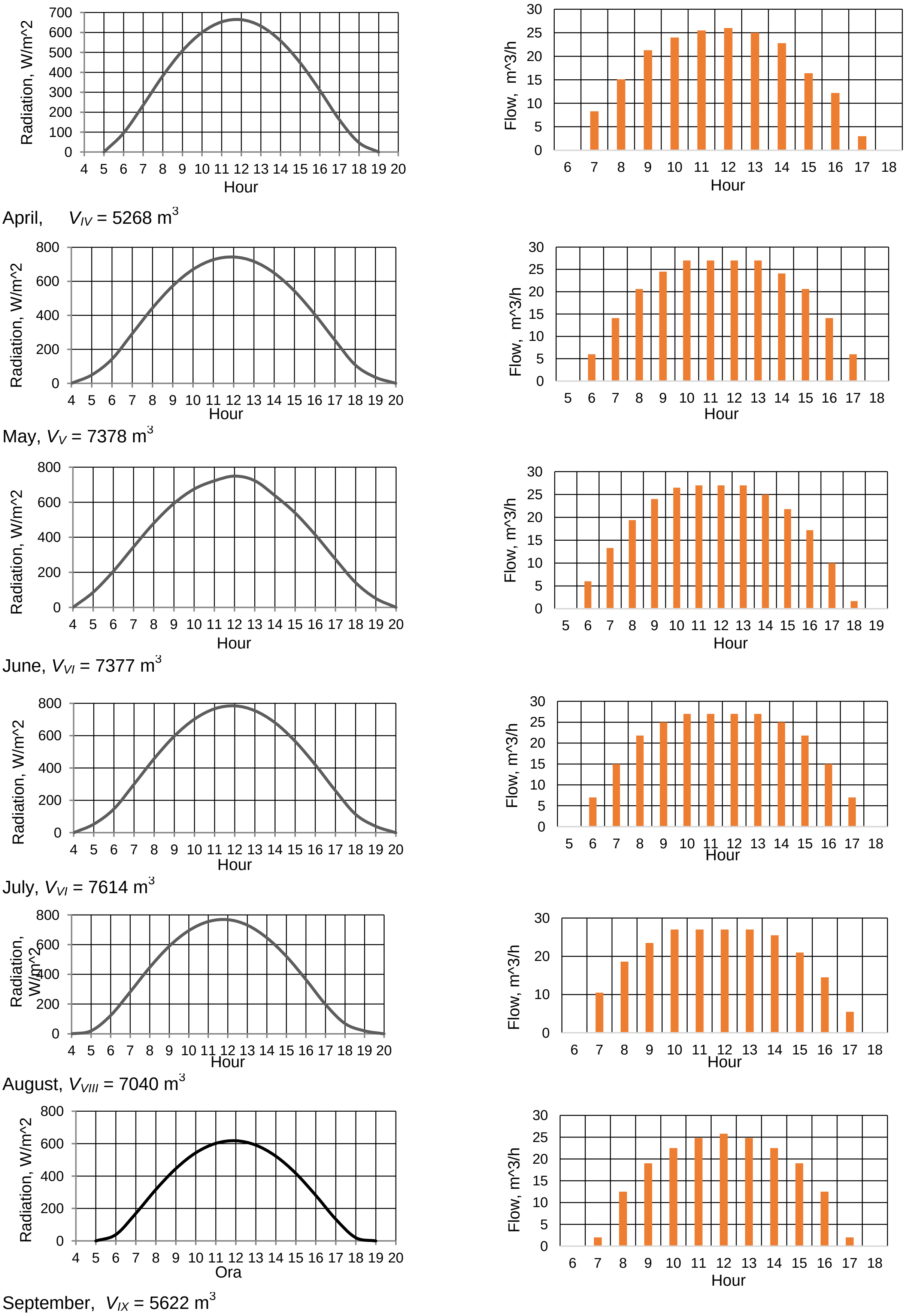

Fig. 8. Hourly radiation (on left) and pump flow (on right)

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