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A Comparative Analysis between Battery- and Solar-Powered Wireless Sensors for Soil Water Monitoring

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Abstract: Wireless sensor networks (WSN) have found wide applications in many fields (such as agriculture) over last few years, and research interest is constantly increasing. However, power supply to the sensor nodes remains an issue to be resolved. Batteries are usually used to power the sensor nodes, but they have a limited lifetime, so solar energy harvesters are a good alternative solution. This study provides a comparative analysis between battery and solar energy harvesters for sensor nodes used for soil water monitoring. Experimental results show that small-sized solar panels with low-power energy harvester circuits and rechargeable batteries distinctly outperform secondary batteries in outdoor and continuous-operation applications. The power level of the energy storage device of sensor node 1, which was powered by a small PV panel, remained constantly close to 90% for all days. The power of the other three nodes, which were powered by a rechargeable battery, was initially at 100% of the charge and gradually started to reduce. Sensor node 1 performed a total of 1288 activations during the experimental period, while sensor nodes 2 and 4 behaved satisfactorily and performed a total of 781 and 803 activations, respectively. In contrast, sensor node 3 did not exhibit the same behavior throughout the experiments.

Keywords: wireless technology; sensor node; power source; photovoltaics; solar irradiance

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1. Introduction

Wireless technology can be used in many fields, such as industry, transportation, agriculture, etc. Wireless sensor networks (WSN) have found wide applications in agriculture over the last few years, and research interest is constantly increasing. A WSN is a group of spatially distributed smart sensors for monitoring and recording data (such as air temperature, relative humidity, soil water content, etc.), storing the collected data, and transmitting the gathered information to a central station [1]. Morais et al. [2] developed a wireless sensor network for irrigation applications. This network was based on several solar-powered wireless acquisition stations suitable for soil moisture monitoring in greenhouses and open-field crops to save water and energy. Xiao et al. [3] deployed a smart irrigation control system based on a wireless soil moisture sensor network. The wireless sensor nodes were powered by three 1.5 V dry batteries. With this power supply, each sensor node could operate for a period of about 100 days. Savić and Radonjić [4] presented the architecture of the wireless sensor network for a smart irrigation system. The prototype of soil moisture wireless sensor node provided low power consumption and therefore it was appropriate for these uses.

The main building block of the wireless sensor network is the sensor node. The system architecture of a sensor node includes the following components: a microcontroller for processing data, an LCD display to show data, wireless communication for transmitting and receiving data, and memory for data storage [5]. Each of these components works with different amounts of energy. Thus, the sensor node is powered by one or more batteries or a solar energy harvesting unit. Batteries have high energy density, are available in various sizes, and eliminate the need for power electronics. Batteries are classed into two main categories: primary and secondary. Primary batteries can only be used once, while secondary batteries, the so-called rechargeable batteries, can be discharged and recharged many times. When the battery voltage is below a threshold value, the node is out of service. Thus, it is necessary for batteries to be replaced or recharged. However, the replacement or recharging is costly and time-consuming work [6]. Various approaches have been adopted to slow down battery depletion. Among these approaches, the low power (sleep) mode of the wireless transceivers is one of the most used for energy saving. In any case, the batteries are soon discharged, and energy consumption therefore is a serious matter for sensor node designers. Hence, the designers have adopted a new technique that combines the use of rechargeable batteries with energy harvesting systems [7].

Energy harvesting systems can collect surrounding energy from various sources and convert it into usable electrical energy. It is a very important method to implement long-running systems in which there is no need to recharge in order remain active. Among all energy harvest systems, photovoltaic (PV) systems [8,9] provide the best power outcome and can efficiently transform outdoor light so as to supply continuous and reliable power to the wireless sensor nodes. Some recent studies on PV harvesting systems are described in [10–12]. A solar energy harvesting system consists of a solar (PV) cell (harvester), an energy converter (DC-DC converter, maximum power point tracking (MPPT)), and energy storage (battery or super-capacitor) [13]. The PV cell is composed of a semiconductor material (wafer) that absorbs the sunlight's energy and converts it into electricity due to the photovoltaic effect. The efficiency of a PV cell is due to the maximum electrical power output provided by the cell as compared to the energy from the light absorbed by the cell. The amount of electrical power produced from PV cells depends on the characteristics (intensity and wavelengths) of the available light and the technical parameters of the PV cell [14].

Converting power from the PV cell to the storage device is crucial for any energy harvesting system. There are several power converter architectures that can be used to regulate the supply voltage from the energy harvester to a suitable output voltage. Among these architectures, the low-dropout (LDO) regulator and switched-mode power supply (SMPS) systems are widely used in power management circuits [15]. LDO is a DC linear voltage regulator that is used to maintain regulation with small differences between supply and load voltage. SMPS is a type of power supply that incorporates semiconductor switching techniques rather than standard linear methods to convert the required output voltage. Moreover, in energy harvesting systems it is crucial to track the maximum power point (MPP) to maximize the harvesting efficiency. To this aim, it is necessary to use maximum power point tracking (MPPT) techniques to keep input voltage close to the operating voltage [16].

The current study is part of a broader project on wireless sensor nodes for the monitoring and logging of the soil moisture of crops. It focuses on a comparative analysis between two different power supply modules to find a suitable solution for powering wireless sensor nodes. In particular, a comparison is made between the rechargeable battery as energy reservoir and the solar energy harvesting system. The rest of this study is organized as follows. Section 2 describes the architecture of the sensor node. Section 3 presents the results and discussion of this study. Finally, conclusions are drawn in Section 4.

2. Materials and Methods

The study was conducted in the experimental field located at the Department of Agrotechnology—University of Thessaly, Larissa, Greece (39°37′34.0″ N, 22°22′52.8″ E, elevation of 80 m above sea level). The total area used for the experimental site was 520 m^2 (20 m × 26 m). A hemp crop (*Cannabis sativa* L.) was established on 5 May 2020 at the experimental site for the purposes of the study. The variety selected for the experiment was Futura 75. Its selection was based on climate adaptation requirements, as well as seed and fiber yields.

The wireless sensor network (WSN) in the proposed remote soil water monitoring and logging system consists of 4 wireless soil moisture sensors and a weather station (Figure 1). Measurements of volumetric water content (VWC) are essential for assessing the status of the hemp crop-available water in soil. Wireless sensor nodes, which are distributed on the experimental site, collect, process, and transmit field sensing data using the GPRS communication protocol by making HTTP requests. The data are accessible to the end users (farmers) through a dedicate GUI that was developed for projecting the received data. In addition, the data were accessible to the users though an API that was developed using OpenAPI 3.0 specifications (OAS 3.0). The data can be exported from the API in XML, JSON, YAML, and CSV format.

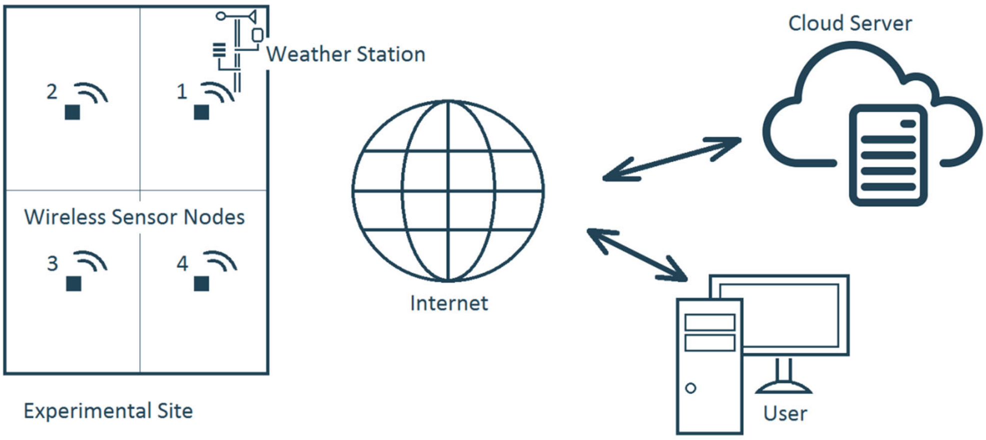

Figure 1. Overall view of wireless sensor network (WSN).

Wireless sensor nodes were developed by the Agricultural & Environmental Solutions Private Company (AGENSO), Athens, Greece. Each node plays the role of a base station independently transmitting its data through the Internet to a cloud server. A node can support a soil moisture sensor, a weather station, and an external energy harvesting unit (solar cell). The architecture of such node comprises analog sensor channels, an onboard digital signal processor (DSP), RAM and flash memory, a GSM modem, a global positioning system (GPS) receiver, an LCD display, and a power source (Figure 2). Each sensor node was developed to be power efficient and run by 1 rechargeable AA battery (average capacity of 1.940 mAh) for a long period of time. In addition, solar-based energy harvesting technology was adopted in the case of sensor node 1. The hardware components are enclosed in an IP68 box, as shown in Figure 3, to protect them from damage and environmental conditions.

An ultralow power energy harvester and battery charger circuit applies the MPPT function and integrates the switching elements of a buck–boost converter. It allows the charge of battery by monitoring the end-of-charge and the minimum battery voltage to avoid overdischarge. Unregulated voltage output is available (e.g., to supply the microcontroller), while 2 fully independent LDOs are embedded for powering the sensor and wireless transceiver module.

To extend the battery life, the microcontroller and wireless transceiver go to their own standby or sleep mode with a low current consumption when the sensor node is idling. By using the real-time clock, the microcontroller in the sleep mode is periodically awakened by the interrupt, which is set previously (e.g., 1 h). The microcontroller awakening releases the sleep request to the transceiver. As a result, the transceiver also wakes up. The microcontroller acquires the data from the sensor and sends it to the cloud server via the activated transceiver. After finishing the transmission on the cloud server, the microcontroller makes the wireless transceiver sleep, sets the period to the real-time clock, and goes to the sleep mode.

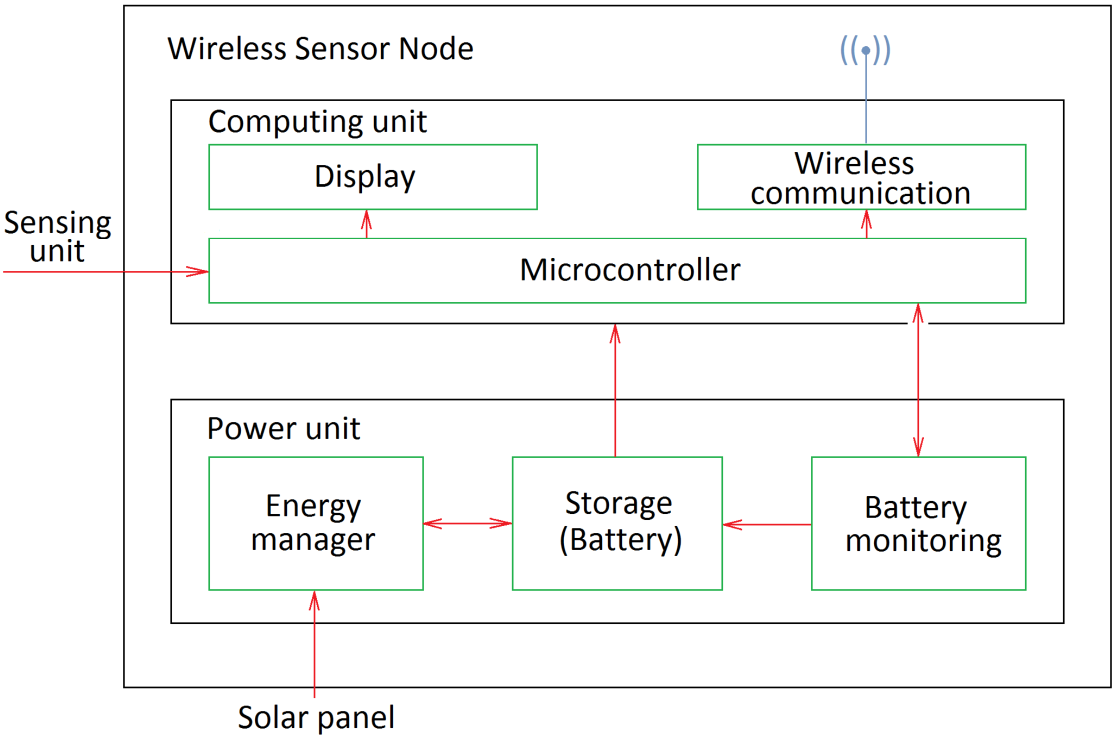

Figure 2. The architecture of the proposed wireless sensor nodes.

Figure 3. Photograph of sensor node 1 and sensor node 2.

Access to accurate weather data can assist in crop management, such as irrigation scheduling. For this reason, a weather station was installed in the experimental field. It integrates sensors for wind direction, wind speed, air temperature, relative humidity, rainfall, barometric pressure, and solar radiation. All sensors are included in plastic enclosure with a built-in solar panel. The weather station was connected in sensor node 1 and mounted on a steel tube at height of 2 m, as shown in Figure 4. The technical specifications of the weather station are given in Table 1.

Figure 4. PV panel and weather station.

Table 1. Weather station specifications.

Item		Value
Supply	Console	5 VDC
	Outdoor sensor	3 AA rechargeable batteries
Transmission distance in open field		100 m
Communication frequency		433/868/915 MHz
Measuring interval outdoor sensor		16 s
Alarm duration		120 s

A 112 mm × 84 mm × 3 mm commercial PV panel was used for converting sunlight into usable energy. The PV panel features an open circuit voltage of 7.3 V and a short circuit current at 204 mA. The maximum power it can produce is around 1.1 W. Table 2 details the specifications of the used PV panel. The PV panel was placed on the steel tube, facing south with a tilt angle of 30° (see Figure 4).

Table 2. PV panel specifications.

Item	Unit	Value
Cell	-	Polycrystalline
Operating voltage	V	6
Working current	mA	183
Maximum output power	W	1.1
Open circuit voltage	V	7.3
Short circuit current	mA	204
Size	mm	112 × 84 × 3

3. Results and Discussion

Figure 5 shows the number of activations of the sensor nodes per day during a 93-day period after the start of the experiment (from 10 June to 10 September 2020). Sensor node 1 was set to be activated every 3 h until the 62nd day when it was set to every 1 h. Thus, it performed a total of 1288 activations during the experimental period. Except for the first 5 days (trial period), sensor nodes 2, 3, and 4 were set to activate every 3 h (i.e., 8 activations in 24 h). Sensor nodes 2 and 4 behaved satisfactorily and performed a total of 781 and 803 activations, respectively. In contrast, sensor node 3 did not exhibit the same behavior throughout the experiments. It was observed that between days 6 and 18, as well as between days 76 and 93, sensor node 3 faced difficulties in wireless communication. During the inactive period all sensor nodes were in sleep mode.

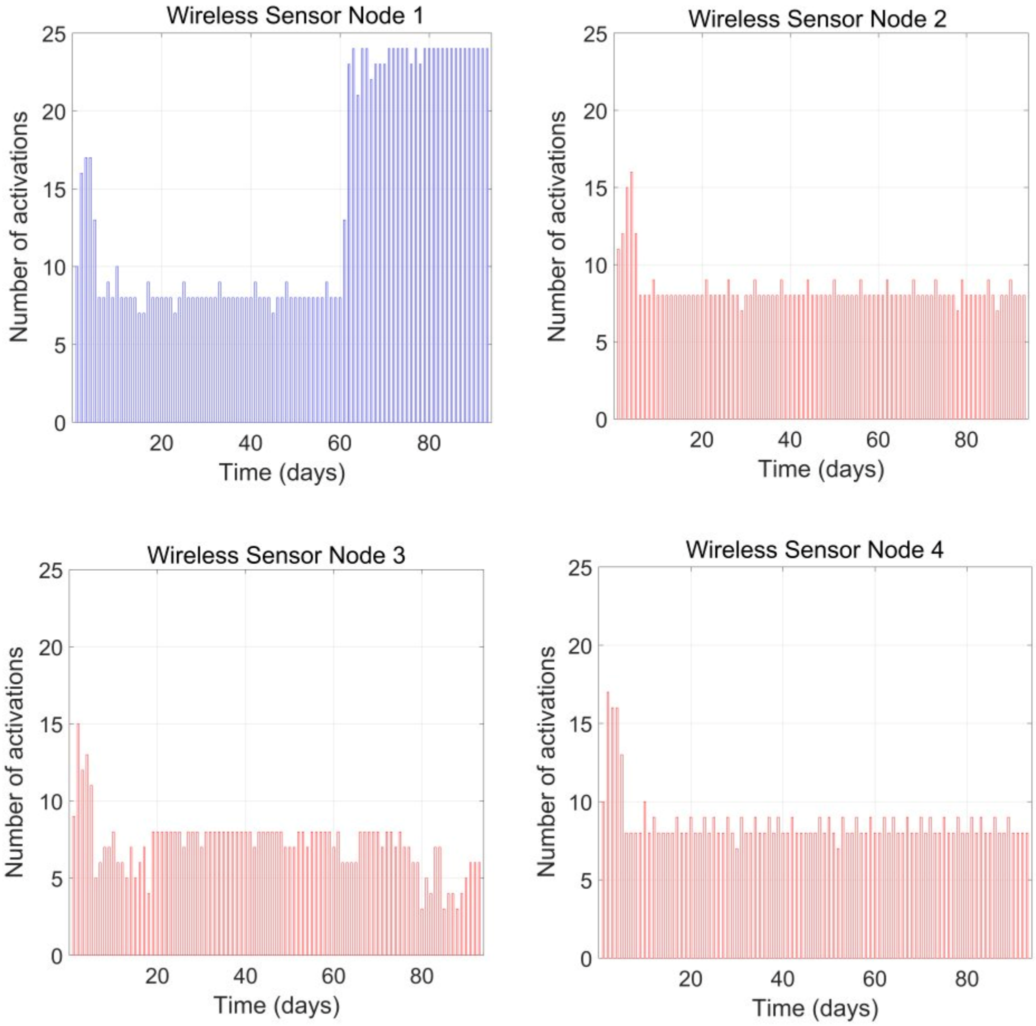

Figure 5. Number of activations per day of the sensor nodes during the experimental period.

Figure 6 shows the remaining power (%) of the energy storage devices of the four sensor nodes during the experimental procedure. The power level of the energy storage device of sensor node 1, which was powered by a small PV panel, remained constant close to 90% all days. The other three nodes were powered by a rechargeable battery. The power of all three nodes was initially at 100% of the charge and it gradually started to reduce. The power drop at energy storage device of the sensor node 3 was greater compared to the other nodes and sharper after the 73rd day. A data transmission problem was the main reason for the higher power consumption in sensor node 3.

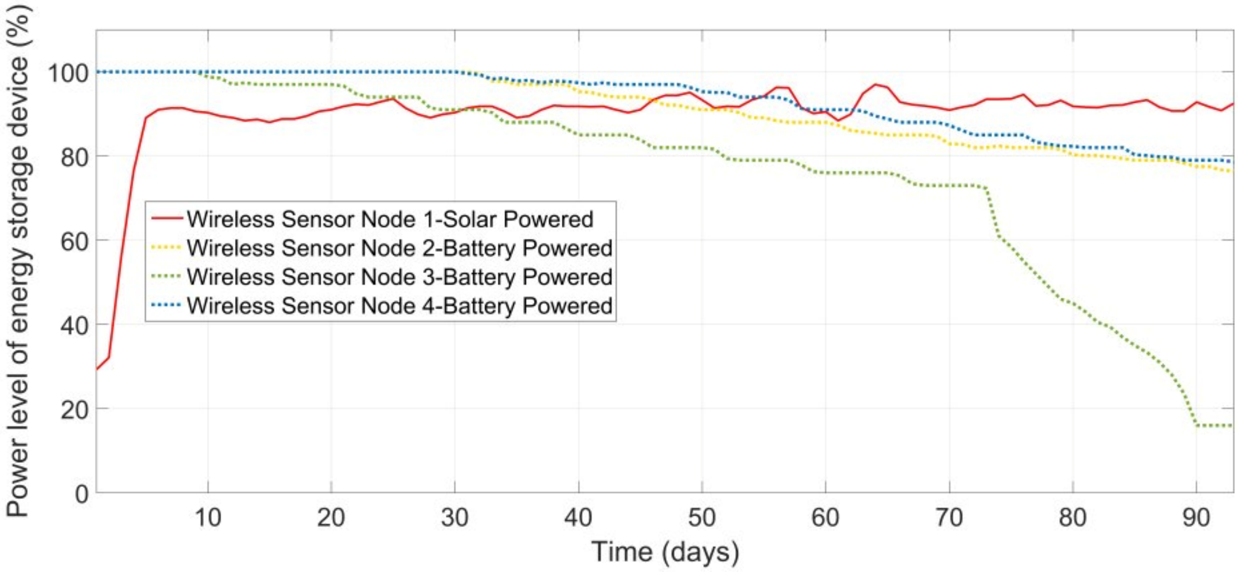

Figure 6. Remaining power of the energy storage devices of the 4 sensor nodes.

Here, the environmental conditions that prevailed in the experimental field are presented. A knowledge of environmental conditions is necessary for an understanding of the behavior of the solar-based energy harvesting system. Figure 7 shows the solar irradiance acquired by the weather station. The solar radiation reached high values during the days with increased sunshine, while it decreased and reached minimum values on cloudy days. It is obvious that there were several days with limited sunshine and therefore during these days the energy production from the PV panel was also limited. Figure 8 shows the air temperature acquired by the weather station. The air temperatures exceeded 30 °C in only two cases, so the changes in the air temperature do not seem to affect the energy production.

Figure 9 shows a comparison between the power level of the energy storage device of sensor node 1 and solar irradiance on different days. It is obvious that on days with increased sunshine (for example on 1 September 2020 and 4 September 2020) the level of stored energy was close to 95%. On the contrary, on cloudy days (for example on 18 September 2020) the level of stored energy fell below 80%.

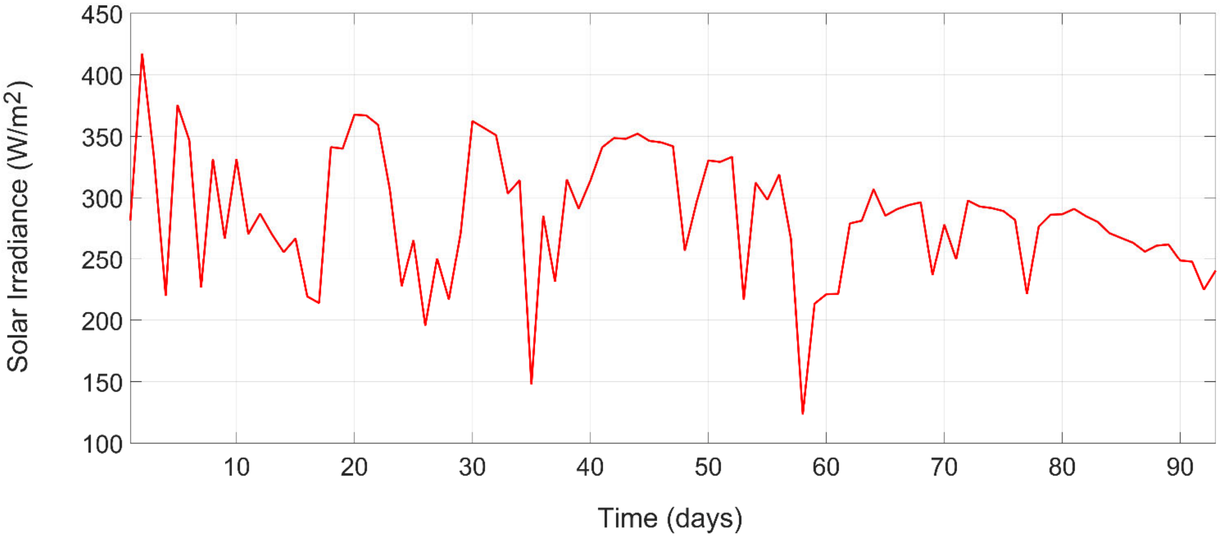

Figure 7. Solar irradiance readings during the experiment.

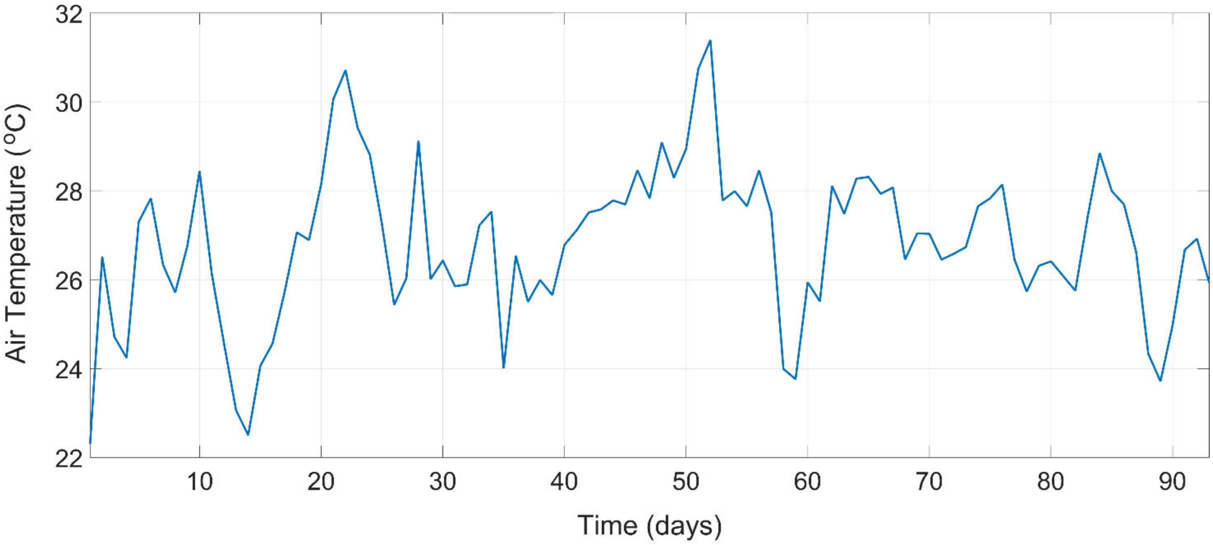

Figure 8. Air temperature readings during the experiment.

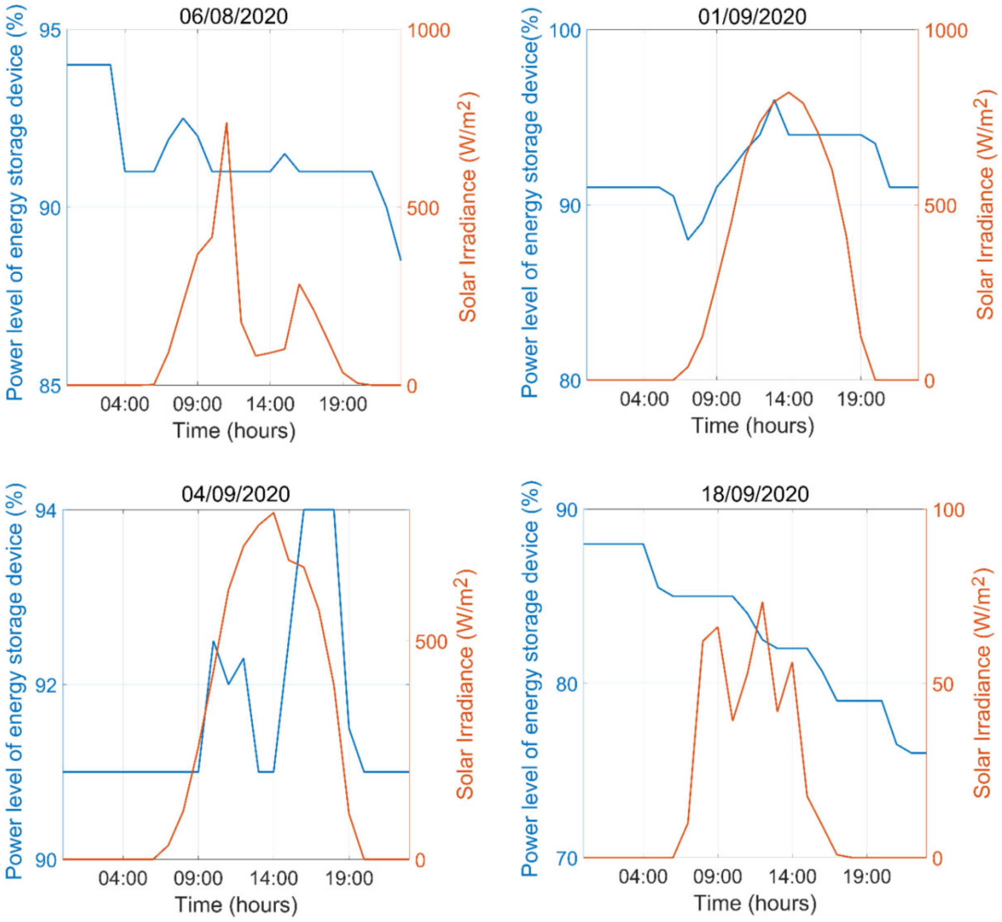

Figure 9. A comparison between the power level of the energy storage device and solar irradiance.

In recent years, there has been a great interest in developing wireless sensor networks for agricultural applications such as soil water monitoring. Wireless sensor nodes have become increasingly complicated. Sensor nodes have evolved gradually into small embedded systems. Attributes such as low power consumption module design or the integration of modules in a chip are essential for energy-constrained portable applications.

An energy-harvesting system converts usually solar energy into electrical energy for direct use by the sensor node or indirectly by the node energy storage device. The main devices that are used to store harvested energy for powering sensor nodes are rechargeable batteries or capacitors [17]. Sensor nodes need to have long-lifetime energy storage devices due to the inherent difficulty in physical access to replace or recharge them.

The experimental results confirmed the suitability of the energy-harvesting system and energy storage device. The small PV panel successfully charged the rechargeable battery of the solar-powered node. The battery voltage increased gradually from the day we installed the sensor nodes and was maintained at a certain level during all days of the experiment. This also satisfied our expectations of charging the rechargeable battery and keeping the sensor node running without problems. Moreover, the system was not affected by the increased wireless communication (24 activations in 24 h) during the last phase of the experimental procedure. The comparison between the solar-powered and battery-powered nodes showed that solar power distinctly outperformed the battery in outdoor applications. Finally, the experimental results showed that two of the nodes powered by rechargeable batteries started gradually discharging. The third node began to discharge sharply after day 73. A better solution for the nodes would be having two separate energy supply units: a capacitor as the main source and a rechargeable battery as the backup source [18]. For sensor nodes operating continuously, only solar energy harvesters can offer a suitable solution.

Some previous works have considered energy harvesting by WSNs for smart agriculture monitoring applications. In reference [19], power consumption field tests on an agricultural environment monitoring server system using WSNs were performed. It was found that the proposed system collected information without malfunctions and provided real-time monitoring and various application services. In reference [20], the research work aimed to maximize the WSN network lifetime using solar energy-harvesting technique. From the simulation results, it was proven that the sensor network lifetime increased from 5.75 days to 115.75 days. Furthermore, the network throughput was also increased from 100 Kbits/s to 160 Kbits/s. Greg Jackson et al. [21] proposed a low-cost moving solar tracker for environment monitoring with 99% harvester efficiency. An intelligent solar energy harvesting system was proposed in [22] for the supply of long-term and stable power in WSN. In the proposed system a maximum power point tracking circuit was adapted to take full advantage of solar energy, and guaranteed a lithium battery with an appropriate charging method for long-term operations. In addition, it reduced the frequency of the battery charge–discharge cycle.

4. Conclusions

This study provides a comparison between battery- and solar panel-powered sensor nodes. The sensor nodes were used for soil water content monitoring. The results showed that to keep a rechargeable battery life of several months, the number of activations per day had to be lower than 10 data transmissions. The power level of the energy storage device of the solar panel powered sensor node remained constantly close to 90% through all days. Furthermore, the energy storage device of this node was not affected by the increased wireless communication (24 activations in 24 h) during the last phase of the experimental procedure. Thus, the solar panel permits us to reach a potentially infinite sensor node lifetime. The energy requirements of the nodes will decrease as the integration of the node circuits increases. The use of low-power, low-size wireless sensors is the most appropriate way to acquire soil water content data at different soil depths, close to plant roots, and across large geographical areas.

WSN are used to monitor soil water content in annual crops such as hemp (*Cannabis sativa* L.), which are mainly cultivated in the summer months. Therefore, the interest regarding the energy power of the sensor nodes is mainly focused on the 3 months of summer, from the beginning of June to the beginning of September. In future work, for perennial crops such as orchards, additional tests will be carried out in different seasons such as spring and fall.

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Conflicts of Interest: The authors declare no conflict of interest.

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