



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

Volume 3, Issue 6, November 2014

An Intelligent and High Efficiency Street Lighting System Isle based on Raspberry-Pi Card, ZigBee Sensor Network and Photovoltaic energy

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Abstract— A system based on ZigBee telecommunication mesh wireless network and Raspberry-Pi control card is realized for a complete remote management of an isolate high efficiency street lightning system. The system uses devices and sensors to manage the single street lamppost and to send information by a ZigBee tlc network to a central lamppost equipped with a Raspberry-Pi control Card able to collect and elaborate information. The device allows a remote access through the Web becoming a powerful and complete system able to check the state of the street lamps and allowing appropriately acting in case of failure. The lamp posts are powered by Photovoltaic energy and represents an excellent example of Sustainable Energy paradigm.

Index Terms— lighting system, photovoltaic energy, Raspberry-Pi, sensors, wireless networks, ZigBee.

I. INTRODUCTION

New technologies used on streetlight plants aim to give important benefits both for environment and for economic saving [1-8]. In front of an initial cost, moderately higher than that of a classic technology, alternative energies and lamps, based on new technologies, allow to quickly reach the break-even and, then, to save money. Moreover, this trend is likely to widen because the cost of these technologies is constantly decreasing [9]-[10] while the traditional technologies costs have reached the saturation level and further optimizations are difficult to get.

Combining these technologies with an intelligent lamppost management, we obtain a high efficient system able to decide the time of lighting and to optimize the maintenance, so meeting the needs of cost savings and environmental protection. The intelligent lamppost management is realized using local sensors, able to drive the time of lighting, and using a remote control, which gives the operating conditions in real time. Several authors have studied remote control system based on GSM (Global System for Mobile Communications), power line carrier or GPRS (General Packet Radio Service)[11-15]. These papers show as, from a remote station, it is possible to receive a large information amount about the operating conditions of the devices under control. Unluckily these systems are quite expensive because need to drive the GPRS modem, activity usually performed by a personal computer.

For local and low baud rate transmissions, for its ability to create Mesh network and for the low power consumption, ZigBee technology seems to be highly competitive both from economic side and from functional one [16-25].

This article shows as the combination of these technologies can be successful used in the remote control of a spatially close sensors set placed far from buildings although still achieved by internet wireless signal. The reception of this signal is obtained through a commercial internet pen provided by an Italian internet provider.

To test the new proposed system, we remotized an isle of lamp posts lighting a crossroads placed in a rural area far from buildings. The lamp posts have a local control card based on microcontroller able to pick up and evaluate an operating parameters set. Data are temporarily stored in the control card and, when required, are sent to the only lamp post connected to internet and able to transfer data with high baud rate and for longer distance. This last is called lamp post master, while the others are called secondary.



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The local tlc network allows the transfer of the information between lamp posts and it is based on ZigBee technology; the isle communicates with the world using the web. The access is performed using a RaspBerry-Pi card [26-29], which assures good performances for a very low cost, and an internet pen.

To get the maximum efficiency, the lamp posts use LED (Light Emitting Diode) technology which, together with an intelligent lighting policy based on local sensors information, allows a targeted sizing of photovoltaic panels and batteries used to supply the lamp posts. The combination of all these technologies allows creating an example of sustainable energy application. In the field tests have been realized to verify the goodness and the performances of the system.

II. ARCHITECTURE AND APPLICATION

Proposed system architecture consists of three layers: a) local measuring; b) local transmission network; c) internet facilities. The first two layers make the local section of the architecture, doing only local activities, while the third is the remote one. The first layer is made of single systems each one with an independent monitoring station. These receive and analyze data coming from sensors and, automatically and independently each one from the others, drive the actuators. The monitoring stations are developed with the idea of reducing the design complexity: the same hardware is used for different usages (only the software is different) and the stations have a ZigBee transmitter/receiver module to communicate between them.

The second is the local communication layer that, through a mesh network based on ZigBee technology, allows sending information between wireless sensors and the lamp posts.

The master lamp post realizes the third layer being able to collect data coming from the whole system, to make statistical analysis and to show the results to the world through internet. This provides useful data to evaluate the system performances, allowing verifying if there are malfunctions, and allows to easily implementing maintenance actions.

The hardware also foresees a power supply based on photovoltaic panel similar in the structure but specifically sized for each kind of lamp post. Fig. 1 shows a typical application of the proposed system: an isle of lamp posts used to light a crossroad.

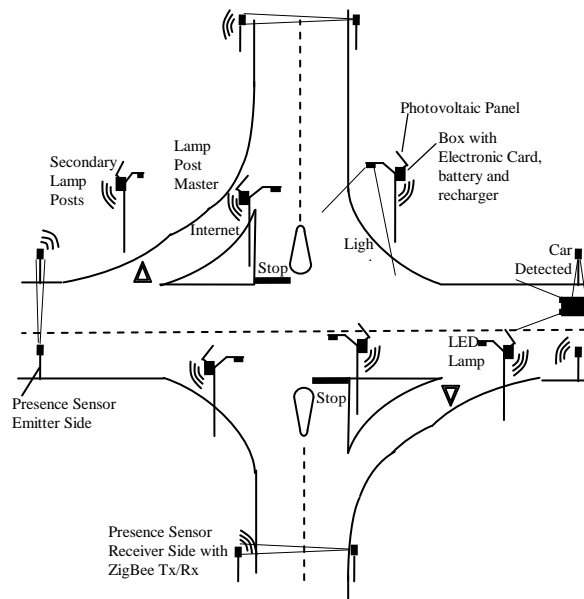


Fig. 1 Schematic image of the on street system.

Every lamp post is equipped with a control unit connected with a series of sensors (wireless and no) and a local base station able to collect all the local information and able to present them on a web page. The lamp posts isle is driven



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by the AND combination between intensity sunlight sensors signal and presence ones. If the sunlight is lower than a fixed limit, the whole system is on and, when a car is approaching the crossroad, the presence sensors detect the car and send a wireless alert signal toward the isle. All lamp posts receive the signal and turn on the light. Every lamp post is equipped with a measuring station able to check if the lamp is properly working, and sends the information to the master through the local ZigBee network. The master collects all data in a RaspBerry card; this last is connected to internet through an USB internet pen (802.11g IEEE protocol). If any malfunction is detected, the service engineer is informed through a graphical interface and can perform corrective actions.

III. DEVICES AND METHODS

The proposed system is divided in three principal devices:

- A) *Monitoring Station: used for wireless sensors, and lamp posts;*
- B) *Master Lamp Post base control station;*
- C) *Supply Devices.*

A. *Monitoring station*

The monitoring station is based on a Microchip PIC 16 f 688 microcontroller. It allows to collect data from sensors (wireless or no), to drive actuators and to transfer information. This card is the core of the first architecture layer and it has two versions:

1) *Presence Sensor Electronic Card; 2) *Monitoring Station for Lamp Posts;**

1) *Presence Sensor Electronic Card:*

These cards, using a photoelectric sensor, are located along the roadside, about 45 m far from the intersection, with the aim to monitor the road. The light sensor enables the card when the sunlight goes down a fixed threshold. After its switch on, if a passing car interrupts the light beam, the card sends a wireless alert signal toward the isle.

a) *Light Sensor:*

For its high sensitivity, a phototransistor TEPT5700 [5]-[30] has been chosen to measure the sunlight brightness. It allows switching off the lamp posts during the day so allowing to save energy.

b) *Presence Sensor*

The presence sensor task is to identify the transit of a vehicle or pedestrian giving a signal to turn on the lamp posts. The photoelectric sensor chosen is the GLV18-6/59/102/159 of Pepperl+Fuchs with its reflectors [31], which offers optimal performance and is quite affordable. They are placed 45 m far from the crossroad on every street connected to the intersection. When the light beam is interrupted by a transit, the sensors provide an input signal for the microcontroller. The choice of a photoelectric sensor avoids all problems associated with the assessment of a possible optimum height for the sensor position. In fact, even if a small animal crosses the beam, if the system has been correctly designed, the associated energy loss due to the lighting of the lamps, is absolutely negligible.

c) *ZigBee Tx/Rx*

As known, ZigBee is a technology for wireless communication among multiple devices in a Wireless Personal Area Network. It has been designed to be more affordable than other WPANs (e.g. Bluetooth) in terms of costs and of energy consumption [32-37]. As shown in [5] transmission capabilities (ranges, consumption and...) have been widely tested giving optimal performances for applications with low baud rate and limited transmission ranges, as in our application. In the proposed system, the network is a mesh built to transfer information from presence sensor card to the lamp posts, secondary and master, and vice versa. Each lamp post, exploiting the multi hop ability typical of ZigBee network, sends its information toward the base station placed in the master lamp. In this way, transmission power is limited and the signals sent by the lampposts do not interfere with each other.

Considering the distance between lamp posts and presence sensors, the ZigBee network has been realized using the XBee modules equipped with on-chip antenna provided by Digi-MaxStream [5]-[32]. Thanks to the very high sensitivity of the receiver, they have less than 1% of receiving corrupted packets. In the field tests assured these performances obtained with very low consumption (3 V, 50 mA). Moreover, in sleep mode, their consumption is less than 10 μ A.

2) *Monitoring Station for Lamp Post*

The monitor station for lamp post is similar to the presence sensor card, but it is able to manage the lamp. Compared to the previous one, it replaces the presence sensor with a current one to verify the lamp activity and with an emergency device to face emergencies. The presence of a car in the street is detected and sent by the presence sensor card. When the lamp post card receives this signal, if the sun light is low, it turns on the lamp.

a) *Current Sensor*

This sensor (a Hall one), measuring the current flow toward the lamp, allows to recognize its activity resulting very useful for the system maintenance. Through the ZigBee network, the information reaches the master lamp station control unit and any malfunction is observable by the operator; then a technician could be sent to repair it. For its low cost and for its precision, an ACS756 [38] of the Allegro Microsystems has been chosen. To detect the operation of the lamp, the threshold value has been set between 1 and 1.5 A. Moreover, the current values are stored in the PIC's memory allowing the power measurement.

b) *Emergency device*

During the night, only for emergency, a button can be pressed to directly turn on the lamp for a preset time. It has maximum priority jumping any other control. To prevent the system from being accidentally activated when the necessity ends, after the fixed time, the button must be pressed again.

c) *Operating Control*

Fig. 2 shows the control software flowchart for the first and second layer, moreover introduces the Lamp Post Master to understand how the whole system works.

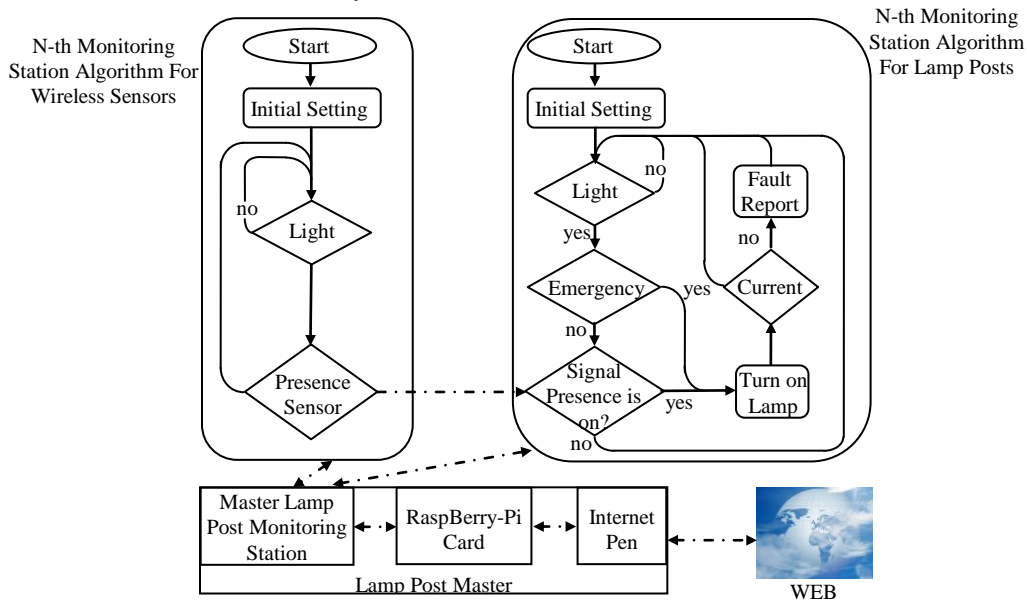


Fig. 2 Control software flowchart and connection with Lamp Post Master

B. *Master Lamp Post base control station*

In addition to the monitoring station, the Master Lamp Post has a RaspBerry-Pi card, which assures high computing power and, by a GPRS modem, internet connectivity [26-29]. RaspBerry-Pi is a low-cost ($\approx 25 \text{ €}$), basic computer contained on a credit-card size single circuit board and features ports for HDMI, USB 2.0, Composite video, Analog audio, Power, Internet, SD Card. It has a Broadcom BCM2835 system on a chip (SoC), which includes an ARM1176JZF-S 700 MHz processor which firmware includes a number of "Turbo" modes so that the user can attempt overclocking, up-to 1 GHz. It includes also a VideoCore IV GPU and it is shipped with 512 MB of RAM. It does not include a built-in hard disk or solid-state drive, but uses an SD card for booting and long-term storage. Although its performances are not comparable with normal PC ones, this device is revolutionary for its low cost

reducing the global digital divide. In fact, it is a capable little PC, which can be used for many of the things that desktop PCs do, like spreadsheets, word-processing, games, allowing playing also high-definition video. The Raspberry-Pi runs entirely on open-source software and gives the ability to mix and match software according to the work it wish to do.

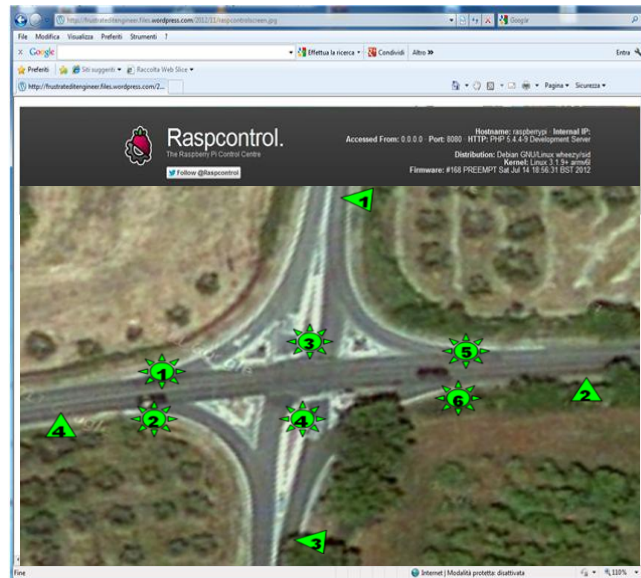


Fig. 3 Lamp Control System GUI and Measurement of Power Consumption

The Raspberry is the hub of the system since it allows the visualization of the entire lighting system (Fig. 3). It is connected to the local monitoring station, which manages the lamp post; at the same time, exploiting the ZigBee network, is able to receive information coming from the secondary lamp posts and from the presence sensor cards realizing the monitoring of the whole isle. Together, the Raspberry and the local monitoring station realize the Master Lamp Post base control station. The terminal has a user-friendly graphical display and allows to monitor the state of the sensors and of lights (green is on, red is off). For these lasts, pressing on the lamp post symbol, it appears another window which shows power consumption and the working time of the lamp and, in case of fault, also the possible problem. Thanks the internet pen, the lamp posts state is available on internet. Finally, Fig. 4 shows the operational test system working in real conditions.



Fig. 4 Test system

C. Supply Devices

To supply an isle of lamp posts placed far from the city, the connection to the mains could be extremely expensive so, the use of alternative energy could be obliged [39]. Moreover, as successive economic analysis will show, after the break-even achievement, the use of new technologies is more convenient than classical one. In fact, the choice



ISSN: 2319-5967

ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

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to use LED lamps, the choice to work only during the night, and the possibility to put in sleep mode all devices during the day, avoids waste of energy allowing decreasing the size of the solar panels and of the batteries.

Only if there is a change in the sleep condition, e.g. caused by presence sensor, the system wakes up to fully work. The characteristics of the territory where the lamp posts will work, suggest what type of alternative energy to use. In our case, for its weather conditions, Italian landscape is particularly suitable for photovoltaic energy use [40]. Applying the UNI 10439 [41] for the solar panels inclination and orientation, it is possible to determine their better sizing. In the studied case, to optimize the battery sizing, we made a preventive check registering the number of cars passing along the street for four months during winter and springtime, when nighttime is longer. We registered an average transit of about two hundred cars every night, often passing in-group of three-four cars each time. Therefore, considering that the lights are turned on for 30 seconds every time during the cars passage, the worst case requires that the total time of ignition of the lamps is about 35 minutes. Reasonably, wanting to consider a safety margin to face also unexpected emergencies, our system provides energy for two hours. Considering the loads, we have three different combinations:

- 1) for the presence sensor card (0.2 A current consumption) the battery has a capacity of 6 Ah and the PV panel has a maximum power of 9 Watt – 12 Volt; this assures a functioning of 10 hours for three consecutive nights;
- 2) secondary lamp posts use a 19 W - 12 V PV panel and a battery of 10 Ah capacity able to ensure two hours per night for three consecutive nights;
- 3) the master lamp post has consumes higher than the secondary ones because it has also the Raspberry-Pi (current consumption 0.5 A) which must always be connected to internet during the night. To limit the consumption the lamp section is managed as secondary lamp posts so the PV panel has a peak of 75 W – 12 V and the battery has a capacity of 48 Ah, which assures an activity of 2 hours/night and the full activity for the hub for 3 consecutive nights.

It is important to underline that, without the intelligent management system the consumption would be at least three times higher and, consequently, PV panels and batteries, with costs three times higher as well; moreover, the lower heavy produces less mechanical stress on the pole.

1) Solar Power Optimizer

Because a solar panels voltage can swing wildly up and down over a wide range of voltages, a Maximum Power Point Tracking controller (MPPT) is strongly suggested. For this aim, a SolarMagic™ SM3320-BATT-EV Charge Controller [42] has been used.

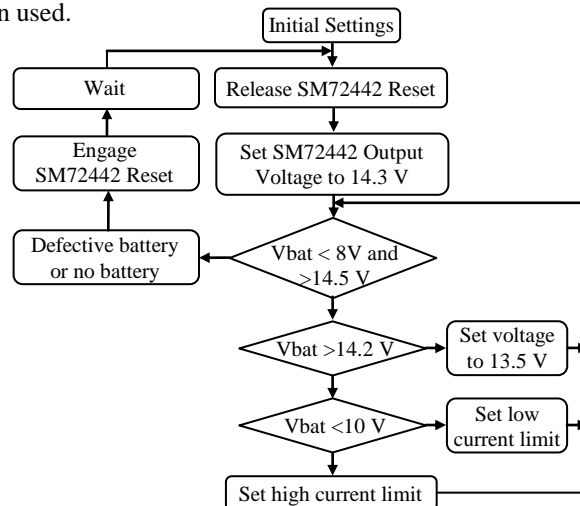


Fig. 5 Core of the SM3320-BATT-EV controller program

The device integrates the SM72442 MPPT digital controller and SM72295 photovoltaic full bridge drivers that are designed to control high-efficiency DC/DC converters commonly found in off-grid charge controller applications such as solar, automotive, marine, and, it is particularly suitable, for street lighting applications. The SM72442 chip implement a “Perturb and Observe” MPPT algorithm method [43-45]. After the initializations, the program



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checks the connections and the voltages of the PV and of the battery. If the voltages are within a specific range, the SM72442 enables the charge by releasing the RESET line of the chip. A safety procedure allows to stop charging the battery if the output is above 14.5 V or below 8 V. The core of the program is depicted in Fig. 5.

Obviously, the charge controller provides other integrated functionality with a wide input voltage range for compatibility with most commercially available solar panels, current driving capabilities up to 100 A, multi-chemistry battery support (e.g. Lithium Ion, Lead Acid), advanced protection and battery management features, along with I2C programming.

Some comparative measurements effected during the month of July 2013 demonstrated that the use of the controllers allowed an increase of the charging current of 30% compared to the case of their absence. This further justifies the little sizes of the PV panels and batteries.

IV. TESTS, MEASUREMENTS AND RESULTS

To verify the functionality, the prototype has been tested in real-life conditions and the collected measurements allowed to evaluate both the energy saving and the correspondent cost savings.

A. Range tests

As the article [5] shows, the reliability of the communication between two or more ZigBee modules in different environmental conditions is satisfactory. Nevertheless, for the proposed architecture, we repeated some tests to confirm and guarantee the communication reliability. The tests were performed in open field directly on the realized system, and were conducted under the supervision of the Electric and Electronic Measurements Laboratory of Roma Tre University. Considering the plant of the system, we have open field and line of sight between the lamp posts (maximum distance 8 meters) and between the presence sensors and the lamp posts (about 45 m).

The tests were carried out using only the Standard Xbee modules with patch antenna because from datasheet [32-35] and from [5] they seem to satisfy the range needs having a nominal outdoors range of about 100 meters; moreover they are the cheapest modules. The tests allowed checking the network both in clear weather conditions and in rain ones. In accordance with [5], using the X-CTU software provided by Digi-MaxStream to check the transmissions, for each test 10,000 transmission were done. The procedure foresees that a known test packet is sending by a XBee module called A through the network. Another prefixed module called B in the network will receive the test packet and will send again the packet through the network. It will be received from the A module which will verify the sameness. Using the lower possible power for the transmission, the average reliability was satisfactory equal to 99.99%. Table I shows as the system can reliable operate.

TABLE I. ZIGBEE RELIABILITY TESTS

XBEE STANDARD - Patch Antenna		
	Sunny	Rainy
	up to 50 m	up to 50 m
No obstacles	100%	99,98%
Vegetation	99,99%	99,96%

B. Transmission tests

Other functionality field tests were realized to verify the communication toward the hub both from the secondary lamp posts and from internet. A first test was to verify what would happen in case of a lamp post or presence sensor fault which were not able to answer a data request from the master. They directly view the master lamp post and are directly interrogated by it. To perform this test we simulate the absence of one of them verifying that the hub software reported the malfunction on its graphical interface.

The second test verified the case of breakdowns of the master lamp post. If the fault interests only own electrical section, the hub software shows the problem on the graphical interface. If the master communication local section is damaged, the impossibility to talk with the other lamp post is again reported on the graphical interface. On the



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ISO 9001:2008 Certified

International Journal of Engineering Science and Innovative Technology (IJESIT)

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contrary, if the RaspBerry-Pi card or the internet Pen are broken, the impossibility to connect to the website is a symptom of its fault or its theft. To solve the last problem a secondary master could be activated on another lamp.

C. Measurements

The switch-on time and the absorbed currents are measured and stored in the microcontroller memory and are sent to the master lamp when its program requires them, memorizing and making them available on the web page.

The local transmission is managed by the master lamp which, exploiting a specific identification number (ID) of each lamp post, calls them one by one, avoiding simultaneous data transmissions from different lamp posts. A more accurate analysis of average current consumption, based on the data collected throughout the months from June to December 2013, is shown in table II, after the activation of the system.

TABLE II. CURRENT CONSUMPTION AND OPERATING TIME OF LAMPPOSTS

Lamp ID	July		August		September		October		November		December	
	Time (h)	I (A)	Time (h)	I (A)	Time (h)	I (A)	Time (h)	I (A)	Time (h)	I (A)	Time (h)	I (A)
Lamp 1	20.66	1.47	21.01	1.48	24.00	1.47	28.25	1.49	33.51	1.51	35.26	1.50
Lamp 2	20.67	1.50	21.00	1.50	24.01	1.48	28.26	1.51	33.50	1.51	35.25	1.52
Lamp 3	20.68	1.47	21.00	1.48	24.01	1.48	28.24	1.50	33.52	1.48	35.24	1.48
Lamp 4	20.66	1.47	21.00	1.51	23.98	1.53	28.23	1.51	33.47	1.53	35.25	1.53
Lamp 5	20.67	1.51	21.02	1.51	24.00	1.52	28.26	1.51	33.52	1.47	35.27	1.53
Lamp 6	20.68	1.50	21.02	1.51	24.01	1.51	28.28	1.53	33.50	1.52	35.23	1.51

The switch-on time differences findable in July for the second lamp post are justified by emergency test, while in August a failure was simulated to verify the third street light maintenance conditions. The energy consumption decreases during sunny months.

D. Comparison with old technology lamp post

To certify the behavior of our lamp post (called L1), a comparison test, with other three old technology lamp posts, has been realized on March 2013. Only a crepuscular sensor manages their switch overnight. The first two lamp posts (called L2 and L3) use again a LED lamp (18 W, 1550 lumen) but the first is supplied by solar panel and battery as L1 while the second is powered by mains through an AC/DC (220 Vac – 12 Vdc) converter. The third lamp post (called L4) uses a 50 W mercury-vapor lamp (OSRAM model HQL50 [46] with 1800 lm), again supplied by mains through an high voltage starter and a reactor.

The mercury-vapor lamp has been chosen because has an emission of 36 lm/W is comparable to the LED one. The mains was close to the crossroads and the lamp used for the analysis is the secondary, which is the most common. The obtained results are in the table III.

TABLE III. CURRENT CONSUMPTION AND OPERATING TIME OF NEW AND OLD LAMPPOSTS

Lamp ID	July		kWh	Cost h X kWh (0.2 €)	Plant Costs					
	Time (h)	I (A)			Battery type and cost	Solar Panel type and cost	Battery Recharger	Lamp €	Power supplier	Electronic Devices €
L1: New Lamp	20.66	1.48	0.37	0	10 Ah – 16 €	19 W – 50 €	10 €	16	0	25
L2: New Lamp without light sensor	217	1.49	3.88	0	50 Ah – 50 €	100 W – 250 €	10 €	16	0	25
L3: New Lamp without presence sensor and supplied by mains	217	0.09	4.49	0.898	None	None	0	16	30	0
L4: Mercury Vapor Technology without presence sensor and supplied by mains	217.01	0.22	10.98	2.196	None	None	0	15	40	0



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ISO 9001:2008 Certified

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Obviously if the master lamp is used, the results will be slightly worse. Not being connected to the mains, L1 and L2 have no costs joined to the power consumption. On the contrary the L3 and L4 pay the kWh consumed at the cost of 0.2 € per kWh [47]. Considering the different settings and so the different cost items, [5] provides the equation to find the break-even:

PC_z - PC_y + sum_{i=1}^x (kWh_{zi} - kWh_{yi}) * C_{kWh} = 0 (1)

where PC is a fixed cost; it points out the plant cost for a specific lamp posts technology, the difference PC_z-PC_y points out the cost difference between two different lamp posts technologies and allows to make the comparison between them;

kWh are the kilowatt per hour used by the specific lamp post technology day by day;

C_{kWh} is the cost of kWh, which could change over time cause the variability of the energy price on the market;

x represents the activity days necessary to reach the break even between two different choices of lamp posts and it is the value to determine.

Analyzing the worst case in which the amount of kWh is quite low (July), and considering constant the kWh price, the break-even time between the different choices are showed in table IV.

TABLE IV. REQUESTED TIME TO REACH THE BREAK EVEN POINT BETWEEN THE DIFFERENT SOLUTIONS

Table with 5 columns (L1, L2, L3, L4) and 5 rows (L1, L2, L3, L4) showing break-even times for different lamp solutions.

The solution L1 is obviously always more convenient than L2 and reaches the break even against the L4 with classical technology in 28 months, while becomes more convenient than the L3 solution after 79 months.

Obviously, using a more convenient month for the calculation, or a secondary lamp, which the electronic units costs is lower than the master one, the break-even can be more quickly reached.

The saving in terms of carbon dioxide is obviously even more convenient because the lamp posts provided with PV panels are CO2 free.

E. Management of lamp post fault

One of the aim of our work is to inform the users about a lamp post fault, so that restore operations could be quickly implemented. In case of communication fault due to both ZigBee interruptions and due to electronic card fault, if the n-ism lamp post doesn't react to the call of the master, the master program shows a breakdown notification on its graphic interface. If the problem is joined only with the ZigBee, the electronic card stores measurements into the microcontroller memory. So, considering a sampling of five minutes and a turn on time of the lamp post for two hours per day, the system is able to store data for about six days. Obviously, within this time the system must be restored otherwise, a more performance Pic has to be used. The card has also a 4.5 V backup battery to supply the PIC if it isn't powered by the battery of the system. The PIC, using its A/D, also provides the reading of the battery voltage so, if the voltage is zero, a signal of battery fault will be sent to the master program.

V. CONCLUSION

The use of new technology opens new perspectives toward the developing of high efficiency systems, which allow saving energy and money.

An example is shown in this article: an isle of lamp posts used to light a crossroad placed in a rural area. It is designed combining LED, alternative energies and an intelligent management. The first guarantees low energy consumption; the second assures the independency from the mains allowing easy application also in rural area, while the third allows turning on the light only when it is useful.

The intelligent management uses hardware architecture with three layers. The first, using sensors mounted on the single lamp posts, manages the lamps independently by each other, storing functioning data. By a mesh ZigBee telecommunication network, which realizes the second layer, data are efficiently sent toward a master lamp. Here a



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RaspBerry-Pi card, real benefit of this application, allows making visible the data by a web site accessible via internet.

The combination of these technologies could have a great impact in the decrease of CO₂ production for this type of plants; moreover, the proposed system can also be happily used to update existing conventional lamp posts. For its reliability, simplicity and low cost, the proposed system makes itself a serious candidate to efficiently manage a set of sensors applicable in different fields including monitoring of energy consumption, smart grids and smart cities which need to a sensor network to realize an efficient management of the system under control.

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