Design Optimization of a RES-based Power-Supply System for Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSNs) are widely used during the last years in various environmental and industrial applications and they are frequently installed in geographically isolated areas, where access to electricity is not available. In such cases, the WSN nodes are power-supplied by Renewable Energy Sources (RES), accompanied by energy-storage units. In this paper, a design optimization method is presented for deriving the optimal configuration of the RES-based energy production system of a WSN node, such that its total lifetime cost is minimized, while simultaneously it is guaranteed that the data-acquisition equipment of the WSN node is uninterruptedly power-supplied during the entire year. The design results verify that by applying the proposed optimization technique, RES-based power-supply structures with a lower lifetime cost are derived, compared to the non-optimally designed configurations. Experimental results are also presented, demonstrating the successful operation of a RES-based power-supply system, which has been optimally designed using the proposed method.**

Keywords—Renewable Energy Sources, power supply, Wireless Sensor Networks, design optimization, Genetic Algorithms

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are widely employed during the last years for monitoring various parameters of interest in the environment, industries, buildings etc. [1]. Frequently, the sensing nodes of WSNs are distributed over geographically isolated areas, where there is lack of access to electricity. In such cases, the WSN nodes are power-supplied by Renewable Energy Sources (RES), such as PhotoVoltaics (PVs) and Wind-Generators (W/Gs), which are interfaced to chargers and storage devices (usually sealed lead-acid or lithium/polymer batteries) [2]. The optimal sizing of the RES units in order to minimize the cost of the WSN energy production system and simultaneously guarantee that the load energy requirements are covered, is of great importance.

Various design techniques for RES systems have been proposed in the scientific literature. The driving force that leads to these design concepts is the fact that the environmental conditions (i.e. solar irradiation, ambient temperature and wind speed), as well as the market prices of the balance-of-system devices differ from place to place around the globe and, additionally, the load energy requirements depend on the target application. These facts render the calculation of the optimal solution in terms of the power capacity of the RES units, as a new challenge for every single case under study.

In [3], a sizing methodology for stand-alone PV systems based on the Particle Swarm Optimization (PSO) algorithm is presented. The Annualized Reliability and Cost of System (ARCS) is used as an objective function of the optimization process, which includes the concepts of Expected-Energy-Not-Supplied (EENS) and Expected-Excessive-Energy-Supplied (EEES). In [4], multi-criteria optimization of a hybrid system is performed by employing the elitist Non-Dominated sorting Genetic Algorithm (NSGA-II), which belongs to the class of multi-objective evolutionary algorithms [5]. In [6], Genetic Algorithms (GAs) are used to detect the optimal size of a PV array for power-supplying a critical load, with the minimum CAPital EXpenditure (CAPEX) and OPerational EXpenditure (OPEX), respectively, while simultaneously achieving the desired Loss of Power Supply Probability (LPSP). The GAs are favorable in such problems, since they are computationally efficient. Two more applications of GAs are presented in [7] and [8], respectively, where the capacity of a PV source and battery bank, as well as the PV-generator tilt angle have been employed as decision (i.e. design) variables, while the investment and maintenance costs have also been taken into account during the optimization procedure. GAs are also applied in [9], which focuses on the design of stand-alone hybrid RES systems using a multi-criteria analysis method for minimizing various system cost metrics, such as the capital, operation and maintenance costs. Similarly, [10-12] aim at the sizing optimization of hybrid RES systems by focusing on the minimization of the total cost of the energy-production system and the maximization of its reliability. In all of these cases, the optimization process is accomplished by using technical and economic simulation models, which are available in the HOMER software [13].

The optimal sizing of a PV/wind/diesel hybrid energy system using daily-averaged meteorological data is presented in [14]. A method for the optimization of a wind/PV/diesel system is proposed in [15], where the minimization of CO_2 emissions is also taken into consideration. The sizing optimization of grid-connected hybrid systems is explored in [16] and [17] by focusing on the reduction of power loss and multi-objective optimization criteria, respectively. An approach of energy management in hybrid renewable generation and energy-storage systems is presented in [18]. It uses a Fuzzy C-Means (FCM) algorithm for grouping data of the meteorological conditions at the installation site into clusters of days with similar data points, in order to account for the

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seasonal variations. Then, GAs are employed for obtaining the optimal energy generation and storage capacities. It has been demonstrated that the flexibility of time-shifting the operation of an electric load, in order to minimize the cost of the power-generation system and maximize its efficiency, depends on a compromise, which must be performed, between the risk of failing to meet the load power demand and a potential reduction of the power-generation system cost. The GA-based optimization of a hybrid topology of a stand-alone RES system, which is comprised of a PV source and a W/G, is presented in [19]. The effect of temporal sampling of the PV source power-production data is examined by comparing the performance of a system optimized using data of high temporal resolution with that of a system optimized using data of lower resolution. It is concluded that by applying a higher sampling rate, solutions closer to the real optimum can be obtained. In [20], the total number of battery replacements (BRPs) is minimized by using a battery cycle-life model in combination with a generalized curve of the relationship between the normalized PV array and battery capacities. This technique has the advantage that the amount of data of the prevailing meteorological conditions, which are required for designing the PV system, is reduced. Thus, this technique is useful in all of those cases where inability to collect such information arises.

The past-proposed design methods of RES systems have been developed for energy-production systems with a relatively high power capacity. However, to the authors' knowledge, no study has yet been carried out investigating the design optimization of a stand-alone RES system, which is intended to cover a rather small power consumption, such as that of the electronic devices (e.g. sensors, data-acquisition systems, wireless transceivers etc.) comprised by the nodes of a WSN. In this paper, an optimization method is presented for optimally designing the RES-based power supply system of a stand-alone WSN node, such that its total capital and lifetime maintenance cost is minimized, while, simultaneously, the energy requirements of the electric load during the entire year are completely satisfied. The design results verify the superiority of the RES-based power-supply system of a WSN node, which has been designed optimally using the proposed technique, compared to non-optimized configurations. Experimental results are also presented in this paper, demonstrating the successful operation of a power-supply system, which has been optimally designed using the proposed method.

II. THE RES-BASED POWER-SUPPLY SYSTEM OF A WSN NODE

A block diagram of the WSN node power-supply system is illustrated in Fig. 1. The electric load of the WSN node, which must be successfully power-supplied by the RES-based energy production system under design, comprises the following units: (i) one or more sensors for monitoring the parameters of interest (e.g. in the environment, buildings, industries etc.), (ii) a data-acquisition device for collecting and processing the measurements collected by the sensor(s) and (iii) a wireless transmission unit for communication with other WSN nodes and/or a central data-collection station. In order to achieve

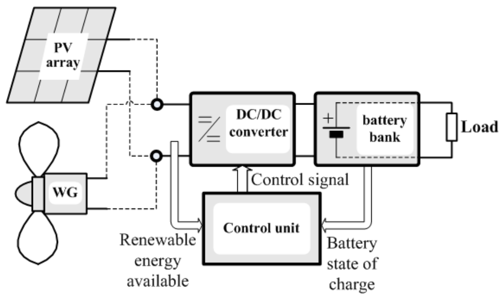


Fig. 1. A block diagram of a RES-based power-supply system for WSN nodes.

energy autonomy, the WSN node is power-supplied by RES sources. Depending on the solar irradiation or wind potential, which is available at the installation site of the WSN node, the corresponding sensor node is power-supplied by either an array of PV modules, or a W/G. Due to the intermittent nature of solar- and wind-based energy production, an electric energy storage unit, in the form of a battery bank, is integrated in each WSN node in order to power-supply the electronic appliances of the sensor node in case of low solar irradiation or wind speed conditions.

A high-efficiency, switching DC/DC power converter is used to interface the energy produced by the RES source to the battery bank. The operation of the DC/DC power converter is controlled by a microelectronic Energy Management System (EMS), which is implemented using a microcontroller or Digital Signal Processing (DSP) device. The EMS ensures that the maximum power is produced by the RES source, under the stochastically varying meteorological conditions at the installation site, by executing a Maximum Power Point Tracking (MPPT) algorithm [21, 22]. Also, it regulates the battery charging process, such that the recharging time of the battery bank is minimized, by optimally exploiting the RES-generated energy [23].

III. THE PROPOSED DESIGN OPTIMIZATION METHOD

With reference to the diagram of the WSN node power-supply system, which is shown in Fig. 1, the target of the proposed design method is to derive, among a list of commercially available PV modules, W/Gs and batteries, the optimal type, number and installation parameters of these units, such that the lifetime cost of the power-supply system is minimized and simultaneously, the energy requirements of the electric load of the WSN node are completely covered, thus resulting in zero load rejection.

A flowchart of the proposed design optimization process is shown in Fig. 2. Initially, the designer specifies whether a PV or a W/G power source will be employed for producing the required energy. In the former case, the design variables considered in the optimization process are the number and tilt angle of the PV modules, the number of PV modules connected in series and parallel, respectively, with the PV array, as well as the rated capacity of the battery bank, which is used as an energy-storage unit. In case that it is selected by the designer to employ a W/G, then the corresponding design variables are the

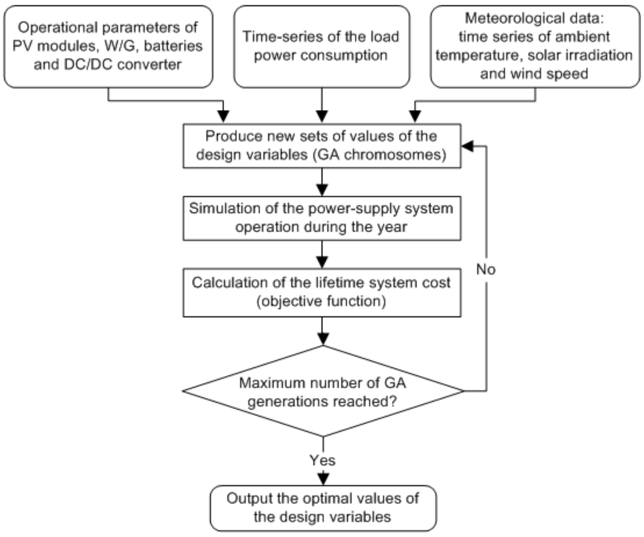


Fig. 2. A flowchart of the proposed optimization process.

rated power and installation height of the W/G, as well as the capacity of the battery bank. Also, the designer inputs the following data to the optimization algorithm:

- the time-series of hourly-average values of the meteorological conditions, which prevail at the installation site and
- the operational characteristics of the PV modules (e.g. open-circuit voltage, short-circuit current etc.), W/G (e.g. power-production vs. wind speed curve etc.), DC/DC converter (e.g. curves of efficiency vs. input power etc.) and battery (e.g. nominal capacity, maximum permissible depth of discharge etc.), which will be considered for building the RES system under design, together with their capital and maintenance costs. These operational data are provided by the manufacturer of the corresponding device (e.g. in the device datasheet).

The optimization process is performed by a GA, targeting to derive the optimal values of the aforementioned design variables, which result in the minimization of the total capital and lifetime maintenance cost of the power-supply system, C_{PS} (€), as follows:

$$\text{minimize}\{C_{PS}\} \tag{1}$$

where:

$$C_{PS} = C_{PV} + C_{Chr} + C_{Bat} \quad \text{or} \quad C_{PS} = C_{WT} + C_{Chr} + C_{Bat} \tag{2}$$

and

$$C_{PV} = \left(C_{PVinvst} + Y \cdot C_{PVmntnc}\right) \cdot N_{pv} \tag{3}$$

$$C_{WT} = C_{WTinvst} + C_{WTrod} \cdot H_{inst} + Y \cdot C_{WTmntnc} \tag{4}$$

$$C_{Bat} = \left(C_{BATinvst} + Y \cdot C_{BATmntnc}\right) \cdot N_{BAT} \tag{5}$$

with C_{PV} (€) being the total cost of the PV source, C_{WT} (€) being the cost of the W/G, C_{Chr} (€) being the cost of the DC/DC converter, C_{Bat} (€) being the total cost of the battery bank, $C_{PVinvst}$, $C_{WTinvst}$ and $C_{BATinvst}$ (€) being the market price of each PV module, W/G and battery respectively, $C_{PVmntnc}$, $C_{WTmntnc}$ and $C_{BATmntnc}$ (€/year) being the corresponding yearly maintenance costs, Y (years) being the planned lifespan of the RES system under design, C_{WTrod} (€/m) being the cost of the W/G tower per meter of height, H_{inst} (m) being the W/G installation height, and N_{pv}, N_{BAT} being the total number of PV modules and batteries, respectively, to be used.

During the execution of the optimization process, the GA produces multiple alternative values of the vector of design variables (i.e. chromosomes) [24] and calculates the corresponding values of the total system cost using (2)-(5). Then, a simulation of the operation of the RES-based power-supply system during the year is performed with a time step of 1 h, in order to detect whether each vector of design variables produced by the GA satisfies all of the following constraints:

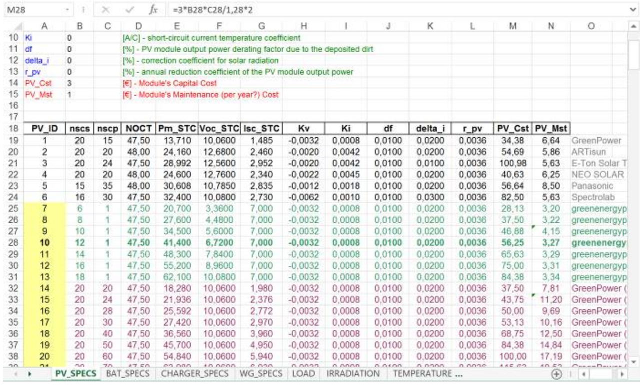
i. the electric load energy requirements are completely covered during the entire year, in order to obtain a reliable power-supply configuration,
ii. the stored energy and voltage of the batteries never fall below the minimum permissible limits, which have been specified for the battery under consideration and
iii. the battery bank State of Charge (SoC) at the end of the year is higher than the initial SoC.

In case that during the GA evolution process it is detected that any of the design-variables vectors does not fulfill requirements (i)-(iii), then this set of design variables values is rejected, without being considered as a potentially optimal solution of the design optimization problem. In the simulation process, the energy produced by the RES source is initially calculated, using the time-series of meteorological data in combination with appropriate mathematical models of the devices comprising the RES-based power-supply system [25, 26]. When the RES-generated power is more than that required by the electric load of the WSN node, then the excess energy flows into the battery bank up to the point that it is fully charged, while the remaining power is dropped. In case that the power generation of the RES source is not adequate to cover the load requirements, then the battery bank is discharged accordingly. At each time-step of the simulation process, the energy stored in the battery bank is calculated as follows:

$$E_b(t) = E_b(t-1) + n_b \cdot P_b(t) \cdot \Delta t \tag{6}$$

where $E_b(t)$ is the energy stored in the battery bank at hour t of the year (i.e. $1 \le t \le 8760$), $n_b = 81\%$ is the battery round-trip efficiency during charging and $n_b = 100\%$ during discharging, $P_b(t)$ is the battery input/output power [i.e. $P_b(t) < 0$ during discharging and $P_b(t) > 0$ during charging] and $\Delta t = 1\text{h}$ is the simulation time-step.

The procedure described above is repeated until a predefined number of GA generations has evolved, each comprising multiple vectors of the design-variables. The set of design variables which results in the minimum value of (2) is



M28 =3*B28*C28/1,28*2

	A	B	C	D
10	Ki	0		[A/C] - short-circuit current temperature coefficient
11	df	0		[%] - PV module output power derating factor due to the deposited dirt
12	delta_i	0		[%] - correction coefficient for solar radiation
13	r_pv	0		[%] - annual reduction coefficient of the PV module output power
14	PV_Cst	3		[€] - Module's Capital Cost
15	PV_Mst	1		[€] - Module's Maintenance (per year?) Cost

18	PV_ID	nscs	nscp	NOCT	Pm_STC	Voc_STC	Isc_STC	Kv	Ki	df	delta_i	r_pv	PV_Cst	PV_Mst	
19	1	20	15	47,50	13,710	10,0600	1,485	-0,0032	0,0008	0,0100	0,0200	0,0036	34,38	6,64	GreenPower
20	2	20	20	48,00	24,160	12,6800	2,460	-0,0020	0,0042	0,0100	0,0200	0,0036	54,69	5,86	ARTisun
21	3	20	24	47,50	28,992	12,5600	2,952	-0,0020	0,0042	0,0100	0,0100	0,0036	100,98	5,63	E-Ton Solar T
22	4	20	20	48,00	24,600	12,7600	2,340	-0,0022	0,0045	0,0100	0,0200	0,0036	40,63	6,25	NEO SOLAR
23	5	15	35	48,00	30,608	10,7850	2,835	-0,0012	0,0018	0,0100	0,0200	0,0036	56,64	8,50	Panasonic
24	6	16	30	47,50	32,400	10,0800	2,730	-0,0062	0,0010	0,0100	0,0300	0,0036	82,50	5,63	Spectrolab
25	7	6	1	47,50	20,700	3,3600	7,000	-0,0032	0,0008	0,0100	0,0200	0,0036	28,13	3,20	greenenergyp
26	8	8	1	47,50	27,600	4,4800	7,000	-0,0032	0,0008	0,0100	0,0200	0,0036	37,50	3,22	greenenergyp
27	9	10	1	47,50	34,500	5,6000	7,000	-0,0032	0,0008	0,0100	0,0200	0,0036	46,88	4,15	greenenergyp
28	10	12	1	47,50	41,400	6,7200	7,000	-0,0032	0,0008	0,0100	0,0200	0,0036	56,25	3,27	greenenergy
29	11	14	1	47,50	48,300	7,8400	7,000	-0,0032	0,0008	0,0100	0,0200	0,0036	65,63	3,29	greenenergyp
30	12	16	1	47,50	55,200	8,9600	7,000	-0,0032	0,0008	0,0100	0,0200	0,0036	75,00	3,31	greenenergyp
31	13	18	1	47,50	62,100	10,0800	7,000	-0,0032	0,0008	0,0100	0,0200	0,0036	84,38	3,34	greenenergyp
32	14	20	20	47,50	18,280	10,0600	1,980	-0,0032	0,0008	0,0100	0,0200	0,0036	37,50	7,81	GreenPower (
33	15	20	24	47,50	21,936	10,0600	2,376	-0,0032	0,0008	0,0100	0,0200	0,0036	43,75	11,20	GreenPower (
34	16	20	28	47,50	25,592	10,0600	2,772	-0,0032	0,0008	0,0100	0,0200	0,0036	50,00	9,69	GreenPower (
35	17	20	30	47,50	27,420	10,0600	2,970	-0,0032	0,0008	0,0100	0,0200	0,0036	53,13	10,16	GreenPower (
36	18	20	40	47,50	36,560	10,0600	3,960	-0,0032	0,0008	0,0100	0,0200	0,0036	68,75	12,50	GreenPower (
37	19	20	50	47,50	45,700	10,0600	4,950	-0,0032	0,0008	0,0100	0,0200	0,0036	84,38	14,84	GreenPower (
38	20	20	60	47,50	54,840	10,0600	5,940	-0,0032	0,0008	0,0100	0,0200	0,0036	100,00	17,19	GreenPower (

PV_SPECS BAT_SPECS CHARGER_SPECS WG_SPECS LOAD IRRADIATION TEMPERATURE ...

Fig. 3. A screenshot of the spreadsheet containing the operational data of multiple alternative types of PV modules, which are input by the designer in the proposed design optimization algorithm.

considered as the optimum solution. The optimization algorithm depicted in Fig. 2 is repeated for multiple alternative types of PV modules, W/Gs and batteries, which are specified by the designer, in order to derive the optimal lifetime cost and the corresponding optimal configuration of the power-production system for each combination of device types. Among the individual optimum solutions derived, the overall optimum configuration of the WSN node power-supply system comprises the PV modules, W/G and battery types, which result in the minimum lifetime cost.

Since the power requirements of WSN nodes are typically low (i.e. up to a few tens of Watts), the proposed design method considers that either PVs, or a W/G is employed for power-supplying the WSN node. However, the proposed method can be easily modified for application in hybrid RES configurations too.

IV. OPTIMIZATION RESULTS

The proposed optimization method has been implemented by developing a software program under the MATLAB platform. As an example, a screenshot of the spreadsheet containing the operational data, which are provided by the designer in the proposed design optimization algorithm, is shown in Fig. 3. Each row corresponds to a different PV module type. As analyzed in Section III, the proposed optimization process is executed for each of them, in order to derive the overall optimum type of PV modules. A similar spreadsheet is input by the designer to the optimization algorithm for each device comprising the RES system under design (e.g. W/Gs, batteries etc.), according to the block diagram of Fig. 1.

In order to investigate its performance, the proposed optimization method has been applied for the optimal design of the power-supply system of a WSN node with an electric load, which consumes approximately 3 W continuously during the day. This power consumption has been derived by experimentally analyzing the corresponding requirements of the sensor and data-acquisition/wireless-transmission units employed in a WSN node, which is installed in the area of Chania (Greece). The meteorological conditions at that

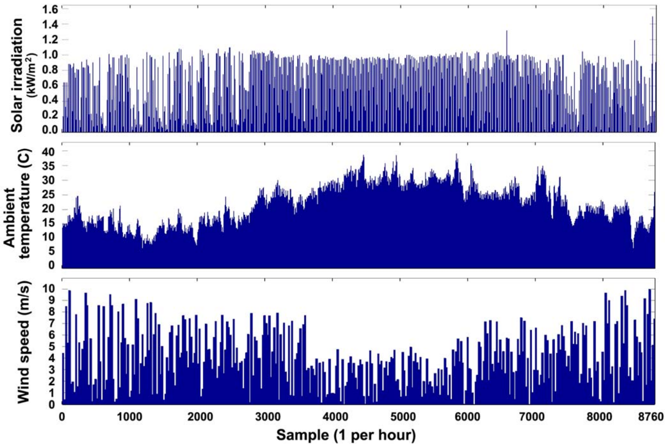


Fig. 4. The time-series of solar irradiation, ambient temperature and wind speed during the year, which were used in the optimization process.

TABLE I. THE OPERATIONAL CHARACTERISTICS OF THE RES-BASED POWER-SUPPLY SYSTEM UNITS

	Solar Panel	*Wind Turbine*	*DC-DC Boost Converter*	*Battery*
Rated Power per unit (W)	Rated power: 20 W (under STC)	Rated power: 30 W (at 10 m/sec)	Nominal power: 50 W	Capacity: 7.2 Ah
Capital cost per unit (€)	28	108	85	9.2
Maintenance cost per unit and per year (€)	1.65	15	1.5	1.4

TABLE II. THE OPTIMAL VALUES OF THE DESIGN VARIABLES

Parameter	**Objective function**		
	Optimized PV-based system	***Optimized W/G-based system***	***Non-optimized PV-based system***
Rated Power (W)	40	30	60
Number of PV modules in series	1	-	1
Number of PV modules in parallel	2	-	3
Tilt angle (^{o})	28	-	60
Number of W/Gs	-	1	-
W/G height (m)	-	13	-
Number of batteries in papallel	4	132	4
Total lifetime cost of the power-supply system (€)	**281**	**3183**	**325**

installation site, which were considered during the execution of the optimization process, are illustrated in Fig. 4. The prices of the RES system devices, which are available in the local market, have been considered in this study. The operational and economic characteristics of commercially available PV modules, W/G and sealed lead-acid battery that were input in the proposed optimization process are presented in Table I. The RES system lifetime has been set equal to 10 years, which corresponds to the planned lifetime of the WSN under consideration. The resulting optimal values of the design

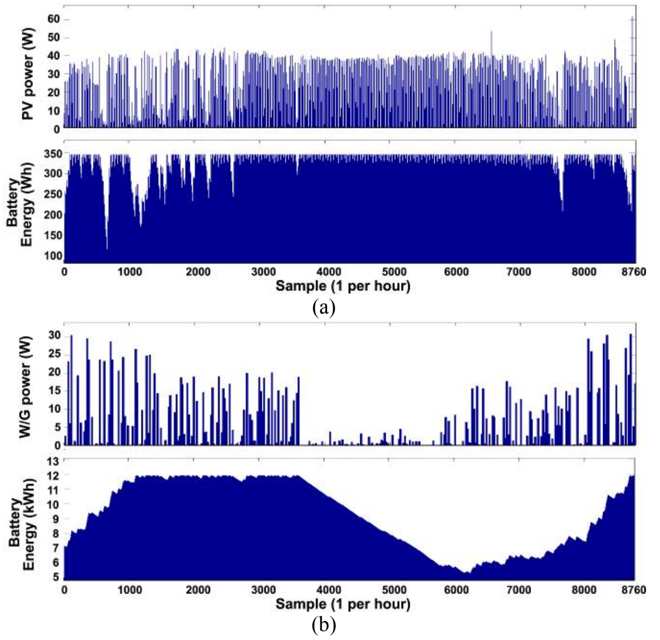


Fig. 5. The simulated time-series during the year in the optimized RES-based power-supply systems: (a) the power produced by the PV source and the energy stored in the battery bank and (b) the power produced by the W/G and the energy stored in the battery bank.

Fig. 6. The experimental prototype of the WSN node power-supply system, which has been designed according to the proposed optimization technique.

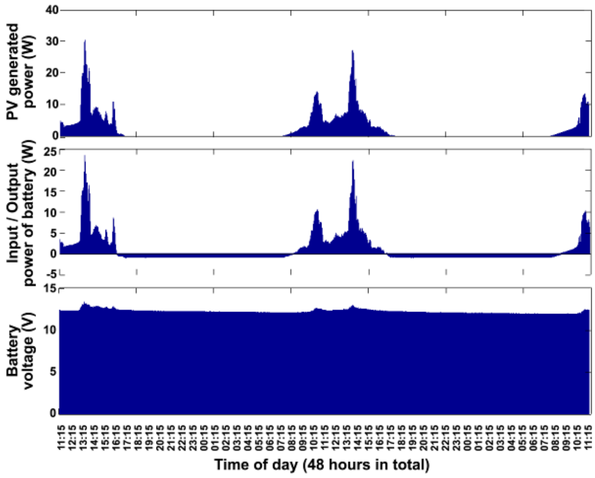


Fig. 7. The experimentally measured time-series of the power produced by the PV source, as well as the voltage and input/output power of the battery bank.

variables and objective function, in case that the WSN node is power supplied by either a PV source or a W/G, respectively, are depicted in Table II. The corresponding results in case of a non-optimized power-supply system are also presented in Table II. The non-optimized power-supply system comprises PV modules and has been designed as described in [26], such that the constraints (i)-(iii) described in Section III are satisfied during its yearly operation. It is observed in Table II that a different set of optimal values is produced, depending on the type of the RES source, which is employed in order to build the RES-based power-supply system of the WSN node. Due to the low wind-speed potential of the installation site and the relatively high cost of the W/G considered in this study, the total lifetime cost of the power-supply system based on PVs is 11.3 times lower, compared to that obtained when a W/G is employed. Thus, the design optimization results indicate that for the specific installation site under consideration, the total lifetime cost of the WSN node power-supply system is minimized by using a PV source instead of a W/G. Also, the lifetime cost of the optimized PV system is lower by 13.5 % compared to the total cost of the non-optimized PV system. Thus, by applying the proposed technique, economically optimized configurations of the WSN node power-supply system are derived.

The simulated time-series of the power produced by the PV and W/G energy sources during the year, as well as the corresponding energy stored in the battery bank, for the optimal solutions presented in Table II, are plotted in Fig. 5. For both RES types considered, the optimization algorithm has properly selected the capacity of the battery bank, such that the stored energy never drops below the minimum permissible limit of 20 % of the nominal battery capacity, which was initially specified by the designer, thus fulfilling constraint (ii) in Section III. The ability of GAs to derive the global optimum solution has also been verified by applying an exhaustive search process, which, however, requires a several times longer execution time in order to be accomplished.

V. Experimental Results

A PV-based experimental prototype of the WSN node power-supply system, illustrated in Fig. 6, has been designed according to the design optimization results, which have been presented in Table II. During normal operation of the power-supply system, the PV modules are installed at a 28^{o} tilt angle, as dictated by the corresponding design optimization results in Table II. The resulting experimentally measured time-series of the power produced by the PV source, as well as the voltage and input/output power of the battery bank during a 48 h time interval, are shown in Fig. 7. The battery bank is discharged during the time intervals that adequate PV energy is not generated (indicated by the negative values of the battery power in Fig. 7), in order to satisfy the power demand of the electric load. However, the maximum permissible depth of discharge limit is never exceeded, thus guaranteeing the reliable operation of the power-supply system, which has been designed using the proposed method.

VI. Conclusion

WSNs are utilized during the last years in a wide variety of environmental and industrial applications. They are frequently installed in geographically isolated areas, where access to electricity is not available. In such cases, the WSN nodes are power-supplied by stand-alone RES systems, accompanied by energy-storage units. The design of the WSN node power-supply system has a great impact on the total cost of the WSN node and affects its reliability. Towards this direction, a technique for the optimal design of a WSN node power-supply system, which is based on the use of RES, is presented in this paper. The proposed optimization method enables to derive the optimal configuration of the RES-based energy production system of a WSN node, such that its total lifetime cost is minimized, while simultaneously it is guaranteed that the data-acquisition equipment of the WSN node is uninterruptedly power-supplied during the entire year. The design results demonstrate that by applying the proposed optimization technique, where the meteorological conditions prevailing during the entire year are also taken into account, enables to derive the RES type, which is mostly suitable for the installation site under consideration. Furthermore, it has been demonstrated that by applying the proposed technique, structures of the WSN node power-supply system with a lower lifetime cost are designed, compared to the non-optimally designed configurations. Future work includes the long-term experimental testing of the optimized power-supply system, in order to evaluate its performance in terms of energy production and reliability throughout all seasons of the year.

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