ХИБРИДНИ "OFF-GRID" СИСТЕМИ НАПАЈАЊА И ЊИХОВА ПРИМЕНА У ПОЉОПРИВРЕДИ –ПРАКТИЧНЕ РЕАЛИЗАЦИЈЕ

HYBRID “OFF-GRID” POWER SUPPLY SYSTEMS AND THEIR APPLICATIONS IN AGRICULTURE: PRACTICAL REALIZATIONS

Željko V. Despotović, Mihajlo Pupin Institute,
University of Belgrade, Serbia, zeljko.despotovic@pupin.rs

Хибридни „off-grid“ системи напајања су добили на великом значају у време енергетске кризе. Пољопривредни системи за наводњавање су у великој мери зависни од мрежног напајања, али у случајеима где напојна мрежа није доступна или је интемитентног карактера хибридни „off-grid“ системи су напајања су практично једино решење. У овом раду су дате неке основне топологије хибридних „off-grid“ система напајања са акцентом на примене у пољопривредним системима наводњавања и неке конкретни практични аспекти. Такође , у овом раду су приказана два конкретно реализована хибридна система напајања у склопу наводњавања пољопривредних повртарских култура: (1) систем за наводњавање AGROKAPILARIS® на огледној парцели средње пољопривредне техничке школе у месту Грабовац-оптина Обреновац и (2) систем за наводњавање ратарских култура на парцели од 8 хектара на приватној пољопривреднот поседу у месту Белегиш. У раду су представљени експериментални резултати који су добијени у реалним експлоатационим условима на поменутим платажама повртарских култура. На крају рада су дати критички осврт на добијене експерименталне резултате и закључци.

Кључне речи: *Енергија; пољопривреда; наводњавање усева; хибридно напајање; енергетски претварач; статичка преклопка; соларни панел; ветрогенератор; дизел електрични агрегат. .*

Hybrid "off-grid" power systems have gained great importance during the energy crisis. Agricultural irrigation systems are largely dependent on power grid, but in cases where the power grid is unavailable or intermittent character, hybrid "off-grid" power systems are practically the only solution. This paper presents some basic topologies of hybrid "off-grid" power supply systems with an emphasis on applications in agricultural irrigation systems and on some concrete practical aspects. Also, this paper presents two concretely implemented hybrid power supply systems for irrigation of agricultural vegetable crops: (1) AGROKAPILARIS® irrigation system on the experimental plot of the secondary agricultural technical school in the village Grabovac-municipality of Obrenovac and (2) system for irrigation of vegetable crops on a plot of 8 hectares on a private agricultural property in the town of Belegis. The paper presents the experimental results that were obtained in real exploitation conditions on the mentioned plots of vegetable crops. At the end of the paper, a critical review of the obtained experimental results and conclusions are given.

Key words: *Energy; agriculture;crops irrigation; hybrid power; power converter; static transfer switch; PV module; wind generator; diesel electric generator.*

1 Introduction

The growth of the population on Earth, the impact of climate change, energy crisis, increasing industrial and communal pollution on the one hand and the development of scientific and technological achievements in agriculture on the other hand, determine the dynamic development of this sector. The growth of the world's population and, consequently, the increase in demand for food and food products are in contradiction with the fact that due to climate change and its immediate consequences (drought and floods, pollution of land, water and air), that the arable agricultural land is constantly decreasing. In addition to this, demographic trends are of such a character that the number of inhabitants in urban areas is growing significantly, while in rural areas the population is very small. These facts lead to a disproportion between the requirements and the possibilities of agricultural production [1-4].

Agriculture is one of the key components of the economic development of the Republic of Serbia because, in addition to economic, it also has a pronounced social and environmental significance. However, agriculture in Serbia is still significantly carried out in the traditional way, without the introduction of modern knowledge and agro-technical measures appropriate to developed and environmentally conscious countries. And were agro-technical measures are applied, it is done in an irrational and economically unsustainable way. An example is the measure of crop irrigation, which is a key link in the production chain in the conditions of climate change. Although only about 2% of usable agricultural land is irrigated in Serbia, this agro-technical measure is carried out mostly with the use of fossil fuel aggregates (petrol and diesel), which release harmful gases that go into the atmosphere and intensify the greenhouse effects, polluting the ecosystem and thus causing significant economic losses [5-7].

Agricultural irrigation systems are largely dependent on power grid, but in cases where the power grid is unavailable or intermittent character, hybrid "off-grid" power systems are practically the only solution. Solar energy in combination with wind energy are one of the most commonly used hybrid energy sources for various purposes, which relate to the application and improvement of agro-technical measures in irrigation systems [8-12]. The key advantage is the fact that in periods when there are lower intensities of solar radiation (late autumn, winter or early spring), wind energy dominates. Also, in the summer period (which otherwise implies the dominant energy of the sun), especially in mountainous areas, but often in plains, at night when there is no solar energy, wind energy becomes dominant.

Considering that crop irrigation is realized mainly, in periods when the strongest solar irradiations in the mentioned hybrid systems has a very significant role the solar power. Solar irrigation is used for smaller agricultural plots during the summer months in places where there is no connection to the electricity distribution network. The problem of irrigation is the latter years is extremely relevant because climate change is evident so that summers are getting warmer and with less rainfall. In the summer period, during the night, wind energy can make a certain contribution in increasing the capacity of the energy storage (i.e. battery bank), which can also be used as part of a hybrid power of agricultural irrigation system. All types of power electronic conversion DC/DC, DC/AC, AC/DC, AC/DC/AC [13-18] take a special place in these systems and as such largely determine the behavior of the entire hybrid power system.

In relation to irrigation with diesel generators, this irrigation has an advantage environmentally and does not have exhaust gases or combustion ingredients, so it can be used for irrigation of environmentally prepared food. The problem is very actual in the world, especially in countries where there is a lot of sun days and underground water sources for irrigation and additionally, on the place where the electricity distribution network is unavailable.

This paper present practical realizations “off-grid“ and hybrid power supply systems (HPSS) mainly based on renewable energy sources (RES), primarily solar and wind energy, which were used for irrigation of vegetable crops and for smart management of agricultural land in two locations in Republic Serbia: (1) the AGROKAPILAROS® irrigation system on the experimental plot of the secondary agricultural technical school in the village Grabovac-municipality of Obrenovac and (2) system for irrigation of vegetable crops on a plot of 10 hectares on a private agricultural property in the town of Belegis. The paper presents the experimental results that were obtained in real exploitation conditions on the mentioned plots of vegetable crops.

2 Topologies of hybrid “off-grid” power supply systems in agricultural irrigation

The structures of HPSS which are very interesting for agricultural irrigations are mainly founded in the form of the two most common topologies: (1) centralized "AC bus", (2) centralized "DC bus".

The centralized “AC bus” topology

The centralized "AC bus" topology of HPSS for supplying the system of drip irrigation with water storage tank is shown in Figure 1. In this case, the generators (solar, wind and diesel) and the battery bank are installed in one place and are connected to the main AC bus. The submersible pump (single or three phase) supplying form main AC bus and their role is pumping out water from an underground water source. On Figure 1(a) is shown the drip irrigation system with two storage: one as storage of potential energy (water storage tank), and second as electrical storage (appropriate battery bank). In the some system the battery bank is not necessary, so the system has only one storage i.e. potential energy storage, or water tank, as shown in Figure 1(b). It should be noted that considering the maintenance requirements and the cost of the battery bank, this variant of the system topology is significantly cheaper and more pricing affordable. The disadvantage of this topology is a significantly shorter time of autonomy of the electrical supply.

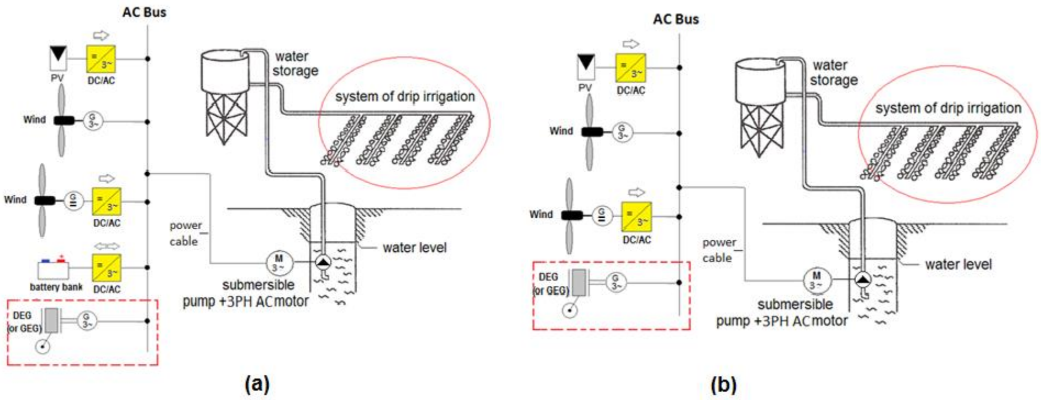

Fig.1. The centralized AC-bus "off-grid" HPSS for drip irrigation system; (a) HPSS with two storage (battery bank and water tank), (b) HPSS with one mechanical storage (water tank)

The centralized "AC bus" topology of HPSS for supplying the system of sprinkler irrigation (so called "spray irrigation") and with only one electrical storage (battery bank) is shown in Figure 2. In this case battery bank storage is necessary, because are requirements for irrigation stricter, in relation to the case of drip irrigation. In fact, it is necessary to provide power of submersible pump with AC motor (single or three phase) in conditions lack or inadequate of solar and (or) wind energy.

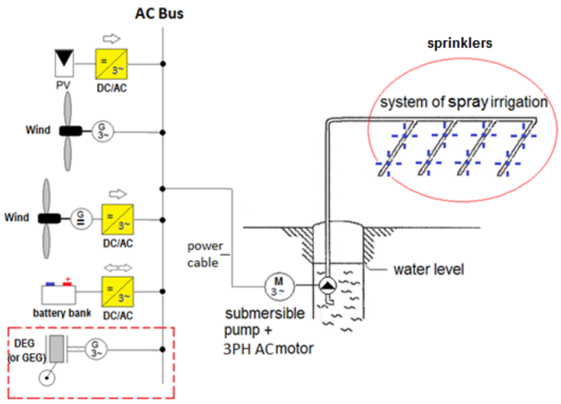

Fig.2. The centralized AC-bus "off-grid" HPSS for sprinklers irrigation system

In the previously shown topologies, the use of PV panels implies the use of MPPT DC/AC converter in order to optimally adapt solar "DC source" to the centralized AC bus system. If a DC wind generator is used in order to adapt to the AC bus, a MPPT DC/AC converter is also used. The use of a battery bank implies the use of a bidirectional AC/DC converter (considering the charge and discharge cycles)

It should be noted that in the case when the energy level from RES (solar and wind source) is low (and) or when the battery bank capacity is low (or at discharged battery when is not possible to provide power to the consumer via the main DC/AC converter) the AC power is taken over by diesel electric generator (DEG) or gasoline electric generator (GEG). This power sources are used in the topologies presented in Figures 1 and 2 only in exceptional cases, i.e. as an emergency power source. The use DEG (or GEG) implies pollution the environment, making noise and does not fit into agricultural systems for the production of "organic food". Therefore, these generators are used in extreme case of emergency.

The centralized "DC bus" topology

The centralized "DC bus" topologies of HPSS for supplying the irrigation systems are shown in Figure 3. Depending on the type of irrigation system (drip or sprinkler irrigation) and the type of submersible irrigation pump, there are several cases of HPSS topologies that can be applied.

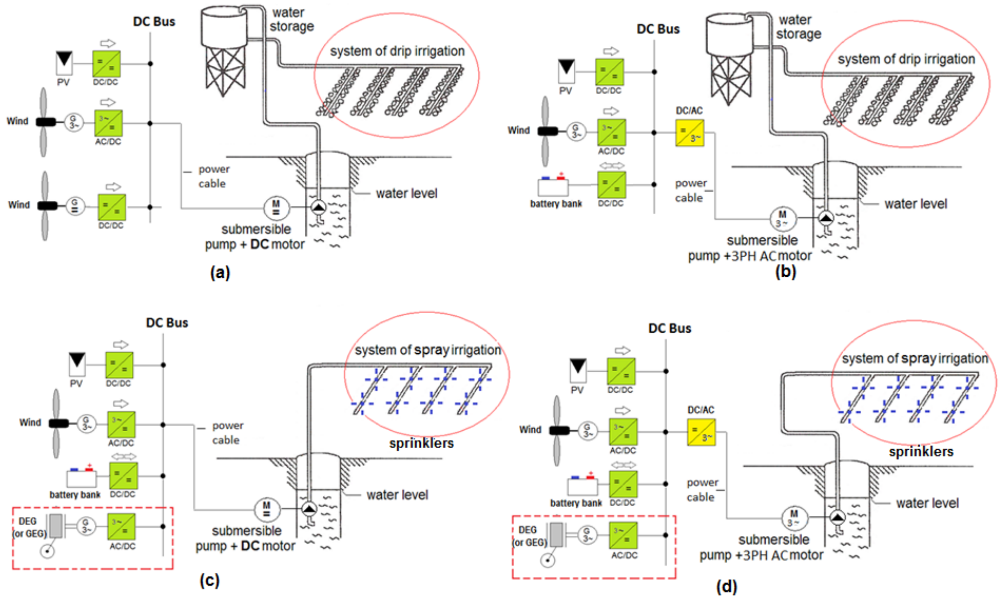

Fig.3. The centralized DC-bus "off-grid" HPSS for irrigation systems;(a) drip irrigation with DC submersible pump, (b) drip irrigation with AC submersible pump, (c) sprinklers irrigation with DC submersible pump, (d) sprinklers irrigation with AC submersible pump

On Figure 3(a) is shown centralized DC-bus system for drip irrigation with water storage and DC submersible pump. These systems are used for smaller plots and the submersible pump with a maximum power of 1.5÷2kW. A battery bank is not necessary in these systems and the energy storage is taken over by the water tank. Between PV panels and centralized DC bus a MPPT DC/DC power converter is use. The same is true for a DC wind generator, in which case MPPT DC/DC power converter is also used. In the case of using an AC wind generator, AC/DC power converter is used to adapt AC output to the DC bus.

On Figure 3(b) is shown the same system as in previous case, with that difference, which is in this case use the AC drive of submersible pump. These systems are used for higher power pump drive motors. Three-phase electric motors with a power of 2.2÷5kW are usually used. For this reason, a battery bank is often used as an additional storage of energy, which is connected to the DC bus via a bi-directional DC/DC power converter. Considering that AC submersible pump is used in these systems, a regulated DC/AC power converter is necessary to ensure optimal operation (V/f or vector control) of the entire electric drive of the AC pump.

On Figure 3(c) is shown centralized DC-bus system for sprinklers irrigation based on DC submersible pump. Considering the energy and autonomy requirements, a battery bank and, if necessary, a DEA are included in this system. The use of a battery bank implies the associated bi-directional DC/DC power converter, while the use of DEG (or GEG) implies the use of an AC/DC power converter. On Figure 3(d) is show the similar system, but with AC submersible pump (usually three phase) and corresponding DC/AC power converter. This configuration is use for 7.5kW maximum power of submersible pump. The disadvantage of previous solutions (Figures 3(c), (d) is the use of DEG (or GEG), which are sources of noise and environmental pollution. In addition, the use of an associated AC/DC power converter makes this solution more expensive.

Based on the above, the idea in some research is to eliminate the use of DEG (or GEG) and to use the electrical AC grid in the RES hybrid system as a supplementary source and not as the main and dominant (or predominant). In some cases, AC grid is available for irrigation systems. In those cases, it is possible to use so called "modified centralized DC bus" topology for irrigation systems of higher power (greater than 7.5kW) with sprinklers and with a three-phase AC submersible pump. One such configuration is shown in Figure 4.

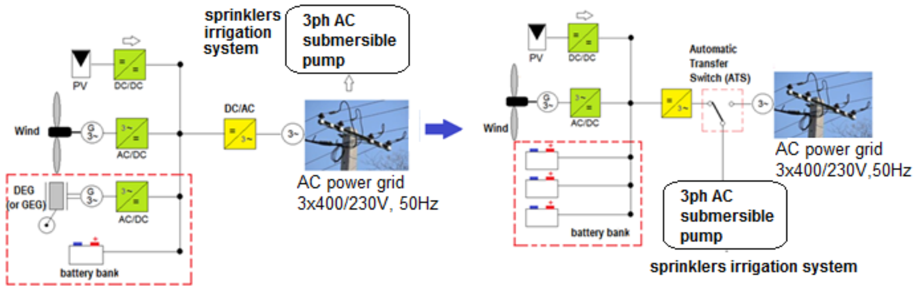

Fig.4. The modified centralized DC-bus HPSS with AC power grid for sprinklers irrigation system

In this case, it is necessary to use automatic static transfer switch (STS) in order the consumer (submersible AC pump) switch from the main inverter of DC bus system to the AC power grid and vice versa. The basic idea is that this irrigation system uses dominantly renewable energy from the sun and wind (popularly called "green energy"), while the use of energy from the AC grid is used only in extreme cases (lack of renewable energy and (or) discharged battery bank).

3 The practical realizations of HPSS for irrigation systems

In the last 10 years, the Robotics laboratory of Mihajlo Pupin Institute has implemented several projects related to „off-grid" HPSS for crop irrigation at several locations around Belgrade. This paper presents the practical realizations and results of two recent projects: (1) HPSS of the sub-surface capillary irrigation system AGROKAPILARIS® on the experimental plot of the Secondary Technical Agricultural-Chemical School from Obrenovac in village Grabovac– Obrenovac municipality (2019.-2020.), (2) HPSS based on RES (sun and wind) and DEG which is used for irrigation of vegetable crops and for smart management of agricultural land on a plot of about 8 hectares at the location of the village "Belegiš, (2020.-2021.).

3.1. HPSS of the sub-surface capillary irrigation system AGROKAPILARIS®

In this project HPSS is based predominantly on the use of RES (wind and solar) with the use of a battery bank, and an electronically controlled fast STS witch is additionally realized. STS switch from the main inverter of DC bus system to the AC power grid 230V, 50Hz and vice versa.

The results presented in this paper are part of the results of the project *"Natural resources of wind and water in order to improve agro-technical measures of irrigation: application of green technologies in the function of sustainable rural development of Serbia"*, within the Incentive Program for improving the creation and transfer of knowledge technological, applied, development and innovative projects in agriculture and rural development in 2019. The project is funded by the Ministry of Agriculture, Forestry and Water Management of the Republic of Serbia.

The AGROKAPILARIS® irrigation system is a method of sub-surface capillary irrigation in which the basic principle is to distribute water to the plant roots by specifically constructed water transmitters, which are installed below the depth of tillage. The water transmitters are located at a depth of thirty centimetres, so that the water is delivered directly to the root. It is a system of underground channels that always keep the water at a certain level and the water moves capillary through the soil, radially upwards and sideways, and this is what gives the plant the ability to feed from the soil [19-20].

The Figure 5 shows the principal block diagram of the irrigation system, as well as the implemented HPSS. The main power consumers in this system are: (1) submersible water pump with mechanical power 750W (for the given pump efficiency of 57%, input electrical power is about 1300W), which serves to pumping water from the draw well , (2) drive of the compressor with power of 100W in the greenhouse (which serves for inflating a double foil in order to create thermal insulation and her tightening), (3) drive for raising and lowering the greenhouse blinds, i.e. for controlled ventilation of the greenhouse, with power 2x100W (i.e. two drives of 100W on each side of the greenhouse).

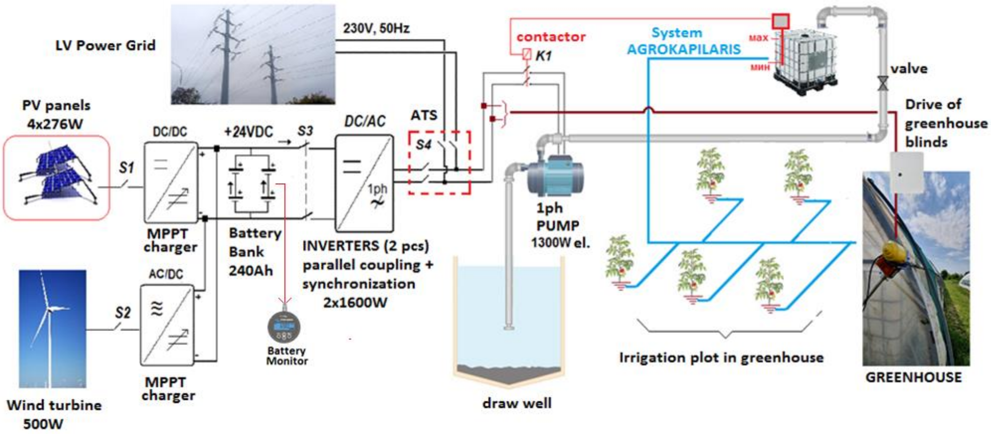

Fig.5. Basic block diagram of the AGROKAPILARIS® irrigation system and the associated HPSS on the experimental plot "Grabovac"

The submersible pump supplies a separate water tank located in the greenhouse. Chemical additives are added to the tank through a special dosing system. The water tank contains an inductive indicator with a float and level controller that serves to maintain the water level in the tank between the minimum (MIN) and maximum value (MAX). The pump that pushes the pressurized water fills the tank when the level is below the MIN level (then the main switch K1 of the pump drive motor is switched on). When the MAX level is reached, the indicator gives a signal to turn off the main switch K1 of the pump drive motor and the water supply to the tank is interrupted. In the event of a level water falling to the MIN value, the pump drive motor is switched on again.

The system of renewable sources (wind and sun) at this location can at best provide a peak power of about 1600W. The DC voltage of 4 parallel connected PV panels is 18÷36Vdc (nominal value is 24Vdc). The current of this PV panels in MPP is 35A (input current of MPPT solar charger). The wind generator MPPT module has the ability to activate the mechanical brake in conditions of strong stormy winds (for wind speeds greater than 10m/s). In this particular case, the mechanical braking of the wind generator assembly is provided at a wind speed of 10 m/s. The line voltage of the wind generator is 30Vrms and it is converted by an AC/DC converter (rectifier) into a voltage of 42Vdc, which is fed to the input of the MPPT wind charger. The maximum battery charging current from this wind charger circuit is about 15A.

The autonomy of the realized HPSS, for the designed battery bank 24Vdc/240Ah is about 2.5h, at a depth of battery discharge of 50%. For greater depths of discharge (about 80-90%) it is possible to provide electrical energy 4 h. The real requirement regarding the time of autonomy, as part of the application of agro-technical measures of irrigation AGROKAPILARIS® is about 2h. In case of battery bank discharge and reduced power from RES (when there is no wind and solar radiation), a system for automatic switching on of the 230V, 50Hz mains power supply has been designed. This is achieved through an automatic STS. This provides uninterrupted HPSS to consumers in the whole irrigation system (pump drive, greenhouse compressor drive, shutter drive for ventilation of greenhouses and other low power consumers).

An electronic digital measuring circuit was realized within the battery bank 24Vdc/240Ah. This measuring circuit basically serves to measure battery voltage and current, so that the monitoring of the battery bank condition is fully provided. The following values of interest can be monitored on the LCD display of this module: battery charging / discharging current expressed in [A], battery voltage in [V], available and estimated battery energy up to the final discharge depth [kWh], discharge depth battery in [%], as well as the state of charge of the battery bank expressed in [%].

The output single-phase AC voltage of the HPSS is 230V, 50Hz, so that the system has a power converter block consisting of two DC/AC power converters, connected in parallel and synchronized according to the principle of one main-MASTER, and the other auxiliary SLAVE. These inverters convert DC battery bank voltage 24Vdc to 230V, 50Hz. The inverters block gives a maximum apparent power of 2x1600VA at its output. At a power factor of 0.8, the total active output power is 2400W. This power refers to the most critical case when the ambient temperature is + 40°C. Since the most critical inverter load is the pump's electric motor (electric power 1300W), an inverter block has been designed that can achieve a maximum output of 16kW at the starting of the pump, in a short time interval of 0.6s. Output inverters have implemented voltage protections at the input and output (under voltage and over voltage). In addition to these voltage protections, current protections are provided (overload protection and protection against direct short circuit at the inverter output).

The aforementioned equipment and power electronics modules are housed in the main distribution cabinet (MDC). The distribution cabinet is mounted on a metal platform. Dimensions of MDC are 1000x800x400mm. MDC is made of double pickled sheet metal, whose thickness is 2.5mm. MDC is painted and plasticized for the purpose of anticorrosion protection. This is important, since it is very exposed to external influences (rain, snow, temperature). Therefore, the MDC is provided in the degree of protection IP66.

Considering the “hard” environmental conditions and climatic influences, the MDC is designed so that the equipment in it is in favourable temperature conditions and conditions of relative humidity. For that purpose, forced cooling of MDC is designed, so that a thermostat-hygrostat assembly was placed inside it in combination with a suitable heater and fan (preventing condensation or removing excess heat due to dissipation of power converter modules). Forced heat dissipation from the inside of the cabinet is provided on the sides of the MDC by means of a fan for extracting hot air. On the side of the MDC, there is a junction box with the main switch of the electric drive of the pump, as well as two visual light indications: green – “operation on RES" and red – “operation on the AC grid power".

Since there is a voltage of 230V, 50Hz in the system, in addition to the mentioned installations in the HPSS a protective earthing and equipotential bonding installation have been performed. In this way, protection against electric shock is provided, and equalization of potentials in the space where the operator can potentially be found. The installation of a device for differential protection against earth faults provides for additional measures of protection against electric shock.

Figure 6 shows the installation of HPSS. Figure 6(a) shows the appearance of a complete HPSS consisting of a wind turbine on 10m high pole, a PV panels system (3 PV panels on the ground + 1 PV panel above the MDC structure) and the MDC itself. Figure 6(b) shows the installation details of the PV panels system. Figure 6(c) shows the appearance of the installed and mounting MDC.

(a) (b) (c)

Fig.6. Installation of HPSS; (a) the appearance of the HPSS after installation, (b) the appearance of the PV panels, (c) the appearance and foundation of the MDC

Figure 7 shows a detailed view of the MDC, on which the inclined solar panel is mounted, and a view of the interior of the MDC with the associated power electronic equipment. Figure 7 (a) shows the side of the MDC, on which the ventilation blinds used in the distribution cabinet cooling system are mounted.

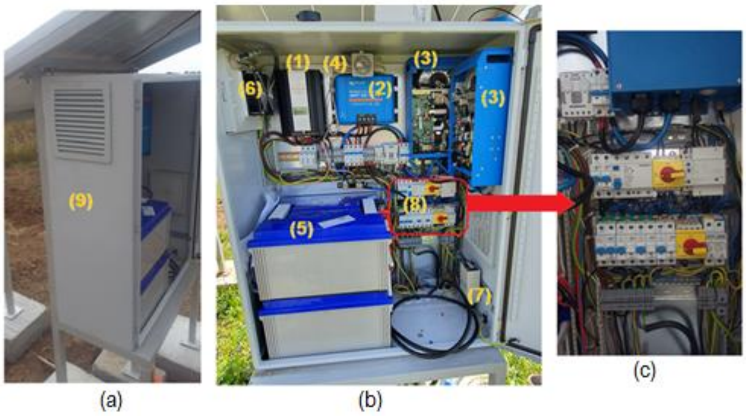

Fig.7. Appearance of the MDC of HPSS with associated equipment; (a) side of the MDC, (b) interior of the MDC, (c) detail of the static transfer switch and other protective and switching equipment

Figure 7 (b) shows the interior of the MDC in which the following electrical equipment is located: (1) MPPT wind controller, (2) MPPT solar controller to which PV solar panels are connected, which provides voltage stabilization and controlled battery charging current, (3) two DC/AC converters (two inverters), (4) digital electronic circuit for monitoring battery bank, (5) battery bank 24V = / 240Ah, (6) air conditioning fans of MDC, (7) heaters, 60W for MDC interior heating, (8) STS assembly and other protective and switching equipment, (9) MDC ventilation drain with blinds.

Experimental results

After the installation of the HPSS, a complete testing and commissioning of the entire system was performed. Follows are some of the most important experimental results obtained during in service testing and commissioning.

Figure 8 shows an oscilloscopic records of the battery charging mode via the MPPT solar charger. When these results were obtained (testing was performed in mid-September 2020), the dominant source of renewable energy was the sun, so the given image refers to a solar charger.

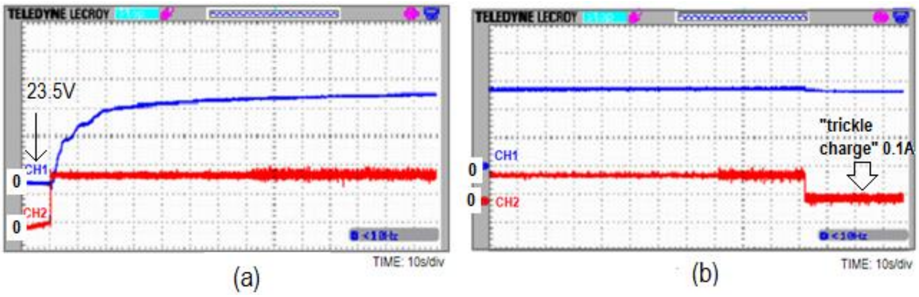

Fig.8. Battery charging mode from MPPT solar charger: (a) time interval at the beginning of charging: battery voltage CH1- [1000mV / div], charging current CH2- [10A / div], (b) time interval at the end of charging: battery voltage CH1- [10V / div], charging current CH2- [20A / div]

Figure 8 (a) shows an oscilloscopic records in the time interval at the beginning of battery charging from the voltage level of 23.5Vdc (at SOC% = 80%) at a constant charging current of 18A. Figure 8 (b) shows an oscilloscopic records in the time interval at the end of charging where the battery voltage was about 28Vdc. In this case the battery was fully charged (the state of charge was SOC = 100%). After reaching SOC = 100%, the current from the MPPT charger was reduced to a trickle charge value of 0.1A.

Figure 9 shows oscilloscope records of the transient voltages and currents in the HPSS. Figure 9(a) shows oscilloscope records of the current and voltage of the AC motor of submersible pump during transition from the inverter power to the AC grid power. From the oscilloscopic records it can be seen that in the transition interval of about 50ms powering of consumer is switched from the inverters power to the AC grid power. During this transition a peak is observed in the pump motor current of about 45A. It is also noticed that during this transition, a certain voltage drop occurs in the interval of about 50ms, which is a consequence of the internal impedance of the inverters output. From the given oscilloscopic records it can also be seen that in normal pump operation, the maximum value of the pump electric motor current was around Imax = 7A (which corresponds to the RMS value of the pump electric motor current of In = 5A). The measured RMS value of the current approximately corresponds to the electrical power of the pump electric motor of 1300W.

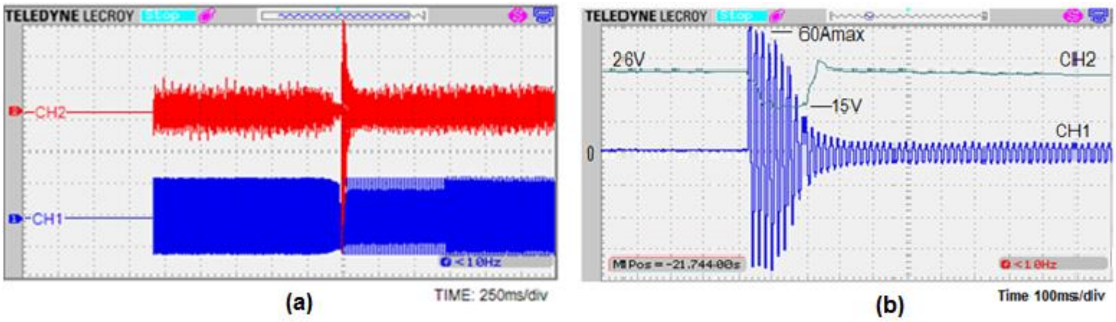

Fig.9. Oscilloscope records of the transient voltages and currents in the HPSS; (a) mode of transition of pump electric motor operation from the inverter power to AC grid power ; CH1-voltage of electric pump motor [250V/div], CH2-current of pump electric motor [15A/div], (b) starting current of the pump electric motor when operate on the inverter power; CH1-current of electric pump motor [15A/div], CH2-voltage of battery bank [10V/div]

Figure 9(b) shows an oscilloscopic records of the starting the pump electric motor in the case when it is powered from the inverter power supply. A significant reduction in battery voltage (up to 50%) is a consequence of the starting current of the pump electric motor, which was around 60A. This output current corresponds to the discharge current of the battery bank (24Vdc/240Ah), of about 600A. In this short interval of starting the electric motor of about 100ms, the battery is relatively deeply discharged (up to almost 60%). Expressed in [Ah], this discharge is $\Delta Q = 600A \cdot 0.1s = 600A \cdot 0.1 / 3600 \approx 0.017Ah$. After this, the battery voltage returns to a value of about 25.5V. It should be noted that during the daily operation of the pump no more than 3 to 4 such "difficult starts" occur, so this case is not so critical and the loss of battery capacity is negligible and therefore no additional electronic circuit for "soft start" of the electric motor pumps is needed, because this would further increase the cost of the technical solution.

Figure 10 shows oscilloscopic records of STS testing during switching from AC grid power to inverters power supply and in the mode of consumption power of about 300W (compressor drive and drive for lifting blinds in the greenhouse were activated).

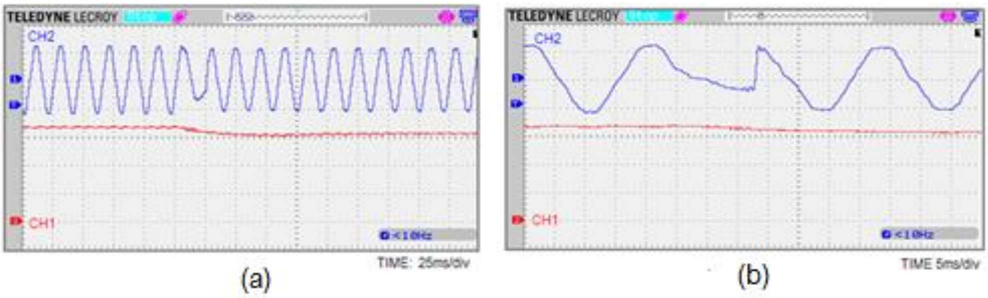

Fig.10. Testing of STS- switching from AC grid power to inverters power; CH1-battery voltage [8V / div], CH2- load voltage (compressor drive and drive for lifting blinds in greenhouse) [250V / div]

Figure 10 (a) shows the oscilloscopic records of battery voltage and load voltage. It can be seen from the recordings that when switching from AC grid power to the inverters power supply, there is a certain voltage drop on the battery, but that this switching was realized in a relatively short interval. A more detailed presentation of this interval is given in the Figure 10(b) where it is observed that the transition time is about 20ms, which is a satisfactory result.

3.2. HPSS for irrigation and for smart management of agricultural land "Belegiš"

The presented results are part of the project form Mihajlo Pupin Institute-Robotics laboratory, "Smart management of agricultural land and natural resources using modern technologies". The project was supported by the United Nations Development Agency and the Ministry of Environment of Republic Serbia. The implemented technical solution was awarded as one of the 11 best innovative and climate-smart solutions within the program "Local Development Resistant to Climate Change" implemented by the United Nations Development Program (UNDP) in partnership with the Ministry of Environment, with financial support from the Global Environment Fund (GEF).

Within the power supply system are realized the PV power plant with an output power of 8 kW, the wind generator with a power of 0.5 kW and battery bank of 48Vdc/720Ah, as primary power sources and a DEG with a output power of 7.5 kW as an auxiliary power source. In addition to this power supply system, a system for remote management of irrigation and smart management of land and natural resources has been implemented. The project also included a system of protection against atmospheric discharges and a complete video surveillance system on a given plot.

Principal block diagram of the "off-grid" HPSS of the "Smart Land" plant "Belegiš" with remote monitoring and management system are given in Figure 11.

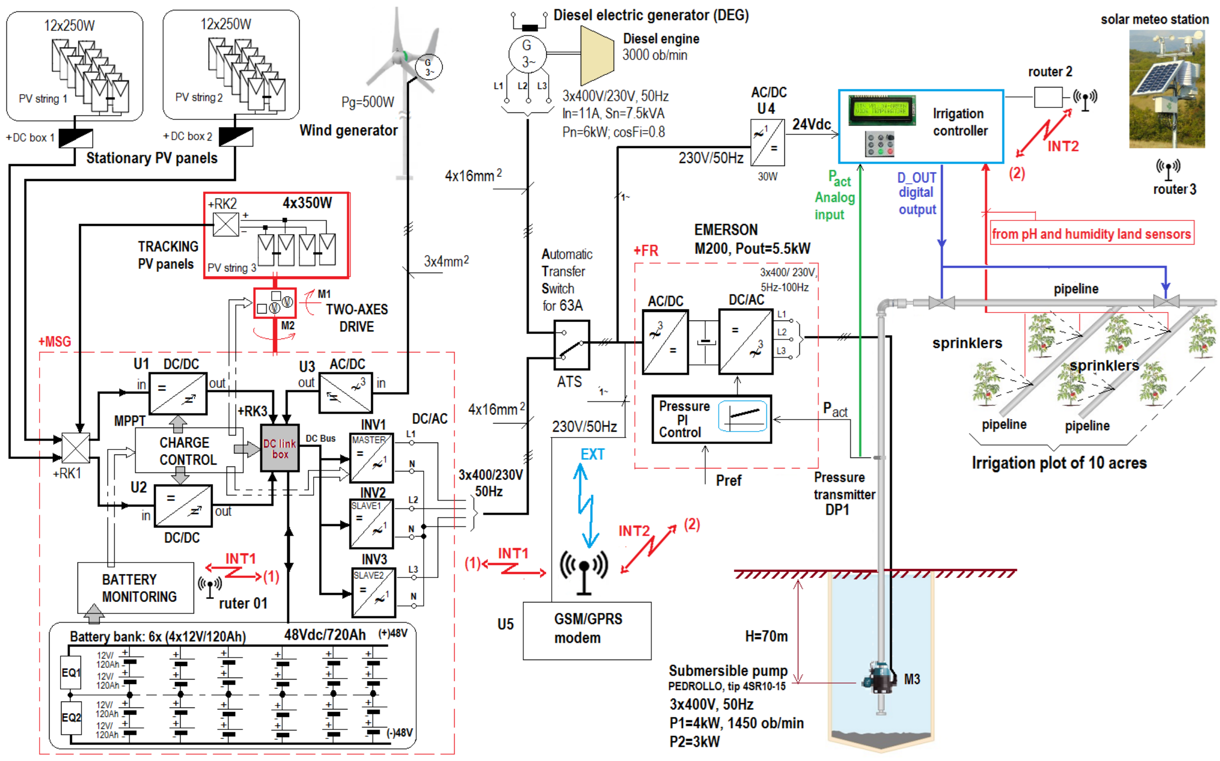

Fig.11. Principal wiring diagram "off-grid" HPSS of the sprinklers irrigation system on the "Smart Land" plant in "Belegiš"

HPSS is based on RES and power electronics devices in which all types of power conversion are represented (DC/DC, DC/AC, AC/DC)[15], [17-18]. The optimization of energy production from this hybrid system was performed according to the sophisticated algorithm proposed in reference [21].

HPSS ensures regulated drive of the electric motor of the submersible pump through the frequency regulator FR. The drive electric motor of the pump is three-phase asynchronous, rated voltage 3x400/230V, 50Hz, maximum input power P1=4.8kW and nominal speed 1450 rpm.

In accordance with the previous requirements for the drive motor of the irrigation pump, a frequency regulator FR with a maximum output power of 5.5kW was designed. As part of this system, a control circuit for pressure regulation was realized (PI pressure regulator was implemented) in the pipeline with sprinklers, which provided irrigation of the land on the given plot [17]. The pressure sensor DP1, range 0÷10bar, manufactured by WIKA, is used as pressure feedback. Setting the reference value P_{ref} is done on the keyboard of the frequency regulator.

The next consumer in the system, but significantly less power consumption (maximum power 100W), is the watering controller. Within this controller, the corresponding digital outputs D_OUT (in three program modes) are activated based on the information from the sensors placed in the soil (humidity sensors and PH sensors).

These outputs ensure the activation of the corresponding solenoid valves in the irrigation pipeline. The controller supports the inclusion of standard 8 solenoid valves. As part of the watering control, an analogue input from the DP1 pressure transmitter is also provided. The watering controller is powered by an AC/DC converter U4 (rectifier) with an input voltage of 230V, 50Hz and a DC output voltage of 24Vdc and an output current of ≈4A, which for an efficiency of this module of 90%, gives an input power of about 110W.

In the irrigation system, a GSM/GPRS modem has been implemented that communicates via two WIRELESS routers (one is used for the battery bank controller, and the other for the watering controller). Through its external link, this modem sends all required statuses and data via SMS messages to the user. The user can also use this link to include or exclude individual consumers. The consumption of this modem system does not exceed 50W. The system also includes a video surveillance system that ensures system protection against burglary and theft. This system is powered by 48Vdc and its maximum power consumption is around 100W. Table 1 shows the summarized power consumption on a given plot "Smart Land".

CONSUMER	**Power (W)**
AC drive (submersible pump+frequency converter + control unit)	5300
Irrigation controller	110
Video-surveillance system	100
Wireless routers (3 pcs.)	30
GSM/GPRS modems (2 pcs.)	60
Auxiliary electronic circuits in „stand by" mode	100
SUMMARIZED – Σ P	**5700**

Table 1. Overview of electricity consumers on the plot "SmartLand" in Belegiš

As can be seen from Figure 11, a 48Vdc/720Ah battery bank was designed for this system (6 parallel branches and four 12Vdc/120Ah batteries connected in series in each branch). A nominal battery voltage of 48Vdc (minimum 40Vdc... maximum 55.6Vdc) was chosen to compromise cable distribution currents, cable heating, and power losses in the DC installation. Each battery branch is provided with voltage and current equalization modules EQ1i, EQ2i (i=1...6), on the serial connections of two batteries. In this way, the working life of the battery bank is significantly extended. The battery bank is connected to the DC-bus in the so-called "DC link box" which is a central power DC collection cabinet to which the solar MPPT chargers U1 and U2, the wind generator charger U3 and the DC power inputs of the DC/AC converters (inverters INV1, INV2 and INV3) are connected.

The available energy from the 720Ah battery bank at a nominal voltage of 48Vdc is 720Ah x 48V=34.56kWh. For a battery bank discharge depth of 50%, the autonomy of the irrigation system is (34.56kWh/2)/5.3kW=3.2h. For a depth of discharge of the battery bank of 80%, the autonomy of the pump system is about 5 hours. In this mode, the life of the batteries is significantly shorter, that is, a lower number of charge-discharge cycles compared to the case when the depth of discharge is 50%.

The previous cases refer to the HPSS operating mode when there is no solar energy, i.e. when the load directly discharges the battery. In real conditions, electricity consumption will also be supported by solar panels that are arranged in three groups, as shown in Figure 11. The system consists of two strings of fixed solar panels mounted on appropriate supports on the ground (PV string-1 and PV string-2). Each string contains 12 panels, with each PV panel having a power of 250W. In addition, a group of four PV panels, each with a power of 350W, are installed in the system, which are mounted on a two-axis solar tracking system of the mobile solar unit i.e. mobile solar generator (MSG) [13-17]. Thus, the total installed power in PV panels is 2x12x250W+4x350W=7.4kW. If we also take into account the wind turbine with the associated electric generator of power P_g=500W, the total yield from RES is approximately 8kW of active power. In the real case, the operation of the pumping plant is realized at an active power of about 4kW, so that approximately half of the produced electricity from OIE will be used to charge the battery bank, and the other half will be used to power the pumping unit. In this way, the balance between produced and used energy was achieved in the mentioned HPSS for crop irrigation with sprinklers and pipeline system.

Within the presented HPSS, a subsystem with power electronics modules (electrical power converters) plays a very important role. This system, together with the central control unit, is located on the MSG and has the task of ensuring the controlled charging and discharging of the battery bank, both from the PV panel and from the wind generator, but also has the role of ensuring the synchronization and operation of the single-phase output inverters INV1, INV2, and INV3 that are connected in a three-phase "star" connection [14-15].

The stabilization of the voltage and current from the PV panel and charging of the battery bank is achieved by DC/DC converters (chargers) U1 and U2, which have implemented algorithms for MPPT of the PV panels. These power electronics devices provide controlled and optimal charging of the battery bank. All converter devices have all the necessary electrical protections (voltage and current) and ensure maximum utilization of the nonlinear curve of the available power of the PV panels [17-18]. Stabilization of voltage from the wind generator is provided by a special MPPT charger U3, which is designed for parallel operation with solar MPPT chargers U1 and U2. The three-phase voltage VG is converted into a DC voltage by means of an input rectifier, and this rectified voltage is then additionally stabilized and adjusted to the battery bank voltage. The output current provided by module U3 at maximal wind speed 10m/s is about 20A. So the total battery charging current that is supplied to the "DC link" distribution is about 140A, taking into account the PV panels (each group of PV panels provides a current of about 60A; two groups 2x60A). Therefore, a current of about 140A is available in the DC link circuit, at maximum input power from RES (wind and solar).

As a backup source of three-phase power supply, a (DEG was used, with a maximum output power of about 6kW at a rotational speed of about 3000 rpm. DEG is used exclusively in the mode when the power from RES is significantly reduced (in the case when there is no wind and solar insolation) and (or) when the battery bank is discharged below the discharge depth of 80%.

In the event of a complete discharge of the battery bank and reduced power from the RES, automatic switching of the three-phase power supply to the three-phase power supply from the DEG is foreseen by means of an automatic static transfer switch (ATS), which is shown on the electrical principle diagram in Figure 11. In this way, a uninterruptible power supply of the consumer system (primarily the irrigation system) is provided.

On Figure 12 are shown the drone recordings of the "Smart Land" system and HPSS for irrigation and remote management on the plot “Belegiš”. Figure 12(a) shown the view of the plot and view of the hybrid power plant based on RES. The basic parts of the HPSS can be seen in the screenshot on Figure 12(b): wind generator, MSG, battery bank, fixed PV panels and pumping station.

Figures 13, 14 and 15 show some of the characteristic views of the realized HPSS on the “SmartLand” at the agricultural plot “Belegiš”.

(a)

Fig.12. The recording from the drone on the "Smart Land" system and HPSS for irrigation and remote management on the plot “Belegiš; (a) view of the plot (above) and view of the hybrid power plant based on RES (below, (b) disposition of subsystems of HPSS .

Fig.13. Disposition of the PV power plant (total power 2x12x250W = 6kW) and wind turbine 0.5kW with mounting pole.

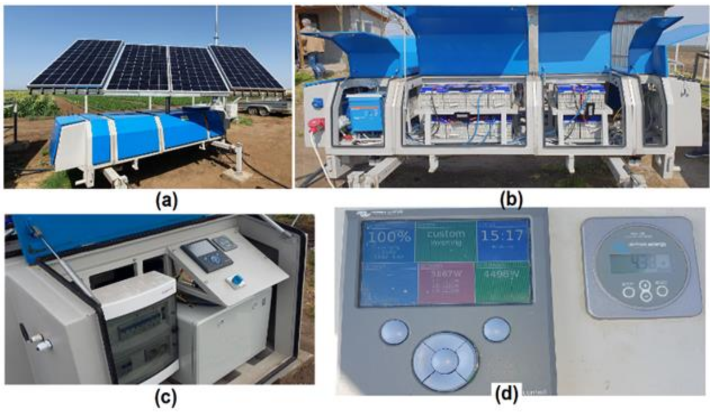

Fig.14. Battery bank and accessories; (a) layout of the MSG device with 4 solar panels with a total PV power of 4x350W, (b) layout of the battery bank 48Vdc/720Ah with accompanying power electronics devices (DC/DC, DC / AC), (c) layout of the control panel with integrated CCGX controller and battery monitor, (d) display of parameters in operating mode

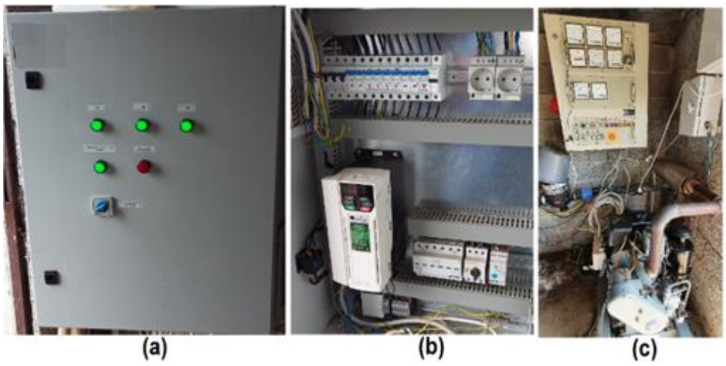

Fig.15. Display of equipment in the room for storing the pump set and DEG; (a) door of the MDC of pump unit with control and signaling equipment, (b) internal appearance of the MDC and position of the frequency converter with output power 5.5kW, (c) disposition of the DEG and the accompanying control cabinet

Experimental results

In this chapter, some key experimental results related to the total balances of produced electricity energy at the annual, monthly and daily level. Of particular interest is month with the highest production (August 2021) are presented. The experimental results were obtained on the basis of data logging, which was realized in the CCGX control module. The measurements were carried out in the period from July 1, 2021 (when the hybrid power supply system and the associated measuring-acquisition system were fully implemented and put into operation) until March 30, 2022.

Figure 16 shows diagrams of electricity energy production from PV panels, electricity energy consumption and the part accumulated in the battery bank (current and average values). The highest production of electricity energy of about 921 kWh from PV panels was achieved in the month of August. Total production of electricity energy was amounted 2723kWh.

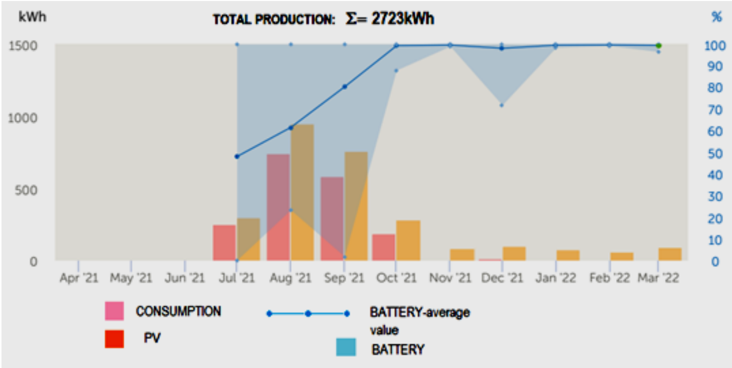

Fig.16. Diagrams of production and consumption of electricity energy on the agricultural plot Smart Land "Belegiš" for the period July 2021-March 2022.

The diagram of the total average monthly production for the month of August 2021 is given in Figure 17. The diagram shows that 531kWh was directly used from the PV panels, while 390kWh was accumulated from the PV panels in the battery bank. The total average PV production was amounted 921kWh. From the electricity energy production diagram on it can be seen that the highest production of 41 kWh was achieved on August 4, 2021. Integral diagrams of daily production and consumption of electricity energy (for August 4, 2021.), as well as the accumulated energy of the battery bank is shown on Figure 18.

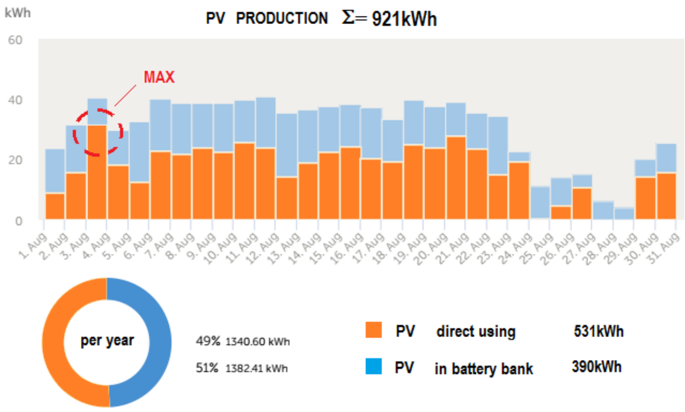

Fig.17. Diagram of average monthly electricity production for the month of August 2021 on the agricultural plot Smart Land "Belegiš"

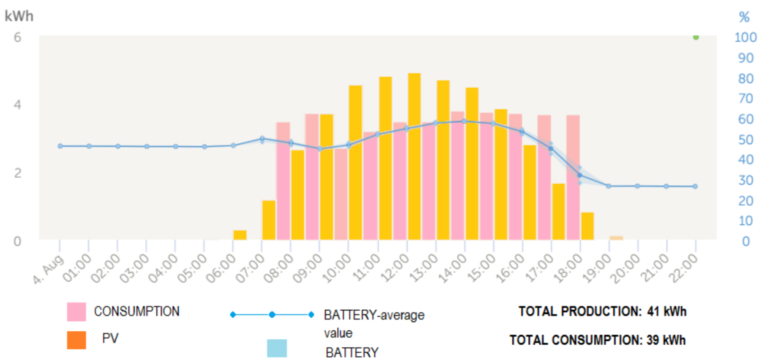

Fig.18. Integral diagrams of daily production and consumption of electricity energy, as well as the accumulated energy of the battery bank on the agricultural plot Smart Land -"Belegiš" on August 4, 2021.

Figure 19 shows oscilloscope recordings of the phase current of the pump motor (the load is symmetrical, so it can be considered that the values of the currents in the other two phases are the same effective values) and the pressure in the sprinkler pipeline installation in the irrigation system.

The set pressure value in the installation was set to P_{ref}=8 bar. The pressure control system is designed in such a way that the type of control (P, PI and PID) can be applied in a relatively simple way.

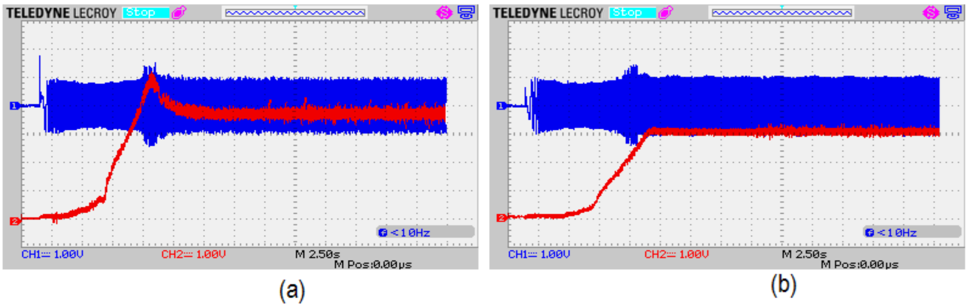

Fig.19. Oscilloscopic records of the phase current of the inverter INV1 (master) and pressure in the installation of sprinklers in the irrigation system;(a) P pressure control , (b) PI pressure control; CH1-phase current of inverter INV1 (master) (5A/div) CH2-pressure in pipeline system (5bar/div); time base (2.5s/div).

Figure 19(a) shows oscilloscope recorded waveforms for the case of the implemented P pressure control. The set pressure value is reached in a significantly shorter time, but with a certain excess of 50%. In this case, it is also observed that the actual pressure value is around 9 bar and that it deviates from the set value of 8 bar, which is a consequence of the fact that the P regulation system was implemented in the pressure regulator. Figure 16(b) shows the oscilloscope recorded waveforms for the case of the implemented PI controller with the appropriate setting of the PI controller parameters (gain and integration time constant). In this case, the set pressure value is achieved with satisfactory accuracy gradually in an interval of about 5s, without exceeding the pressure in the pipeline installation.

4 Conclusion

In this paper, the role and importance of “off-grid” HPSS in mostly use systems of crop irrigation (drip irrigation and sprinkler irrigation) are presented. The emphasis in the paper was given to RES and power electronics devices (i.e. electrical power converters) used in these systems. Practically all types of electrical power conversion (AC/DC, DC/DC, DC/AC, AC/AC) are represented in these systems. The paper was presents the practical realizations of the Mihajlo Pupin Institute in this field, within two recently successfully completed development projects in this area: (1) HPSS for the AGROKAPILARIS® drip irrigation system on the experimental plot of the secondary agricultural technical school in the village Grabovac-municipality of Obrenovac and (2) HPSS for sprinkler irrigation system of vegetable crops on a plot of 8 hectares on a private agricultural property in the town of Belegis. The advantages and disadvantages of implemented technical solutions of HPSS were also pointed out, as well as some exploitation problems that were noticed during the implementation. Practical realizations and experimental results are presented in the paper, which represents an additional quality of the entire engineering work and scientific research. This research presents a small contribution in the field of increasing quality of sustainable development and use of "green energy" in Republic of Serbia, but the author hopes that it will be stimulating and instructive for those who are just entering this complex and interdisciplinary field.

5 References

[1] **Daly, H.E.,** Ecological economics and sustainable development, Selected Essays of Herman Daly, Cheltenham: Edward Elgar Publishing Limited, 2007.

[2] **Sayed Y. A., Fadl . M.E.,** Agricultural Sustainability Evaluation of the New Reclaimed Soils at Dairut Area, Assiut, Egypt using GIS Modeling, *The Egyptian Journal of Remote Sensing and Space Sciences* 24, pp. 707–719, 2021.

[3] **Rikalović, G., Vračarević, B.,** Energetska politika kao faktor održivog razvoja, *Energija, ekonomija, ekologija*, 3, XXXIII, str. 66-72, 2021.

[4] **Rodić, A., Despotović, Ž.V., Stevanović, I.,** Pametna poljoprivreda-Mogućnosti digitalizacije i automatizacije u ekološki i ekonomski održivoj poljoprivrednoj proizvodnji, u monografiji : S.Roljević (Ed.), *Primena novih tehnologija u cilju pametnog upravljanja procesom gajenja povrća u zaštićenom prostoru*, Pogl. 2, (str. 27-58), Institut za ekonomiku poljoprivrede, Beograd, 2021.

[5] **Jeločnik, M., Subić, J., Nastić, L.,** Upravljanje troškovima na poljoprivrednim gazdinstvima, Institut za ekonomiku u poljoprivrede, Beograd, 2021.

[6] **Geoghegan, T., Anderson, S., Dixon, B.,** Opportunities to achieve poverty reduction and climate change benefits through low-carbon energy access programmes, The Ashden Awards for sustainable energy, GVEP International & IIED. (available at 2008)

[7] **Subić, J., Kljajić, N., Jeločnik, M.,** Obnovljivi izvori energije i navodnjavanje u funkciji održivog razvoja poljoprivrede: ekonomski aspekti, Institut za ekonomiku poljoprivrede, Beograd, 2017.

[8] **Eker.B,** Solar Powered Water Pumping System, *Trakia Journal of Sciences*, Vol. 3, No. 7, pp 7-11, 2005.

[9] **Hadj Arab A., Chenlo F., Mukadam K., Balenzategui J. L**., Performance of PV water pumping systems, *Renewable Energy* 18 (1999) pp. 191-204.

[10] **Mokeddem A., Midoun A., Kadri D., Hiadsi S., Raja I. A.**, Performance of a directly-coupled PV water pumping system, *Energy Conversion and Management* 52 (2011) pp. 3089–3095.

[11] **Ramos S., Ramos H. M.,** Solar powered pumps to supply water for rural or isolated zones: A case study, *Energy for Sustainable Development* 13 (2009) pp. 151–158.

[12] **El-Shimy.M., Noor. M., Abdo.T,** Irrigation Water Pumping (IWP) Systens- Comparison Between Photovoltaics and Conventional Energy Sources, *Environmental Engineering* (2016), Vol. 3, No.2, pp. 7-20.

[13] **Rodic A., Despotovic Z.V., Jovanovic M.D., Popic S., Stevanovic I.,** *"Mobile Robotic Solar Generator MobiSunProEnergy™- Application in New Energy Tehnologies"* , VIII International Forum for Clean Energy Technologies 2014 ENERGY CHARTER = SUSTAINABLE DEVELOPMENT OF SERBIA, Novi Sad, 30th September – 1st October 2014.

[14] **Despotovic Z., Jovanovic M., Stevanovic I., Majstorovic M.**, Coupling and Synchronization of the Inverter's Group in Mobile Solar Generator, *Energy - Economy - Ecology*, Vol.3-4, Year XVIII, pp. 252- 260, March 2016. [in Serbian].

[15] **Despotovic Z., Majstorovic M.,** Voltage Stabilization and Synchronisation of DC/AC Power Converters in Mobile "OFF-grid" Solar Power Systems, *Full Papers in Proceeding of International Conference* "Power Plants 2016", 23-27.November 2016, Zlatibor Serbia, pp. E2016-082 (1-11).

[16] **Stevanović I., Popić S. , Rodić A. , Despotović Ž. , Jovanović M.,** " Pokretni robotizovani solarni generator, primer konstruktivnog rešenja mehaničke strukture", *57.Konferencija za elektroniku, telekomunikacije, računarstvo, automatiku i nuklearnu tehniku-ETRAN*, Zlatibor, 3-6. Jun 2013.

[17] **Majstorović M., Despotović Ž.V., Ristić L**., "Application of Mobile Solar OFF-grid Generator in Irrigation System - Case Study", *19th International Symposium POWER ELECTRONICS Ee2017*, N.Sad, Republic of Serbia, October 19th - 21th, 2017.

[18] **Majstorović, M., Despotović, Ž.V., Mrščević, D., Đurić, B., Milešević, M., Stević, Z.**, Implementation of MPPT methods with SEPIC converter, *19th International IEEE Symposium INFOTEH-JAHORINA (INFOTEH) 2020*, East Sarajevo, Bosnia and Herzegovina, 2020. https://ieeexplore.ieee.org/abstract/document/9066296

[19] **Zloh, Z.,** AGRO KAPILARIS – A Revolutionary Method of Irrigation, *PROCEEDINGS of The 1st International Congress on Soil Science, XIII National Congress in Soil Science SOIL – WATER – PLANT* September 23 – 26th, Belgrade, SERBIA, 2013, pp. 493-505.

[20] **Zloh, Z., Miladinović,M., Ugrinović,M., Rudić, D., Savić, N., Koković, N.,** Succeful Aplication of Agro Kapilaris Concept in Agricultural Production, *PROCEEDINGS of The 1st International Congress on Soil Science, XIII National Congress in Soil Science SOIL – WATER – PLANT* September 23 – 26th, Belgrade, SERBIA, 2013, pp. 506-510.

[21] **Ristić, V., Rajaković, N.,** Primena Lagranžove optimizacije na problematiku proizvodnje energije iz obnovljivih izvora, *Energija, ekonomija, ekologija*, 1-2 , str. 145-152, 2020.