Universidad de Jaén
Escuela de Doctorado

TESIS DOCTORAL

•

DEVELOPMENT OF LOW-COST EQUIPMENT BASED ON OPEN SOURCE TOOLS

PRESENTADA POR:

ASCENSIÓN LÓPEZ VARGAS

DIRIGIDA POR:

MANUEL FUENTES CONDE

MARTA VIVAR GARCÍA

JAÉN, SEPTIEMBRE DE 2019

‘The Sun does not forget a village just because it is too small’

African proverb

Agradecimientos

"En vez de su piedra, encontró una fiesta en su salón"

"Año Nuevo". Vetusta Morla

Quiero comenzar este trabajo tan importante para mí dando las gracias a todas las personas que han estado conmigo estos años y que de un modo u otro son artífices de esta tesis.

En primer lugar quiero dar las gracias a mis directores Marta Vivar y Manuel Fuentes por ser mi faro durante el desarrollo de este trabajo. Siempre han estado preocupados por mí, ayudándome y dándome consejos tanto en lo profesional como en lo personal. Me han guiado en este camino, convirtiendo estos años en una de las etapas más bonitas que he vivido. Es difícil encontrar un mirlo blanco, pero yo tengo tanta suerte que he encontrado dos. Gracias por animarme siempre y enseñarme el significado de la perseverancia. Gracias por confiar en mí y encargarme esta preciosa tarea. Os quiero mucho.

Si todo sale bien, con esta tesis alcanzaría el grado académico de doctora y no quiero olvidarme de mis profesores del C.P. Mª Antonia Goñalons (San Fernando de Henares, Madrid), del I.E.S. Vega del Jarama (San Fernando de Henares, Madrid), de la Universidad de Alcalá (Alcalá de Henares, Madrid) y de la Universidad de Jaén (Jaén, Andalucía). Mil gracias a todos ellos, maestros y profesores de la enseñanza pública que consiguen hoy conmigo este logro.

Quiero mostrar mi agradecimiento a las instituciones que han colaborado en la financiación de esta tesis. Al Ministerio de Economía por las "Ayudas para la Promoción de Empleo Joven e Implantación de la Garantía Juvenil", que permitieron mi incorporación en el Grupo Agua y Energía del Instituto IMDEA Agua. Al Instituto IMDEA Agua, por continuar con la financiación hasta el término de este trabajo. A la Universidad de Jaén por las "Ayudas de la EDUJA para la realización de estancias para la obtención de Mención Internacional" que me han permitido realizar una estancia de investigación en el extranjero.

Agradecerle a Vijay Modi que me diera la oportunidad de realizar una estancia con él en el Laboratorio de Ingeniería Sostenible Quadracci del Departamento de Ingeniería Mecánica de la Universidad de Columbia (Nueva York, Estados Unidos).

En estos años, he crecido profesional y personalmente pero además, he tenido la suerte de encontrarme tres tesoros por el camino. A Natalia, que empezó siendo mi compañera del despacho 214 y terminó siendo mi amiga para siempre, que me quiere mucho y me cuida más. Gracias por tu alegría, tus consejos y los viajes juntas. Gracias por acompañarme tirando cable al sol en Agosto. Te quiero mucho amiga. A Arlette, que buscó un huequecito en mi corazón para ella y su Oaxaca y se han quedado a vivir allí conmigo; gracias por ser tan buena y portarte tan bien conmigo. A Jack, mi compañero de laboratorio en Nueva York, que ha estado en todo momento pendiente de mí durante la estancia y se ha esforzado por acercarme su país y su cultura. Gracias por ayudarme y cubrirme siempre las espaldas.

Quiero terminar dando las gracias a mi familia y a mis amigos. A mis padres Sensi y Paco, gracias por darme la mejor educación que habéis podido, por estar siempre para mí y apoyarme en todo lo que hago. A Virgi, el desastre de hermana más brillante y maravilloso que existe, gracias por acompañarme en absolutamente todo lo que hago. A mis otras dos hermanas, Glori y Mari, gracias por vuestros consejos y por cuidar de mí, que si estáis a mi lado todo me sabe siempre a fresa. Gracias a mi Carmencita, por ser tan cariñosa conmigo y rescatar con tu gracia a la púber que llevo dentro. Gracias a mis titos, por educarme, por quererme. A mis primos, gracias por ser comandantes fieros de mi guardia pretoriana. Gracias a mis amigos por tantos momentos bonitos que me regaláis, por hacerme sentir la *treinteenager* más querida y especial de este planeta.

Presento esta tesis gracias a todos vosotros y quiero que sea una razón más para poder celebrarnos juntos. Que donde otros encuentran piedras con las que tropezar, yo gracias a vosotros sólo he encontrado motivos por los que seguir brindando y bailando en mi fiesta.

Abstract

1.06 billion people still lack access to electricity. The majority of the population without access to electricity lives in rural areas of developing countries. This is mainly in sub-Saharan Africa, in Southeast Asia and, to a lesser extent, in Latin America, so rural electrification is still a challenge.

In 2012, the Sustainable Development Goals (SDGs) originated at the United Nations Conference concerning Sustainable Development in Rio de Janeiro. The adoption of the SDG7 in 2015 by 193 countries, the 'Affordable and Clean Energy' goal, to ensure access to affordable, reliable, sustainable and modern energy for all by 2030, as part of the new United Nations SDGs, marked a new level of international recognition. In recent years, great efforts have been made to provide basic access to electricity in households located in rural areas of developing countries. Due to the emergence of electrification programmes, millions of Solar Home Systems have been installed in remote locations; commonly in rural areas of Asia, Africa, and Latin America. These stand-alone photovoltaic (PV) systems have improved the lives of many people, providing access to electricity and giving service to households for the connection of luminaires, mobile chargers, televisions or small refrigerators. The access to modern energy helps to face the multidimensional aspects of poverty such as education, health and climate change. In addition, access to modern energy promotes gender equality and empowerment of women.

One of the main problems in rural electrification programmes is the lack of monitoring. Studies on rural electrification concluded that the monitoring of PV systems is a determining factor in the success of these programmes. Monitoring is a key aspect of rural electrification programmes because it allows the follow up of the photovoltaic systems, detecting failures and extending the long-life of the systems.

There are commercial solutions applicable to the monitoring of PV systems, but the case of stand-alone PV systems is unique. These systems are small and the installations are limited by cost factors; often the cost of the commercial monitoring system exceeds the cost of the complete photovoltaic installation. On the other hand, low-cost commercial monitoring systems

(susceptible to be installed in this type of facility) do not meet the accuracy requirements established by international standards.

In recent years, with the emergence of technologies based on open source tools, high performance designs have been developed at low-cost. Open source tools have also been integrated in the monitoring of photovoltaic systems. However, they present some characteristics that hinder its use in the monitoring of Solar Home Systems installed in rural areas of developing countries. Firstly, some of these photovoltaic systems have a dependency on external hardware (laptops or external power supply) that increases the cost of the system. On the other hand, the monitoring systems are often not validated: the measurements of the systems were not compared with high precision systems, and the measurements do not follow any international standard.

The purpose of this thesis was to offer a suitable solution to the problems presented, for the mass-scale monitoring of Solar Home Systems installed in rural areas of developing countries. The work of this thesis focuses on the development of three different versions of the monitoring system. All versions of the prototype integrate SW/HW tools for accomplishing the low cost objective. Arduino™ boards were selected due to low cost, robustness (mechanical and against high temperatures) and the large community of developers. The first developed prototype used an SD card for storing data. A stand-alone photovoltaic system with the characteristics and loads of those photovoltaic systems installed in rural areas of developing countries was designed and installed for validating the prototypes. A one-month experimental campaign was carried out to validate the datalogger at the IMDEA Water Institute, in Alcalá de Henares (Madrid, Spain). The monitoring system measured correctly under real conditions; it was accurate, accomplishing the requirements established by the international standard IEC61724. However, this system required a human operator for collecting data. This can be a disadvantage in the case of inaccessible and isolated locations in rural areas with difficult access by common types of transport.

An advanced version of the datalogger was developed allowing real-time monitoring of Solar Home systems via website/smatphone, thanks to the integration of wireless technology (specifically 3G). Versions of the first

(SD) and second (3G) prototypes were installed in different sites to study the performance of the datalogger working under different climatic conditions. The installation of prototypes was carried out at the IMDEA Water Institute facilities in Alcalá de Henares (Madrid, Spain), on the rooftop of the Polytechnic School of Linares (Jaén, Spain) and at the School of Sciences of the Benito Juárez University (Oaxaca, Mexico). The datalogger has been operating continuously for three years, working under real and often adverse weather conditions. During this period, only 4 failures were recorded in the version of the prototype with 3G connectivity. The majority of the failures detected have an external origin. The datalogger located in Oaxaca recorded 1 error as a result of network outage. The datalogger installed in Alcalá de Henares failed on 1 occasion due to power shortage. The datalogger in Linares registered two errors: equipment failure and failed access to the server. The error detected in Alcala did not have any consequences as the datalogger was designed to re-hook and resend data after power shortage. However, the other recorded failures revealed that some system operation aspects can be improved. The network outage and access error implied the loss of data during the periods of the failure. The equipment failure was detected in the prototype installed in Linares and it was the most hazardous error recorded: the datalogger stopped working. After inspecting the system, it was confirmed that the data delivery system had stopped working. The connectivity system was not broken, but a manual re-configuration was necessary. So the failure was recorded as an equipment failure in the connectivity system due to extreme temperatures (above 50 ℃). The thermal evaluation of the system to guarantee the reliability of the long-term datalogger was made by running an indoor campaign (temperature cycling tests) and evaluating the dataloggers under real-life conditions for 3 years. The prototype passed the tests satisfactorily increasing the confidence in the system, as well as demonstrating the robustness and reliability of the system. Optimizations were implemented and the data storage system was reinforced. The third version of the prototype integrated remote communication and a backup storage system to avoid the loss of data in case the communication could not be established. This optimised version was running outdoors for 8 months with no failures. In regard to budgets, the cost of the first version of the prototype was below €100. The cost of the prototype with 3G connectivity was less than €150. These are experimental prototypes, so the mass-scale production could reduce the final cost.

To sum up, this work has demonstrated the high precision and robustness of a new datalogger designed for the monitoring of Solar Home Systems. The monitoring system is especially developed for its installation in rural areas of developing countries without access to an electricity network or traditional wired telecommunication networks. All developed prototypes comply with the accuracy requirements of international standard, and work correctly under adverse weather conditions, withstanding extreme temperatures.

List of publications

The following publications (Articles I to V) are presented as part of this thesis. Two of them are already published in international journals indexed in ISI Web of Knowledge and the other three are under review:

- ✓ Article I: **A. López-Vargas,** M. Fuentes and M. Vivar. "Current challenges for the advanced mass scale monitoring of Solar Home Systems: A review".
- ✓ Article II: **A. López-Vargas**, M. Fuentes, M. V. García and F. J. Muñoz-Rodríguez, "Low-Cost Datalogger Intended for Remote Monitoring of Solar Photovoltaic Standalone Systems Based on Arduino™," in IEEE Sensors Journal, vol. 19, no. 11, pp. 4308-4320, 1 June, 2019. Impact factor (2018): 3.076. Instruments & Instrumentation (2018): 13/61 (Q1).
- ✓ Article III: **A. López-Vargas**, M. Fuentes and M. Vivar, "IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino™ With 3G Connectivity," in IEEE Sensors Journal, vol. 19, no. 2, pp. 679-691, 15 Jan., 2019. Impact factor (2018): 3.076. Instruments & Instrumentation (2018): 13/61 (Q1).
    - One of the 25 most downloaded Sensors Journal papers in the month of January 2019: included in this count are all Sensors Journal papers published since the Journal's foundation (about 7,599 papers in total).
- ✓ Article IV: **A. López-Vargas**, M. Fuentes and M. Vivar; "Evaluation of long-term performance of a SHS monitoring system on harsh environments".
- ✓ Article V: **A. López-Vargas**, M. Fuentes and M. Vivar," Challenges and opportunities of the Internet of Things for Development (IoT4D) to achieve Sustainable Development Goals".

Index of contents

Chapter 1

Introduction

1.1. Energy and development

1.06 billion people still lack access to electricity, while 3.04 billion people still rely on solid fuels and kerosene for cooking and heating [1]. Access to affordable and reliable energy systems is essential to reduce poverty [1]. In 2015, the World Bank updated the international poverty line to 1.70€ a day and it estimated that 10.7% of the world population (about 760 million people) are living on less than 1.70€ a day [2]. This population lives in what the World Bank calls 'extreme poverty'.

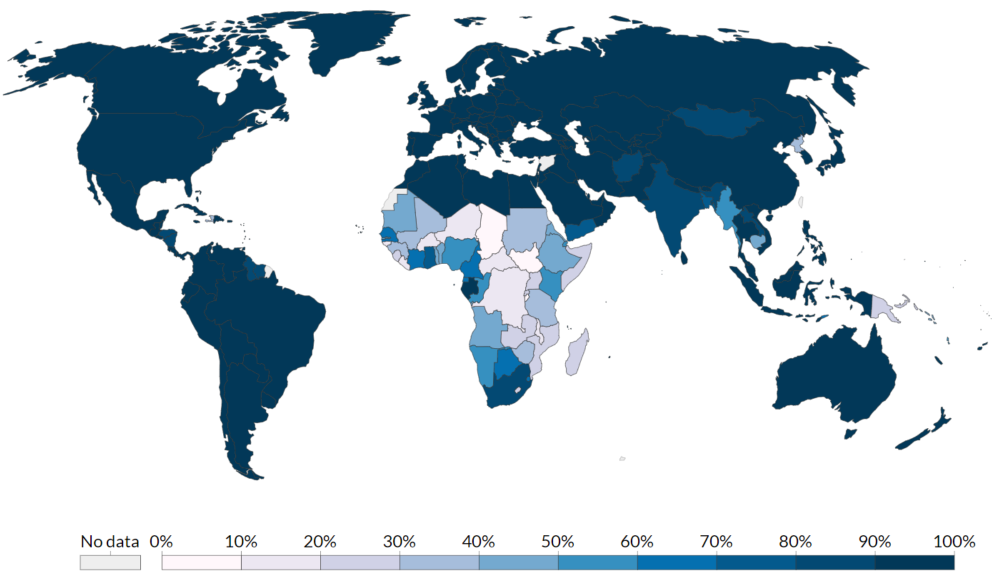


FIGURE 1: Access to electricity distribution, 2016 (% of population) [3]. Main areas without electricity access are Southeast Asia (India) and sub-Saharan Africa.

There is a close correlation between income levels and the lack of access to modern energy: countries with a highest ratio of the population living on an income of less than 1.70€ per day tend to have low electrification rates [1]. Fig. 1 shows the worldwide distribution of access to electricity. A large part of the people without access to electricity lives in sub-Saharan Africa and Southeast Asia, and, to a lesser extent, in the Middle East, Central Asia and Latin America. Likewise, most of the people without clean cooking are living in Southeast Asia (1.9 billion), followed by sub-Saharan Africa (850 million) [1].

There are also differences between cities and rural areas. Urban areas across the world already have close to universal electricity access at 96.89 %, although challenges remain in the rapid growth of cities in Africa and Asia–Pacific. Fig. 2 shows the distribution of the 1.06 billion people living without electricity. Of the total population without access to energy in the world, 861 million people live in rural areas, compared to the 132 million people living in urban areas. Almost half of the world’s population without access to energy lives in rural areas of sub-Saharan Africa (482 million people).

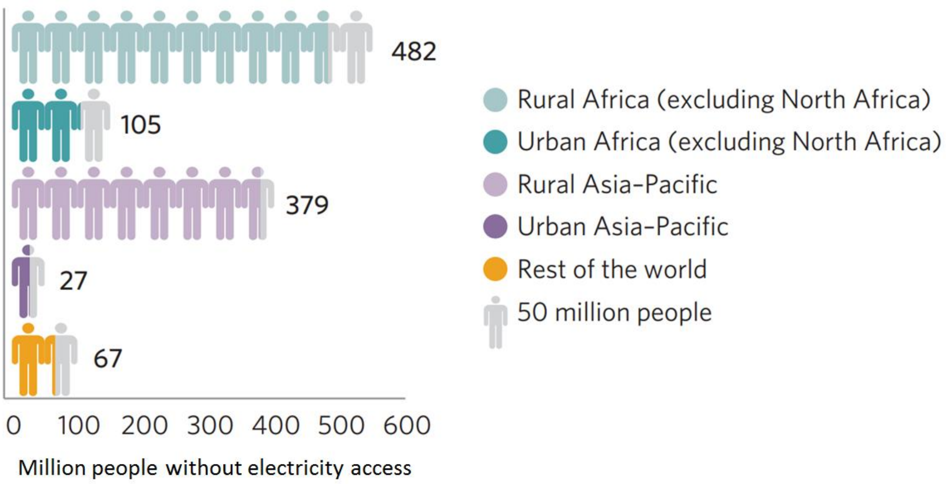


FIGURE 2: Distribution of population without electricity access: rural and urban areas [4], 2014. The 45-47 % of the population without electricity live in rural areas of Sub-Saharan Africa.

Access to energy is very closely related to other aspects of poverty. It is a driving factor in human development and a vital part of the transformation of agrarian societies into industrial ones [5]. Energy poverty has negative outcomes on education: children spend most of their time gathering biomass and drinking water. [6] Without electricity, they have no lighting at night (no more extra hours to study). They might use candles or kerosene, but it is expensive and affects health. Increased electrification rates reduce illiteracy and improve the quality of education [7]. Fig.3 shows the level of literacy by country amongst the youth population (15-24 years old). The highest levels of illiteracy are found in Sub-Saharan Africa (more than 50% of the youth population in countries such as Mali, Niger or Chad) and Southeast Asia, regions that also suffer a high rate of energy poverty.

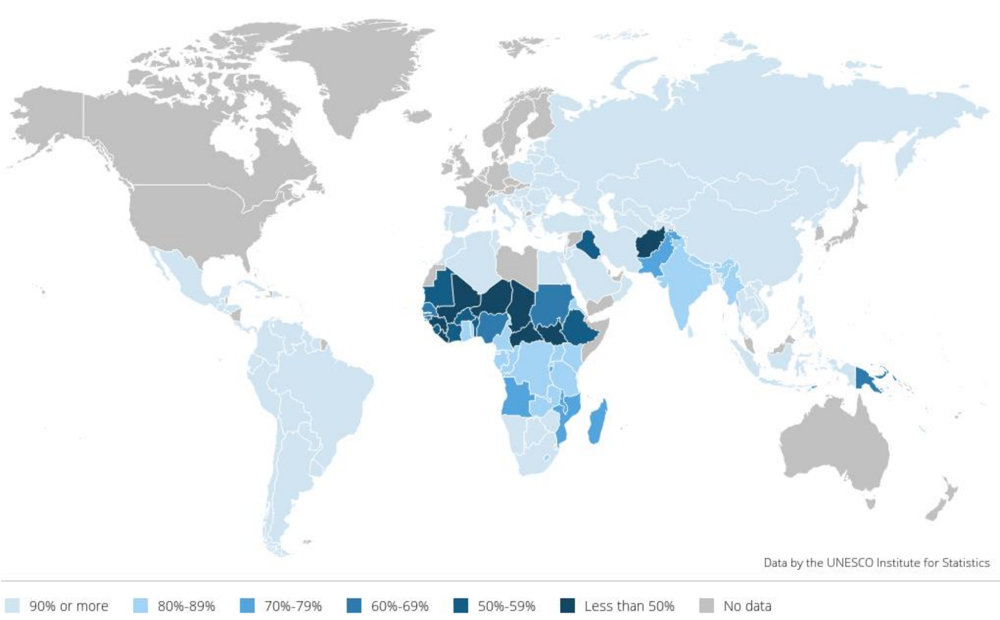


FIGURE 3 [8]**:** Global distribution of youth literacy rate. Population aged 15-24 years old, with no difference in gender. The figure shows the correlation between high levels of illiteracy and energy poverty. Data from UNESCO. 2017.

In addition, energy poverty produces several ghastly health issues [5]. The World Health Organization estimates that each year, 3.8 million people die prematurely from illness attributable to the household air pollution resulting from the traditional use of solid fuels, such as fuelwood and charcoal [9]. The use of polluting fuels such candles or kerosene for lighting has serious implications for health; the use of solid biomass and coal for cooking entail the same risks, often cooking in an enclosed space without proper ventilation. Energy poverty has other consequences in health for example, an estimated 60% of refrigerators used in health clinics in Africa have unreliable electricity, resulting in a loss of almost half of vaccines. While 70% of electrical medical devices used in developing countries fail, with poor power quality a major contributing factor [1]. Fig. 4 shows the Indoor Air Pollution (IAP) deaths per million people. Areas with high rates of energy poverty have more premature deaths because of IAP.

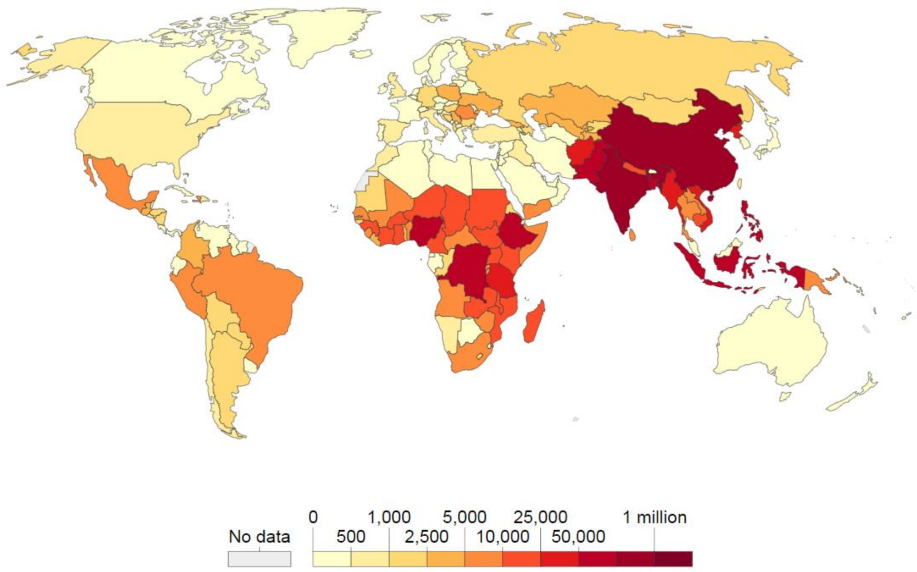


FIGURE 4: Global indoor Air Pollution premature deaths distribution [10]. The image shows the annual number of premature deaths attributed to illness due to the household air pollution, from the use of solid fuels for cooking and heating. Data from the Institute of Health Metrics and Evaluation, 2016 [74].

Access to energy is also linked with the empowerment of women. In most developing countries, women experience energy poverty more severely. Energy poverty is a burden for all poor populations, but women are disproportionately affected because their access to resources and energy benefits is further limited by gender disparities as the role of the woman in developing countries is to collect wood and water [11]. The effects of energy poverty on women and girls are severe, far-reaching. They also include the physical effects of drudgery in traveling long distances to obtain fuelwood, the health effects of indoor air pollution and reduced school attendance [11].

The lack of energy access also has negative effects on the climate change problem that is largely a fossil fuel problem [12]. A changing climate will impact everyone, but it is already having the highest impact on poor communities with the fewest resources to adapt [13]. The poor are disproportionately affected by disasters [14]: of the 30 countries most vulnerable to natural disasters and a changing climate, 26 are least developed countries. The World Bank estimates that, climate change could result in more than 100 million additional people living in extreme poverty by 2030 (without measures to protect poor families from its impacts) [15].

The Millennium Development Goals (MDGs) marked a historic and effective method of global mobilization to achieve a set of important social priorities worldwide for the fight against poverty from 2000 to 2015 [16]. The MDGs established measurable, universally agreed objectives for tackling extreme poverty and hunger among other development priorities [17]. In 2012, the Sustainable Development Goals (SDGs) originated at the United Nations Conference concerning Sustainable Development in Rio de Janeiro replacing MDGs to continue facing poverty beyond 2015. The adoption of the SDG7 in 2015 by 193 countries, the "Affordable and Clean Energy" goal, to ensure access to affordable, reliable, sustainable and modern energy for all by 2030, as part of the new United Nations SDGs, marked a new level of international recognition. [18] It considered the Energy Access as an important key in promoting sustainable development and fighting poverty. In alignment with the SDG7, Sustainable Energy for All [19] is a global initiative launched in 2011 by United Nations that established three global objectives to be accomplished by 2030: to ensure universal access to modern energy services, to double the global rate of improvement in global energy efficiency, and to double the share of renewable energy in the global energy mix. Energy is also at the heart of many of the other SDGs: the access to modern energy such as electricity is one possible solution to multi-dimensional aspects of poverty such as education (SDG4), health (SDG3) and climate change (SDG13) [1, 20]. In addition, access to modern energy promotes gender equality and empowerment of women (SDG5)[21].

A study of the International Energy Agency [1] examined how to achieve access to electricity for all by 2030 in alignment with the SDG7: decentralised systems make up nearly three quarters of the additional connections to meet universal electricity access and concretely, solar photovoltaic systems are presented as the most convenient solution.

1.2. Solar energy for rural electrification

The Global Sun Belt can be defined [22] as the region where the most solar power stands to be harvested. The majority of developing countries fall within the more favorable regions between latitudes 35°N and 35°S. The majority of the world population that lives without electricity access is within this region, as shown in Fig.5; countries that because of their location are potential places for the installation of PV systems.

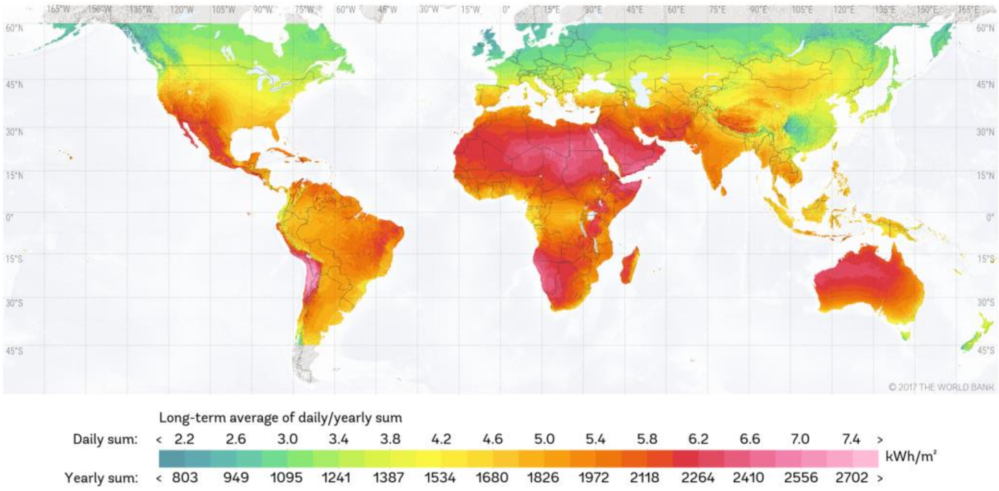


FIGURE 5 : Global irradiance [15]. The areas more appropriate for the installation of photovoltaic systems coincide with the areas of greatest energy poverty.

The global installed capacity for solar-powered electricity has seen an exponential growth, reaching around 2.938 GW of solar photovoltaic off-grid energy at the end of 2018 as reported by the International Renewable Energy Agency [23]. Specifically, a significant number of households (almost 26 million households or an estimated 100 million people in total) are served through off-grid renewable energy systems: around 20 million households through Solar Home Systems, 5 million households through renewables-based minigrids, and 0.8 million households through small wind turbines [24]. Fig. 6 shows an off-grid PV systems classification and their typical loads. Off-grid households' solutions range [25] from very small applications such as Solar Pico Systems (SPS) to mid-scale solutions like SHSs; the latter usually have a capacity of a 10–130 watts peak (up to a 250 watts peak has been installed in some households).

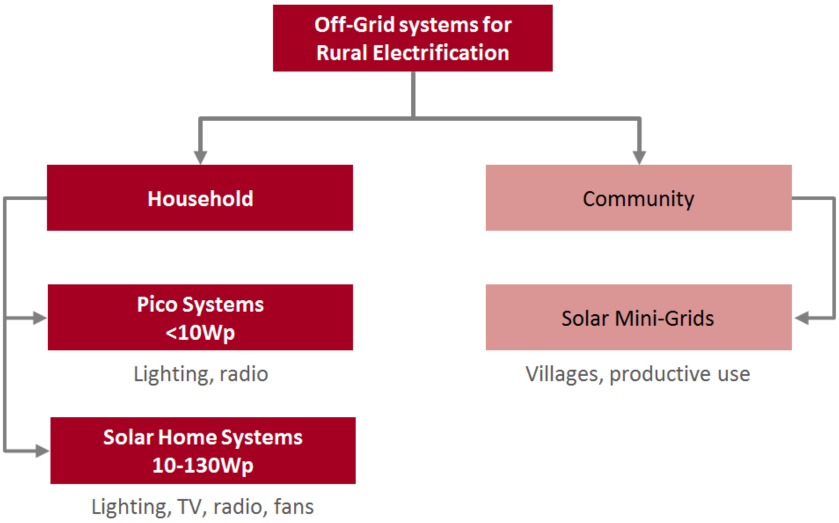


FIGURE 6: Types of Off-Grid system for rural electrification. The classification includes systems for domestic and community level, including the most common load system for each PV system.

Solar Home Systems are cost-effective stand-alone PV systems that supply electricity for lighting and appliances to remote off-grid households [26]. Generally, as stated before, SHS is low power, less than 100 Wp and SHS is suitable for residential applications, such as home appliances, lighting, computers or water pumps [27].

In the early 1990s, the World Bank and many governments began to perceive that Solar Home Systems could provide low-cost rural electrification and could supplement grid-based electrification policies (World Bank 1997). As a result, technology was advacing, costs were declining, and commercial markets were developing [28]. To overcome the obstacles to deliver Solar Home Systems in rural areas, and because of the development and environmental benefits, several organisations have considered assistance for Solar Home Systems to be highly relevant and have supported these projects [28]. Usually, Solar Home Systems are only one component of a vaster project with several development goals such as power sector reform, rural electrification, and rural development.

Due to the emergence of electrification programmes, millions of SHSs have been installed in remote locations, commonly in rural areas of Asia, Africa, and Latin America. In recent years, the market for off-grid PV systems is mainly located in developing countries. The figures are especially high in India (843.11 MWp), China (387.80, Bangladesh (135.35 MWp), Kenya (36.84 MWp), Uganda (28 MWp), Burkina Faso (27MWp) and

Tanzania (25.34 MWp), according to their PV capacity at the end of 2018 [23]. The coverage of population in these countries for the same capacity is higher, i.e. 5 MWp SHS with an average size of 50 Wp represent a solar power solution for 100.000 families [29]. In terms of SHS the most mature markets exist in India (450,000 SHSs), China (150,000 SHSs), Kenya (120,000 SHSs), Morocco (80,000 SHSs), Mexico (80,000 SHSs), and South Africa (50,000 SHSs) as reported by Moner- Girona et al. [30] in 2016.

The rise of the SHS installations is due to the emergence of new projects such as Lighting Global [31] that support sustainable growth of the international off-grid solar market in developing countries. Many initiatives targeting access to electricity in rural areas of developing countries promote the installation of SHSs worldwide:

a) In Asia, the 2005-2010 Village Electrification Programme, connected 3.5 million people to renewable sources, installing more than 400,000 SHSs in China [32]. In Bangladesh, a programme for SHSs installation started in 2003 and in July 2014, the figure had risen to 3.2 million installations benefiting 14 million Bangladeshis, carrying out more than 50,000 SHSs installations per month [33]. In India, an estimated 239 million people (total population of 1324 million people) were without access to electricity in 2016 [1]: the equivalent to almost a quarter of the worldwide population without electricity access. However, India, a leading country in the area of mini-grids and off-grid applications, has made a tremendous electrification effort: half a billion people have gained access to electricity since 2000 [1]. Thousands [34] of SHSs have been installed under the National Solar Mission [35], and one of the main goals is to promote programmes for off-grid applications. Three settings have been commonly used in India as reported by Thrive™ Solar Energy Private Limited Corporation [36]: 110Wp solar modules and 75Ah batteries, 250Wp solar modules and 100Ah batteries, and 300Wp solar modules and 120Ah batteries.

b) When it comes to the African continent, SHSs constitute around 75% of the installed solar PV capacity in Tanzania [33]. These systems include a solar module of 80-200Wp, a battery and a charge controller. An estimated 300,000 rural households in Kenya have an SHS according to Kenya Renewable Energy Association [37]. The most typical solar PV system size for households in Kenya is 25-30Wp. Generally, systems integrate a module of 20-120Wp, a battery of 30-100Ah and a charge controller.

c) In Latin America, in Peru, the Rural Electrification Project began in mid-2006 and it oversaw the installation of 7,100 SHSs for households (about 31,500 people) in remote rural areas [15]. The Peruvian SHS program uses a crystalline module of 60-80Wp, a 100Ah gel sealed lead-acid battery and a 10A charge controller. Mostly systems installed operate using 80Wp according to Acciona Microenergía Corporation [38]. In Brazil, the program 'Light for all' launched in 2003 [39] aimed to universalize access to electricity in Brazil. By May 2016, 15.6 million Brazilians had benefited from the programme and over 485,000 jobs were created [40] installing systems with 160Wp solar photovoltaic modules.

With regards to the loads, in general, a typical home in a developing country has several lamps for lighting, it might have a TV, fans, phone charger or a small refrigerator [41]. Table I shows typical configurations identified in the literature, including the typical sizes and load systems.

TABLE I: POWER GENERATION OF THE SYSTEM AND TYPICAL LOAD CONFIGURATION USED IN SHSS PROGRAMMES

Country	PV power generation range	Load system
Bangladesh	10-350Wp	Basic LED tube lighting, fans and LCD/LED TVs [42]
India	10-200Wp	Compact fluorescent lamps, fans and TV [43]
Kenya	20-120Wp	Lights and TV/radio [44]
Tanzania	80-200Wp	LED lights, radios, mobile phones, TVs [45]
Peru	60-80Wp	Energy efficient lamps, cell phone charger, TV/radio [46]

Many of these countries also manufacture the required components for SHSs, such as batteries, charge controllers, and lights [47]. In general, all these initiatives used crystalline-silicon PV modules. With regards to the other key component of an SHS system, the battery backup unit, in the SHS initiatives reviewed, the most common battery type installed was lead-acid. Finally, most small SHS employed charge controllers using PWM to regulate the charge current to the battery [48].

There are many challenges facing the PV electrification in developing countries that act as limiting factors for the SHSs implementation. When drawing from the experiences found in the literature published, a number of common barriers have been identified:

1. The initial cost is too high [49]. To spend 300€ on a household electricity system in a poor rural village is a considerable investment (comparable to buying a new car in a developed country).

2. Lack of financial infrastructure [49]. For example, in Latin America, there are hardly any banks or institutions that provide microfinance. Other options have been launched such as business plans based on renting revolving loan fund [51].

3. Lack of knowledge or suspicion among rural populations [49]. It is possible that the customer does not have previous experience with photovoltaic systems, and they have not heard of Solar Home Systems at all.

4. Lack of maintenance [50]: Premature damage on the system and reduced lifetime for the storage battery are often caused because of a badly maintained system. Also, a lack of educated personnel working in rural areas of developing countries. Often, the users are not able to repair basic failures correctly. This was linked to the fact that usually, maintenance training is not aimed at the right people. [50]. To overcome this point, it is necessary to invest enough resources in outreach, demonstrations, and training [49].

5. Equipment failures [52]: It was detected that batteries and fluorescent lights are the two components with the most frequent failures; the battery is the one that usually determines the longetivity of the SHS. The battery longevity can be increased with improved charge regulators, avoiding overloads in the PV system.

6. Lack of information about SHS programmes: The information available about experiences with Solar Home Systems is limited. Often, it is difficult to access information and data is dispersed amongst different sources. This information is of high value for improving the design of new projects. Shared tools with projects information (i.e. databases) could facilitate the exchange of information [52].

7. Lack of monitoring: Nieuwenhout et al [50] reviewed previous experiences with SHSs in developing countries, and their main conclusion was that there is not enough information available about the performance of Solar Home Systems and projects. For a high number of cases, there are descriptions of the organisational set up, but very few studies describe, in some level of detail, how SHSs are actually used by households. More information is required to organise better deployment activities, to decrease the default rate in credit schemes, and to improve the quality of hardware and installation of systems. To increase insights into the use of solar PV in households, monitoring and evaluation activities are required, using household surveys and data loggers as their main instruments. Monitoring needs to be continued after the installation stage of the project.

8. Lack of standardization: It was identified that field monitoring, along with laboratory tests, are required to achieve stronger feedback from experiences with actual quality in the field towards formulation of standards, as well as requirements by national governments such as the IEC (International Electrotechnical Commission) and the PV-GAP (Global Approval Programme for Photovoltaics)[52].

1.3. Lack of monitoring of SHS in rural areas

Of all the challenges mentioned in the previous section, this work focuses on the problem of the lack of monitoring.

The monitoring of these SHSs warrants further study of their use for both research and for applications in developing countries. The monitoring of SHSs has been identified as a one of the factors that contribute towards rural electrification programme success [53]. Because of these actions there is an increase the system lifetime and a reduction in the failure of operation of the PV system. Nieuwenhout et al. [52] in 2000 presented a study entitled ‘Monitoring and evaluation of Solar Home Systems’ based on the experiences with applications of solar PV for households in developing countries. The most significant conclusion from the extensive literature research carried out during their study, was that there was not enough information available about the performance of SHSs and projects. So, this slows down further development and successful dissemination. To increase insights into the use of solar PV in households, monitoring and evaluation activities are required; using household surveys and dataloggers as their main instruments. In addition, monitoring needs to be continued after the installation stage of the project [50].

In 2014, Md. Zahidul Islam at al. [54] presented a study on SHSs installed in Bangladesh focused on the current status, the future prospect and the constraints of installations. They detected various user-based constraints: a proper tilt angle of PV modules was not maintained in the majority of houses due to their lack of knowledge on SHS and the lack of awareness, shadings that resulted in hotspot problems, and the dirtiness of PV modules due to the lack of awareness concerning panel cleaning which decreases the efficiency of solar modules. In addition, they studied the user satisfaction. In highly remote areas the ‘service provider response’ is highly unsatisfactory, and most people in these areas do not want to increase their connection because they cannot rely on service providers. The lack of appropriate monitoring of SHSs, and therefore the detection of operation and maintenance problems, that in most cases these are caused by poor practice by the final users, which can lead to a dramatic shortening of the lifetime of the systems or even the withdrawal of their usage [55]. Urmee et al. [53] 2009 identified 'regular maintenance and monitoring' as a one of the factors that contribute to rural electrification programme success. This is because these actions increase the system's lifetime and reduce the failure of operation of the PV system, thus improving the level of confidence of the user in the system. As result, the monitoring of these PV systems following the international standards would have advantages such as, following the performance of the system, detecting failures in its operation, and reaching the point of influencing the success or failure of rural electrification programmes.

The monitoring of SHSs is a challenge in itself. The location of the PV installations implies that the required monitoring system should be accurate, reliable and autonomous allowing remote monitoring, everything in agreement with the low-cost objective. To monitor SHSs three fundamental requirements have been identified:

a) *Low cost requirement:* Grid-connected PV systems usually have high budgets, and the associated monitoring devices allow measurement of the main parameters to carry out the necessary corrective and maintenance actions without a great impact on the total installation cost. However, in the case of SHSs the installations are limited by size and cost factors. The cost of commercial dataloggers has decreased in recent years, although it is still too high, in some cases even surpassing the price of the complete stand-alone PV system. As a result, further development of data acquisition systems is required to monitor Solar Home Systems under operation, under the premise of obtaining the measured parameters using low-cost systems.

b) *Monitoring systems should accomplish international standards*: The measurements of electrical parameters provide information on the consumption and the efficiency of SHSs. International standards establish accuracy requirements for electrical measurements. Standards also specify the climatic parameters that must be measured, generally at a location that is representative of the Solar Home System conditions as well as the accuracy requirements for these parameters, establishing optional and mandatory measurements. In addition, other key aspects of monitoring such as the sampling interval, the recording interval, synchronization protocols or data storage methodology are established by the standards.

c) *Remote monitoring:* Generally, SHSs are located in isolated locations so remote monitoring is a must. It allows a strong reduction of response time for maintenance, repair and product improvement [56]. Focusing on decentralized systems, wireless technologies seem to be the most appropriate communications method. Commonly SHSs are located in remote and inaccessible regions, in locations without access to traditional wired telecommunication networks. The communication technology should be capable of operating autonomously, without requiring additional wired communication networks.

In general, SHSs installations are limited by size and cost factors, and most of these systems are located in rural areas of Asia, Africa, and Latin America as stated before. In recent years, several solutions have been proposed which are applicable to the monitoring of SHSs installed in remote regions. The price of commercial dataloggers has decreased but it is still too high, in some cases even surpassing the total cost of the SHSs installation. As a result, further development of data acquisition devices is required to monitor SHSs, under the premise of obtaining the measured parameters using accurate, autonomous and low-cost systems. In recent years, the tendency has been the development of low-cost designs based on open software and open hardware tools; this trend has been applied to the development of monitoring equipment. The use of open hardware platforms (Arduino™, Rapsberry™…) considerably reduces the final cost of the system, and the monitoring of photovoltaic systems is a great potential application for Internet of Things (IoT). As a result, the integration of IoT and the use of open source tools in the monitoring of SHSs are presented as an optimal potential solution allowing the development of low-cost ad-hoc monitoring systems.

1.3.1. Conventional monitoring

After reviewing the published literature during the past 20 years, it was identified that it is difficult to track the functioning of these SHSs mainly because, a) the required dataloggers are too expensive compared to the total

PV system cost b) often dataloggers depend on a PC or external power supply c) the proposed datalogger did not measure according to the international standards.

The use of commercial software is one of the main drawbacks found in the monitoring attempts reviewed; it increases the price of the monitoring system, often even exceeding the total price of the PV system. The use of auxiliary equipment to store data (laptops…) also increases the final cost. In 1998, M. Benghanem and A. Maafi [57] developed a real-time monitoring system based on a central computer used as a microserver. The microsystem was structured around the microprocessor MC68B09, allowing the acquisition of many meteorological parameters and the parameters related to the PV systems. After the acquisition of data by the microsystem, data was transmitted to the PC through a serial connection RS232C. The data was treated and decoded into the real physical values (current, voltage, energy), and used by the PC computer to study the performance of the PV system. According to the distance between the PC and the microcomputer there were special considerations: short connection serial of type RS232C, longer connection via a modem using a private phone line or a network commuted PTT (modem) and connection HF was also used. The use of this external hardware as well as the PC increased the price of the monitoring system. In 2003, E. Koutroulis and K. Kalaitzakis [58] presented an integrated data acquisition system for renewable energy sources; the system measured both meteorological (e.g. temperature, humidity etc.), and electrical parameters (photovoltaic voltage and current). The proposed datalogger used a DAQ card installed in a PC with 16 single ended or eight differential analogs, an ADC converter with a 12-bit accuracy, 8 digital input/output channels and 2 up/down timer/counters. However, the use of commercial software for processing, displaying and storing the collected data and the dependence on a PC, increased the price of the system.

Aimed to monitor PV system in remote areas of developing countries with lack of electricity and wired telecommunication networks, the independence of the data acquisition system on an external source is vital. One of the first attempts for solar radiation monitoring was developed by R. Mukaro et al.

[59] in 1998. The monitoring system was low-cost, and it relied on an 8-bit microcontroller. With 4 analogue inputs, an analogue-digital converter (ADC) was used; data was stored until uploaded to a portable computer. The sampling interval was 10 min, and, between intervals, a low-power mode was implemented for minimizing power consumption. The results were compared against precision equipment and the error of measurement was studied. This system was suitable for monitoring climatic parameters at remote stations, especially in developing countries, but the connection of this system to PC was a disadvantage. In 2006 N. Forero et al. [60] proposed a system developed for monitoring PV solar plants using a novel procedure based on virtual instrumentation. The system was designed for collecting environmental data, as well as for monitoring the performance of a stand-alone PV solar plant, including the plant I–V curve. The datalogger was based on precision electronic modular field point I/O devices and a high speed data acquisition card. The process control, as well as the acquisition, processing, storing and reporting of all data, is achieved with the help of the graphic programming software. The requirement of a PC connection was the main inconvenience.

One of the problems found in the review of the PV monitoring system was that usually, they were not evaluated in terms of quality of the measurements by comparing the results with calibrated equipment. Commonly, the errors were not bound according the international standards related to the monitoring of PV systems. In 2011, Purwadi et al. [61] developed a datalogger prototype based on a microcontroller, battery powered, and equipped with internal memory for data storage, Real Time Clock, and sensor. The datalogger was installed inside the PV LED Street Lighting controller in a remote area of Jakarta province. The prototype was developed based on a low-cost solution using Atmel Atmega8 microcontroller, Dallas DS 1307 Real Time Clock and 64k serial EEPROM from microchip. The datalogger measured daily energy used, total energy used, charging or discharging status and failure condition. The system was low power consumption, low-cost, portable and easily embedded inside the PV LED Street Lighting controller. However, measurements were not compared with other calibrated data acquisition system and the error of measurements was not bound. In 2008, Demirtas et al. [62] presented a low-cost and highly sensitive data acquisition system for renewable energy sources. The data acquisition system was successfully designed and implemented with a PIC 18F452 and an 18F2550 microcontroller, and then tested on a 2.5 kW solar panels and 2.5 kW wind turbine. It was low-power consumption and low-cost. A 10-bit A/D converter with up to 8 single-ended analog inputs was used. Parameters of the solar and the wind sources such as the current, the voltage and the direction of wind could be illustrated on an LCD and displayed on a PC using the card developed. The main inconvenience was that the design did not follow any international standard, and the accuracy of the system was not demonstrated by comparing with calibrated equipment.

1.3.2. Novel open-source and IoT technologies for SHS monitoring

In recent years, the design of monitoring systems tends to use open source tools (software and hardware), and the integration of the IoT. Open source tools have undergone an exponential rise and have become a trend during the last decade. With the proliferation of open source hardware based (OSHW) projects, novel OSHW platforms have been progressively incorporated in the design of precise and low-cost data acquisition systems. In the case of the PV application monitoring, microcontrollers and microprocessors included in platform such as Arduino™ UNO [63], Arduino™ Mega [64, 65], PcDuino [66] or Raspberry PI [67, 68, 69] have been integrated.

Monitoring attempts for PV systems designed around OSHW platforms were found in the literature. M. Fuentes et al. [63] 2014 developed a low-cost prototype based on the Arduino™ UNO board for monitoring PV systems (SHSs and a micro-grid-connected PV system), specifically in remote areas or regions in developing countries. The datalogger accomplished the accuracy requirements of the IEC standards. The datalogger resolution was 18-bits, including 8 analogue inputs for measuring up to 8 PV modules parameters or weather sensors, 3 inputs for low-cost analogue temperature sensors and virtually unlimited inputs for digital temperature sensors. The datalogger was tested under the harsh environmental conditions of the summer and winter in

Southern Spain. The results indicated that the data acquisition system was reliable and exhibited comparable performance to commercial systems, but it presented various shortcomings. Meteorological parameters measured were insufficient (only temperatures and irradiance were measured, and input voltage range was quite limited). In 2015, Gad et al. [64] developed a new temperature data acquisition system for solar energy applications. The monitoring system consisted of four parts: a master control board, an Arduino™ MEGA board, the power supply unit and the sensors terminals unit. The datalogger stored data in a local memory until the system operator downloaded them to a computer; this is a disadvantage for the monitoring of SHSs located in isolated and inaccessible regions. In 2018, Pereira et al. [67] developed a monitoring system applied to real-time cloud monitoring of a decentralized photovoltaic (PV) plant based on the Raspberry PI platform. Raspberry PI was chosen due to the small size and low-cost, compared to conventional PCs and dataloggers, plus zero cost of free Linux software. Climatic and electrical parameters were measured; the datalogger was tested in the Brazilian Northeast region. The biggest drawback of this datalogger was that when the plant is remotely located, WiFi signal must be available. Hence, in decentralized plants a WiFi modem or router is required, and as stated before, often this is not available in rural regions of developing countries.

With the emergence of IoT and its application for modern designs, final designs include a cloud service as a data storage technique. The application to the mass-scale monitoring of SHSs provide the potential of IoT; SHSs could be monitored in a remote way using computers or smartphones. In 2016, Friansa et al. [70] developed a battery datalogger to monitor the operational and performance of batteries in a smart microgrid system based on IoT. The embedded system utilized as an IoT was a Raspberry PI Model 2; its primary function was to execute data acquisition, and as an internet gateway to the cloud server. The data acquisition was scheduled to execute every minute as mentioned in the IEC61724 standard. The data stored in the cloud system database was processed and analyzed to produce information that could be understood easily by users as it was displayed in HMI using ExtJS/HTML5 framework which can be accessed using a desktop or mobile device.

These novel monitoring systems need connection to the Internet and generally, modern dataloggers use wireless communications. A wide range of different wireless technologies can be used to provide full connectivity which may include: short-range radio protocols (such as ZigBee, Bluetooth and Wi-Fi), mobile networks, or longer-range radio protocols (such as Dash 7). In the monitoring systems reviewed, it was found that Zigbee (short range) technology was the most popular wireless communication transmission used [71, 72, 73, 74, 75]. However, some wireless technologies are not applicable to the SHSs case because of the short reach of the communication technology, or the need of a backup wired network that is not available in many of the potential locations. In addition, over the past 10 years the tendency is to integrate the use of cloud services as a preferred storage system. The use of open cloud platforms allows the design of a monitoring system completely based on open source tools, reducing maximum costs. In the literature reviewed, the most used open cloud platform was ThingSpeak™. In 2016, Touati et al. [68] used this open cloud service for storing data. They proposed a cost-effective PV monitoring system with ubiquitous access, and data processing through a local wireless system. The hardware components consisted of a microcontroller, 6 sensors with signal conditioning circuits, a DC-DC buck-boost converter and Zigbee modules. Some modern projects [75, 20] rely on a web-based application, allowing the distribution of the data over the Internet to remote users.

The specific purpose of this thesis is to design and develop a low-cost monitoring system for the monitoring of Solar Home Systems, suitable for installing in rural areas of developing countries. The datalogger is specifically designed to solve all the problems that arise in the monitoring of SHSs. The design allows its implantation at a global level, allowing the detection of errors and problems in SHSs at both technical and maintenance levels. This contribution is intended to contribute to the success of rural electrification programmes and allow better access to energy in rural areas of developing countries.

1.4. References

[1]"Energy Access Outlook 2017. From Poverty to Prosperity" report. International Energy Agency, 2017.

[2] World bank website <https://www.worldbank.org/ > (accessed 29.07.19).

[3] <https://ourworldindata.org/energy-production-and-changing-energy-sources> (accessed 29.07.19).

[4] <https://trackingsdg7.esmap.org/data/files/download-documents/eegp17-01_gtf_full_report_for_web_0516.pdf> (accessed 29.07.19).

[5] <https://www.borgenmagazine.com/understanding-impact-energy-poverty/> (accessed 29.07.19).

[6]<http://siteresources.worldbank.org/INTENERGY/Resources/EnergyWorkingNotes_4.pdf > (accessed 29.07.19).

[7] Electricity and education: The benefits, barriers, and recommendations for achieving the electrification of primary and secondary schools< https://sustainabledevelopment.un.org> (accessed 29.07.19).

[8] UNESCO <https://www.tellmaps.com/uis/literacy/#!/tellmap/-1082895961 >(accessed 29.07.19).

[9] <http://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health> (accessed 29.07.19).

[10] < https://ourworldindata.org/indoor-air-pollution > (accessed 29.07.19).

[11] Danielsen, K., 'Gender Equality, Women's Rights and Access to Energy Services: An inspiration paper in the run-up to Rio+20', Danish Ministry of Foreign Affairs, Denmark, 2012.

[12] Energy for Sustainable Development: The Energy– Poverty–Climate Nexus <https://www.intechopen.com/books/greenhouse-gases/energy-for-sustainable-development-the-energy-poverty-climate-nexus > (accessed 29.07.19).

[13] < https://www.odi.org/faq-coal-poverty-and-environment > (accessed 29.07.19).

[14]World Risk Report Analysis and prospects 2017 < https://reliefweb.int/sites/reliefweb.int/files/resources/WRR_2017_E2.pdf > (accessed 29.07.19).

[15] < http://www.worldbank.org > (accessed 08.01.2018).

[16] < http://peoplebuildingbettercities.org/wp-content/uploads/2013/04/MDGs-to-SDGs-Lancet.pdf > (accessed 29.07.19).

[17] < http://www.undp.org/content/undp/en/home/sustainable-development-goals/background/> (accessed 29.07.19).

[18] < http://www.un.org> (accessed 07.04.2018)

[19] < https://www.seforall.org/ > (accessed 29.07.19).

[20] M. Kanagawa, T. Nakata,"Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries",Energy Policy, Volume 36, Issue 6, 2008, Pages 2016-2029, ISSN 0301-4215.

[21] T. Winther, M. N. Matinga, K. Ulsrud, and K. Standal, "Women's empowerment through electricity access: scoping study and proposal for a framework of analysis," J. Dev. Eff., vol. 9, no. 3, pp. 389–417, Jul. 2017.

[22] < http://solarone.me/2016/07/27/living-in-the-sun-belt-the-solar-power-potential-for-the-middle-east/ > (accessed 07.04.2018)

[23] < https://www.irena.org/publications/2019/Mar/Renewable-Capacity-Statistics-2019> (accessed 29.07.19).

[24] R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, "Off-Grid Renewable Energy Systems: Status and Methodological Issues," Irena, p. 29, 2015.

[25] Feron, Sarah. Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review. Sustainability. 8. 1326. 10.3390/su8121326. 2016.

[26] <http://ieeacademy.org/renewable-energy-projects/ > (accessed 29.07.19).

[27] V.Salas. "Stand-alone photovoltaic systems". In: The Performance of Photovoltaic (PV) Systems, 2016.

[28] World Bank/GEF Solar Home Systems Projects: Experiences and Lessons Learned 1993-2000 <http://documents.worldbank.org> (accessed 29.07.19).

[29] C. Werner and A. Gerlach, "Global Installed Photovoltaic Capacity and Identification of Hidden Growth Markets," no. October, 2014.

[30] M. Moner-Girona, S. Szabo and S. Bhattacharyya, "Off-Grid Photovoltaic Technologies in the Solar Belt: Finance Mechanisms and Incentives, Reference Module in Earth Systems and Environmental Sciences", Elsevier, 2016. 08- Mar-2016 doi: 10.1016/B978-0-12-409548-9.09713-X.

[31] < https://www.lightingglobal.org/ > (accessed 09.02.2018)

[32] R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, "Off-Grid Renewable Energy Systems: Status and Methodological Issues", International Renewable Energy Agency, 2015.

[33] < http://www.irena.org/ > (accessed 04.03.2018).

[34] "The Synergies between Mobile, Energy and Water Access: Africa". Groupe Speciale Mobile Association (GSMA), 2014.

[35] < https://unu.edu > (accessed 08.01.2018).

[36] Recommendation ITU-T Y.2060

[37] < http://kerea.org > (accessed 08.01.2018).

[38] < https://www.acciona.com/es/ > (accessed 10.02.2018).

[39] Tara Slough, Johannes Urpelainen n , Joonseok Yang . "Light for all? Evaluating Brazil's rural electrification progress, 2000–2010"

[40]< https://www.solarnovus.com/off-grid-solar-in-south-america_N11659.html > (accessed 10.02.2018).

[41] A. López-Vargas, M. Fuentes, M. V. García and F. J. Muñoz-Rodríguez, "Low-Cost Datalogger Intended for Remote Monitoring of Solar Photovoltaic Standalone Systems Based on Arduino™," in IEEE Sensors Journal, vol. 19, no. 11, pp. 4308-4320, 1 June1, 2019.

[42] < http://www.gshakti.org > (accessed 16.06.17).

[43] < http://mnre.gov.in > (accessed 16.06.17).

[44] < http://sollatek.co.ke/shop/solar-lighting/solarhomekit/ > (accessed 16.06.17).

[45] U.E. Hansen, M.B. Pedersen and I. Nygaard, Review of Solar PV Market Development in East Africa, UNEP Risø Centre UNEP Risø Cent. Work. Pap. Ser., no. 12, 2014.

[46] Luz en casa – Case study, Fundación ACCIONA ,2014 < http://www.accioname.org/ > (accessed 16.06.17).

[47] Jäger-Waldau, "PV status report 2014", JRC Science and Policy Reports, 2014.

[48] N.J. Williams, E. Ernest van Dyk, F.J. Vorster, "Monitoring solar home systems with pulse width modulation charge control". J Sol Energy Eng 2011;133:021006- 1–021006-7.

[49] Rolf Posorski Steve Rudolph, Dahlke. Solar Home Systems for Rural Electrification in Developing Countries; An Industry Analysis and Social Venture Plan Posted: 2011.

[50] F. D. J. Nieuwenhout, A. Van Dijk, P. E. Lasschuit, G. Van Roekel, and V. A. P. Van Dijk, “Experience with Solar Home Systems in Developing Countries : A Review,” vol. 474, no. June, pp. 455–474, 2001.

[51] Enersol < https://www.grupoenersol.com/ > (accessed 29.07.19).

[52] F. D. J. Nieuwenhout, A. Van Dijk, V. A. P. Van Dijk, D. Hirsch, P. E. Lasschuit, and G. Van Roekel, “Monitoring and evaluation of experiences with applications of solar PV for households in developing countries” September, 2000.

[53] T. Urmee, D. Harries, and A. Schlapfer, “Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific,” Renew. Energy, vol. 34, no. 2, pp. 354–357, 2009.

[54] M. Z. Islam et al., "A study of Solar Home System in Bangladesh: Current status, future prospect and constraints," 2nd International Conference on Green Energy and Technology, Dhaka, 2014, pp. 110-115

[55] M. Fuentes, M. Vivar, H. Hosein, J. Aguilera, E. Muñoz-Cerón, Lessons learned from the field analysis of PV installations in the Saharawi refugee camps after 10 years of operation, Renewable and Sustainable Energy Reviews, Volume 93, 2018, Pages 100-109.

[56] G. M. Tina and A. D. Grasso, “Remote monitoring system for stand-alone photovoltaic power plants: The case study of a PV-powered outdoor refrigerator”, Energy Convers. Manag, vol. 78, pp. 862–871, 2014.

[57] Benghanem, M., Maafi, A., “Data acquisition system for photovoltaic system performance monitoring, 1998 IEEE Transaction on Instrumentation and Measurement, vol.47, pp.30-33

[58] E. Koutroulis and K. Kalaitzakis, Development of an integrated data-acquisition system for renewable energy sources systems monitoring, Renew. Energy, vol. 28, no. 1, pp. 139–152, 2003.

[59] R. Mukaro, X. Carelse, and L. Olumekor, First performance analysis of a silicon-cell microcontroller-based solar radiation monitoring system, Sol. Energy, vol. 63, no. 5, pp. 313–321, Nov. 1998.

[60] N. Forero, J. Hernández, and G. Gordillo, Development of a monitoring system for a PV solar plant, Energy Convers. Manag., vol. 47, pp. 2329–2336, 2006.

[61] A. Purwadi, Y. Haroen, F. Y. Ali, N. Heryana, D. Nurafiat, and A. Assegaf, Prototype development of a Low Cost data logger for PV based LED Street Lighting System, Proc. 2011 Int. Conf. Electr. Eng. Informatics, no. July, pp. 1–5, 2011.

[62] M. Demirtas, I. Sefa, E. Irmak, I. Colak, Low-cost and high sensitive microcontroller based data acquisition system for renewable energy sources, in: Int. Symp. Power Electron. Electr. Drives, Autom. Motion SPEEDAM, 2008, pp. 196–199.

[63] M. Fuentes, M. Vivar, J. M. Burgos, J. Aguilera, and J. A. Vacas, “Design of an accurate, low-cost autonomous datalogger for PV system monitoring using ArduinoTM that complies with IEC standards”, Sol. Energy Mater. Sol. Cells, vol. 130, pp. 529–543, Nov. 2014.

[64] H.E. Gad, H.E. Gad, “Development of a new temperature data acquisition system for solar energy applications”, Renew. Energy 74 (2015) 337–343.

[65] L. J. Claros-Marfil, J. F. Padial, and B. Lauret, “A new and inexpensive open source data acquisition and controller for solar research: Application to a water- flow glazing”, Renewable Energy, vol. 92, pp. 450–461, 2016.

[66] N. Erraissi, M. Raou, N. Aarich, M. Akhsassi, and A. Bennouna, “Implementation of a low-cost data acquisition system for ‘ PROPRE . MA ’ project”, vol. 117, no. November 2017, pp. 21–40, 2018.

[67] R. I. S. Pereira, I. M. Dupont, P. C. M. Carvalho, and S. C. S. Jucá, “IoT embedded linux system based on Raspberry Pi applied to real-time cloud monitoring of a decentralized photovoltaic plant”, Measurement, vol. 114, no. August 2017, pp. 286–297, 2018.

[68] F. Touati, M. A. Al-Hitmi, N. A. Chowdhury, J. A. Hamad, and A. J. R. San Pedro Gonzales, “Investigation of solar PV performance under Doha weather using a customized measurement and monitoring system”, Renew. Energy, vol. 89, pp. 564–577, 2016.

[69] A. J. Lewis, M. Campbell, and P. Stavroulakis, “Performance evaluation of a cheap, open source , digital environmental monitor based on the Raspberry Pi”, Measurement, vol. 87, pp. 228–235, 2016.

[70] K. Friansa, I. N. Haq, B. M. Santi, D. Kurniadi, and E. Leksono, “Development of Battery Monitoring System in Smart Microgrid Based on Internet of Things (IoT),” Procedia Eng., vol. 170, pp. 482–487, 2017.

[71] M.E.A. López, F.J.G. Mantiñan, M.G. Molina, “Implementation of wireless remote monitoring and control of solar photovoltaic (PV) system”, in: Transm. Distrib. Lat. Am. Conf. Expo., 2012, pp. 1–6.

[72] F. Shariff, N.A. Rahim, W.P. Hew, “Zigbee-based data acquisition system for online monitoring of grid-connected photovoltaic system”, Expert Syst. Appl. 42 (2015) 1730–1742.
[73] K.H. Chao, C.T. Chen, “A remote supervision fault diagnosis meter for photovoltaic power generation systems”, Measurement 104 (2017) 93–104

[74] P. Papageorgas, D. Piromalis, K. Antonakoglou, G. Vokas, D. Tseles, and K. G. Arvanitis, “Smart solar panels: In-situ monitoring of photovoltaic panels based on wired and wireless sensor networks”, Energy Procedia, vol. 36, pp. 535–545, 2013.

[75] A. López-Vargas, M. Fuentes and M. Vivar, "IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino™ With 3G Connectivity," in IEEE Sensors Journal, vol. 19, no. 2, pp. 679-691, 15 Jan.15, 2019.

Chapter 2

Objectives and Thesis Structure

2.1. Justification of thesis

Almost 26 million households (an estimated 100 million people) are powered through off-grid renewable energy systems, and specifically 1.20 million households through Solar Home Systems [1], mainly in rural areas of developing countries. Recent studies indicated that, over the coming years, the tendency to rely on the installation of SHSs for rural electrification will continue [2].

The installation of millions of Solar Home Systems worldwide has been promoted due to the emergence of rural electrification programmes in developing countries. One of the factors that have been identified as decisive in the success [3] of these rural electrification programmes, has been the system monitoring; it extends the lifetime of the system. In addition, it was demonstrated that the lack of information about the performance of the SHSs slows down further development and successful dissemination [4].

The required monitoring system should be accurate, reliable and autonomous allowing remote monitoring, everything in accordance with the low-cost objective. In the past few years the price of commercial monitoring systems has decreased, but it is still too high compared to the cost of the complete Solar Home Systems. For this reason, a further development of data acquisition systems to monitor Solar Home Systems is required, as it is essential to obtain the measurements at low-cost.

2.2. Objectives

The main **objective of this thesis** is to develop a robust and autonomous low-cost ad hoc system based on open source tools for Solar Home Systems monitoring located in isolated areas of developing countries. To achieve the final objective, a set of specific objectives must be accomplished:

1. To study the current challenges for the mass scale Solar Home Systems monitoring in developing countries, highlighting the weaknesses and the strengths of the currently available methods, and the requirements of a suitable system that could meet all the needs for monitoring at low cost and high accuracy. Similarly, to review the data acquisition systems that could be applicable to Solar Home Systems monitoring meeting the monitoring requirements, including the recent solutions that apply new technologies based on open source tools and IoT.

2. To design a first prototype based on Open Source Hardware and specifically designed for monitoring Solar Home Systems located in remote regions. The datalogger should include improvements at the level of hardware and software that allow to monitor the PV system, and to store the collected data, all at a low cost.

3. To develop an improved version of the prototype by integrating open source tools and IoT, allowing the remote monitoring of the Solar Home System via web or via mobile application, meeting the low-cost requirement. The new design should allow data receival in real-time from monitoring, so problems in the PV system can be immediately detected.

4. To study the datalogger reliability and to optimize it, subjecting the system to a comprehensive experimental campaign under real-life operation conditions and evaluating the system performance. Special

attention must be paid to the datalogger performance under thermal stress. From the results of the long-term outdoor campaign and the required indoor laboratory tests an optimisation of the datalogger will be conducted.

2.3. Thesis structure

This thesis focuses on the development of low cost dataloggers for the real-time monitoring of Solar Home Systems located in rural and isolated regions of developing countries. To accomplish the low-cost requirements, open source tools (hardware and software) were employed for the design, always in accordance with international standards.

First, the study of the current challenges for the mass scale SHSs monitoring located in rural regions of developing countries was conducted (Chapter 3). The data acquisition systems that could be installed for the monitoring of SHSs were reviewed, including the designs that apply new technologies based on open source tools and IoT. This work also studied the open source options applicable to the monitoring system designs, focusing on the comparison of open source hardware platforms and the integration of the IoT using open cloud platforms.

The new prototype specifically designed for monitoring Solar Home Systems located in remote areas is described in Chapter 4. Main new datalogger characteristics were: (a) low-cost, employing free software and hardware, (b) autonomous operation, independently of a computer, (c) high accuracy, meeting the IEC standard requirements, (d) robustness in harsh environments, (e) low power consumption, using software and hardware techniques, (f) flexibility to be adapted to different Solar Home Systems, (g) user-friendly interface, using a pushbutton system and a LCD display and (h) data storage in an SD card, allowing the installation of the system in areas deprived of telecommunications networks, requiring minimal maintenance.

Chapter 5 describes the development of a novel and improved version of this solar low-cost datalogger based on the application of Open Source Hardware and IoT . Thus adding internet connectivity and allowing the Solar Home System to be monitored remotely via web or via mobile application. It means that not only long-term system performance data is retrieved, but also that instantaneous information is received. So the problems related to the operation and maintenance of the Solar Home System can be rapidly detected and solved. Additionally, another novelty of this work lies in designing, manufacturing and testing the prototype under real-life (electrical and environmental) working conditions.

Chapter 6 presents the evaluation of the longevity of different versions of the low-cost datalogger. Optimisations were implemented, performing the monitoring system under stream temperatures and reinforcing the data storage system. To guarantee the reliability of the long-term dataloggers, a thermal evaluation was carried out through an indoor campaign (temperature cycling tests), and an evaluation of the dataloggers under real-life conditions for 3 years, demonstrating the reliability and the robustness of the system.

Finally, Chapter 7 presents a review of the novel possibilities that IoT opens for meeting the SDGs. Due to the positive results of the IoT application and the integration of OSHW for monitoring systems, this Chapter focuses on the study of the application of these technologies to PV monitoring and other areas of the developing world, paying attention in the achievement of the SDGs.

2.4. References

[1] R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, “Off-Grid Renewable Energy Systems: Status and Methodological Issues,” Irena, p. 29, 2015.

[2] “Energy Access Outlook 2017. From Poverty to Prosperity” report. International Energy Agency, 2017.

[3] T. Urmee, D. Harries, and A. Schlapfer, “Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific,” Renew. Energy, vol. 34, no. 2, pp. 354–357, 2009.

[4] F. D. J. Nieuwenhout, A. Van Dijk, V. A. P. Van Dijk, D. Hirsch, P. E. Lasschuit, and G. Van Roekel, “Monitoring and evaluation of experiences with applications of solar PV for households in developing countries” September, 2000.

Chapter 3

Current challenges for the Advanced Mass Scale Monitoring of Solar Home Systems: A Review

A. López-Vargas, M. Fuentes and M. Vivar. “Current challenges for the advanced mass scale monitoring of Solar Home Systems: A review”.

3.1. Introduction

The access to energy has long been considered a key issue for the development of a country, but the adoption of the ‘Affordable and Clean Energy’ goal in 2015 by 193 countries, to ensure access to affordable, reliable, sustainable and modern energy for all by 2030, as part of the new United Nations Sustainable Development Goals (SDGs), marked a new level of international recognition [1]. An estimated 1.1 billion people currently live without access to electricity [2], mainly in sub-Saharan Africa and Southeast Asia, and to a lesser extent in the Middle East, Central Asia and Latin America as shown in Fig. 7 [3].

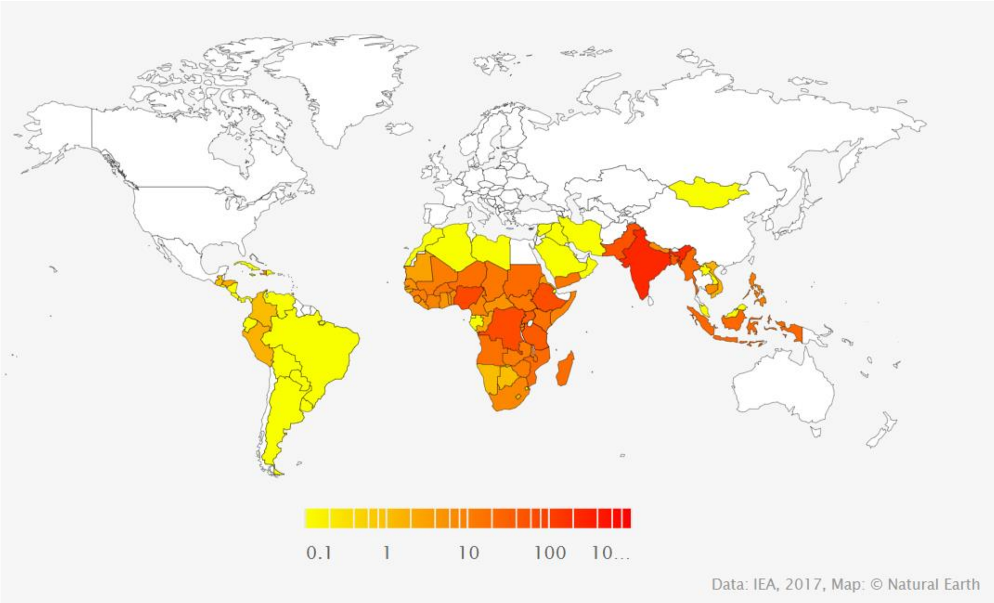


FIGURE 7: Population without access to electricity, 2016 (millions).

Global installed capacity for solar-powered electricity has seen an exponential growth, reaching around 227 GW at the end of 2015 as reported by the World Energy Council [4]. In particular, a significant number of households (almost 26 million households or an estimated 100 million people in total) are served through off-grid renewable energy systems: around 20 million households through SHSs, 5 million households through renewables-based mini-grids, and 0.8 million households through small wind turbines [5].

The SHSs' monitoring warrants further study of their use for both research and for applications in developing countries. The SHSs' monitoring has been identified as a one of the factors that contribute to rural electrification programme success [6]. As a result of these actions, there is an increase in the system lifetime and a decrease in the photovoltaic (PV) system operation failure. In addition, it was demonstrated [7] that there was not enough information available about the performance of SHSs and projects, and this slows down further development and successful dissemination.

Over the coming years, the tendency to rely on the installation of SHSs for rural electrification continues. A study of the International Energy Agency [2] examined how to achieve access to electricity for all by 2030. Decentralized systems make up nearly three quarters of the additional connections to meet universal electricity access, and solar PV stands out over the rest as shown in Fig. 8. In summary, there are millions of SHSs installed worldwide and forecasts indicate that the number of systems will increase, this means millions of PV installations susceptible to monitoring.

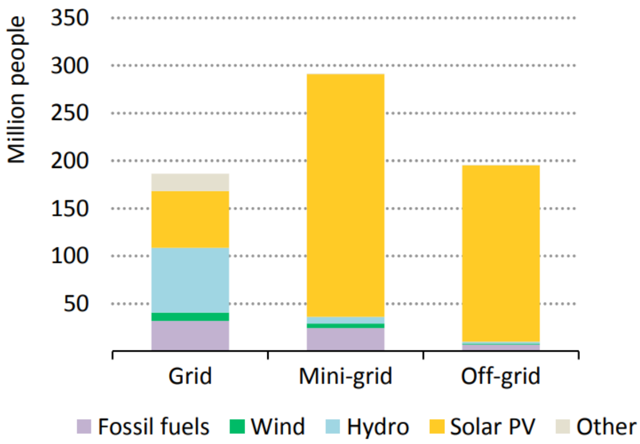


FIGURE 8: Additional population gaining access: 2017-2030 scenario. 'Other' includes nuclear, bioenergy, geothermal, concentrating solar power and marine. Source: International Energy Agency [2].

The mass-scale SHS monitoring is a challenge in itself. The location of the PV installations implies that the required monitoring system should be accurate, reliable and autonomous allowing remote monitoring; maintaining everything in agreement with the low-cost objective. In recent years, photovoltaic installations have proliferated throughout the world thanks to the advancement of technology in the field of renewable energies. In the case of photovoltaic systems, the grid-connected systems usually have their own monitoring system allowing the supervision and maintenance of the PV systems without a high impact on the total cost. But in the case of small stand-alone PV (SAPV) systems, there are limitations in size and cost. In recent years, the tendency has been to develop low-cost designs based on open software and open hardware tools; this trend has been applied to the development of monitoring equipment. The use of open hardware platforms (Arduino™, Raspberry…) considerably reducing the final cost of the system and the monitoring of photovoltaic systems is a great potential application for IoT.

The ultimate goal of this work is to study the current challenges for the mass scale SHSs monitoring in developing countries, highlighting the weaknesses and the strengths of the applicable methods available. The data acquisition systems that could be applicable to the monitoring of SHSs are reviewed, including the attempts that apply new technologies based on open source tools and IoT. This work also studies the open source options applicable to the monitoring system designs focusing on the comparison of open source hardware platforms and the integration of the IoT using open cloud platforms.

3.2. Solar Home Systems in developing countries: The problem of insufficient monitoring

The Global Sun Belt can be defined [8] as the region where the most solar power stands to be harvested; Fig 9 shows the worldwide distribution of solar radiation into the belt, where the use of solar technologies is feasible. The majority of developing countries fall within the more favorable regions, between latitudes 35°N and 35°S. Within this region is the majority of the world population that lives without electricity access, countries that because of their location are potential places for the installation of PV systems.

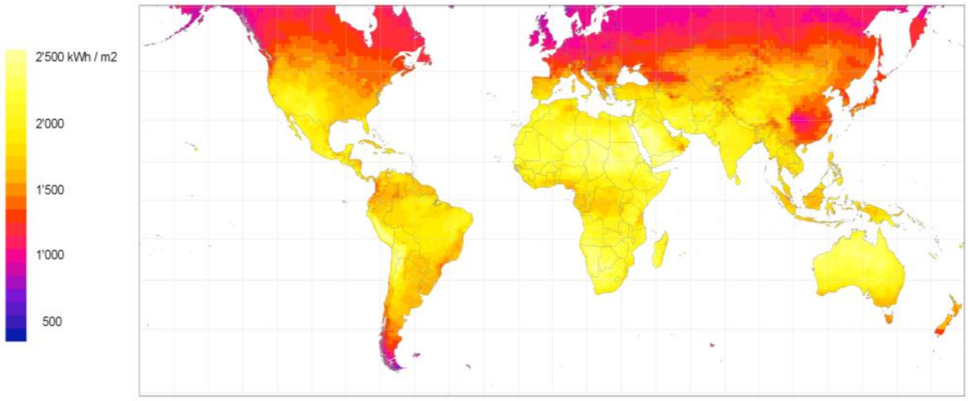


FIGURE 9: Solar irradiation received over the year [9].

3.2.1. Solar Home Systems in developing countries

Due to the emergence of electrification programmes, millions of SHSs have been installed in remote locations, commonly in rural areas of Asia, Africa, and Latin America. The term SHS refers to an SAPV system. Generally, SHS is low power, less than 100 Wp and SHS is suitable for residential applications, such as home appliances, lighting, computers or water pumps [10].

In recent years, the market for off-grid PV systems is mainly located in developing countries. The figures are especially high in India (2,610 MWp) Bangladesh (140 MWp), Kenya (25.40 MWp), Ethiopia (13.40 MWp), Nigeria (37.8 MWp), Sri Lanka (15.3 MWp), and Senegal (19.10 MWp) according to their PV capacity at the end of 2013 [11]. The coverage of population in these countries for the same capacity is higher, i.e. 5 MWp SHS with an average size of 50 Wp represent a solar power solution for 100,000 families [11]. In terms of SHS the most mature markets exist in India (450,000 SHSs), China (150,000 SHSs), Kenya (120,000 SHSs), Morocco (80,000 SHSs), Mexico (80,000 SHSs), and South Africa (50,000 SHSs) as reported by Moner- Girona et al. [12] in 2016.

The rise of the SHS installations is due to the emergence of new projects such as Lighting Global [13], initiatives targeting access to electricity in rural areas of developing countries that promote the installation of SHSs worldwide:

a) In Asia, the 2005-2010 Village Electrification Programme, connected 3.5 million people to renewable sources, installing more than 400,000 SHSs in China [14]. In Bangladesh, a programme for SHSs installation started in 2003 and, in July 2014, the figure had risen to 3.2 million installations benefiting 14 million Bangladeshis, carrying out more than 50,000 SHSs installations per month [15]. In India, an estimated 239 million people did not have access to electricity in 2016 [2]; the equivalent to almost a quarter of the worldwide population without electricity access. However, India, a leading country in the area of mini-grids and off-grid applications, has made a tremendous electrification effort; half a billion people have gained access to electricity since 2000 [2] as shown in Fig. 10. Thousands [16] of SHSs have been installed under the National Solar Mission [17], and one of the main goals is to promote programmes for off grid applications. The most used configurations under the Indian programme are from 10W to 200W. However, three settings have been commonly used in India as reported by Thrive™ Solar Energy Private Limited Corporation [18]: 110Wp solar modules and 75 Ah batteries, 250 Wp solar modules and 100 Ah batteries, and 300 Wp solar modules and 120 Ah batteries.

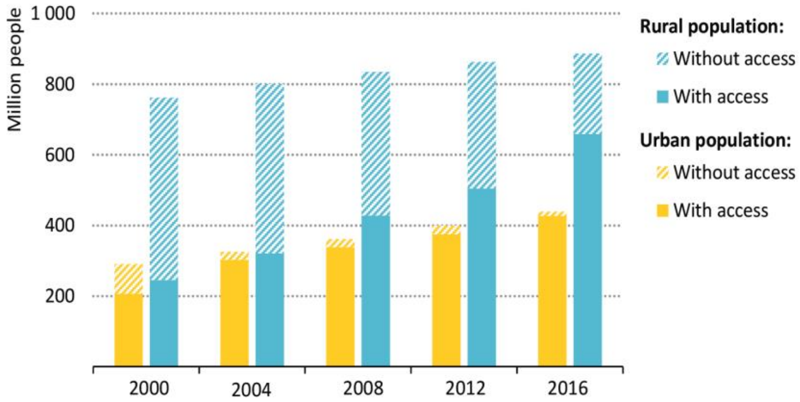


FIGURE 10: Access to electricity of rural and urban population in India [2]

b) When it comes to the African continent, SHSs constitute around 75% of the installed solar PV capacity in Tanzania [15]. These systems include a solar module of 80-200 Wp, a battery and a charge controller. An estimated 300,000 rural households in Kenya have a SHS according to Kenya Renewable Energy Association [19]. The most typical PV system size for households in Kenya is 25-30 Wp. Generally, systems integrate a module of 20-120 W, a battery of 30-100 Ah and a charge controller.

c) In Latin America, in Peru the Rural Electrification Project began in mid-2006 and it oversaw the installation of 7,100 SHSs for households (about 31,500 people) in remote rural areas [20]. The Peruvian SHS program uses a crystalline module of 60-80 Wp, a 100 Ah gel sealed lead-acid battery and a 10A charge controller. Most systems installed operate using 80Wp according to Acciona Microenergía Corporation [21].

Many of these countries also manufacture the required components for SHSs, such as batteries, charge controllers, and lights [22]. In general, all of these initiatives used crystalline-silicon PV modules. In regard to the other key component of a SHS system, the battery backup unit, in the SHS initiatives reviewed, the most common battery type installed was lead-acid mainly due to the cost. Finally, most small SHSs employed charge controllers using PWM to regulate the charge current to the battery [23].

Nieuwenhout et al. [7] in 2000 presented a study entitled 'Monitoring and evaluation of Solar Home Systems' based on the experiences with applications of solar PV for households in developing countries. The main conclusion from the extensive literature research performed during their study, was that there was not enough information available about the performance of SHSs and projects. This slows down further development and successful dissemination. To increase insights into the use of solar PV in households, monitoring and evaluation activities are required, using household surveys and dataloggers as their main instruments. In addition, monitoring needs to be continued after the installation stage of the project [24].

The lack of appropriate monitoring of SHSs, and thus the detection of operation and maintenance problems, that in most cases are caused by poor practice by the final users, can lead to a dramatic shortage of the lifetime of the systems or even the withdrawal of their usage [25]. Urmee et al. [6] in 2009 identified ‘regular maintenance and monitoring’ as a one of the factors that contribute to rural electrification programme success. As a result of these actions, there is an increase in the system lifetime and a decrease in the PV system operation failure, improving the level of confidence for the system user. As result, the monitoring of these PV systems following the international standards would have advantages such as following the performance of the system and detecting failures in its operation, reaching the point of influencing the success or failure of rural electrification programmes.

3.2.2. Solar Home Systems monitoring requirements: International Electro-technical Commission standard

The standard of the International Electrotechnical Commission (IEC) entitled ‘Performance of the photovoltaic system’ [26] contains the general recommendations for the monitoring and analysis of photovoltaic systems, both autonomous and grid connected. The standard defines three classes of monitoring systems, corresponding to different levels of accuracy and different intended applications: Class A (high accuracy), Class B (medium accuracy) and Class C (basic accuracy).

An example of the IEC61724 standard appliance for a typical SHS is shown in the Fig.11.

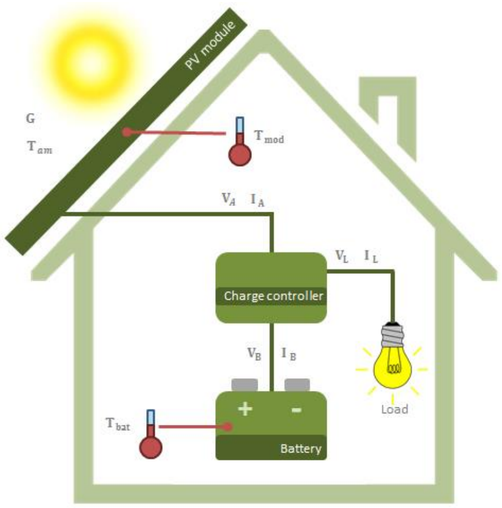


FIGURE 11: Example of a SAPV system monitoring. Diagram of the electrical and meteorological parameters measured in real time.

The IEC61724 standard established that the monitoring of a SHS should include the measurement of a wide range of electrical and climatic parameters: irradiance (G_i), ambient temperature (T_{amb}), PV module temperature (T_{mod}), PV battery temperature (T_{bat}), PV generator output voltage (V_A), battery voltage (V_S), load voltage (V_L), PV generator output current (I_A), battery current (I_S) and load current (I_L). The IEC61724 standard stablishes the requirements for accuracy of electrical and climatic measurements. The accuracy (the most restrictive case, high accuracy class) of the voltage, current and power measurements, including signal conditioning, must be better than 2% of the reading, according to IEC61724 standard. Climatic parameters must be measured at a location that is representative of the SAPV system conditions. The accuracy of temperature measurements must be better than ±1 ºC and the accuracy of irradiance measurements must be better than 8% of the reading from 100 $W \cdot m^{(-2)}$ to 1,500 $W \cdot m^{(-2)}$ (including signal conditioning). The IEC standard advises on synchronization processes; maximum sampling interval, recording interval, format (timestamps) and synchronization processes.

3.3. Solar Home Systems conventional monitoring

In general, SAPV systems installations are limited by size and cost factors. Most of these systems are located in rural areas of Asia, Africa, and Latin America as stated before. In recent years, several solutions have been proposed applicable to the monitoring of SHSs installed in remote regions. Over the past few years the price of commercial data acquisition systems has decreased, but it is still too high in the case of the SAPV systems (compared to the total price of the PV installation). In many cases, the price of the monitoring system is higher than the PV system. As a consequence, there is a need to develop accurate, autonomous and low-cost data acquisition devices for the monitoring of SHS. Table II shows a comparison focusing on the main characteristic of the conventional monitoring systems developed over the past 20 years found in the literature. After reviewing the published literature, it was identified that it is difficult to track the functioning of these SHSs mainly because, a) the required dataloggers are too expensive compared to the total PV system cost, b) often dataloggers depend on a PC or external power supply and c) they did not measure according to the international standards

3.3.1. The required dataloggers are too expensive compared to the total photovoltaic system cost

The use of commercial software is one of the main drawbacks found in the monitoring attempts reviewed. It increases the price of the monitoring system; often even exceeding the total price of the PV system. The use of auxiliary equipment to store data (laptops…) also increases the final cost. In 1998, M. Benghanem and A. Maafi [27] developed a real-time monitoring system based on a central computer used as a micro server. The microsystem was structured around the microprocessor MC68B09 allowing the acquisition of many meteorological parameters and the parameters related to the PV systems. After the acquisition of data by the microsystem, data was transmitted to the PC through a serial connection RS232C. The data were treated and decoded into their real physical values (current, voltage, energy) and used by the PC to study the performance of the PV system.

According to the distance between the PC and the microcomputer there were special considerations: short connection serial of type RS232C, longer connection via a modem using a private phone line or a network commuted

TABLE II: COMPARISON CHART OF CONVENTIONAL PV MONITORING SYSTEM DEVELOPED IN THE LAST 20 YEARS (1998-2018)

Year	Author	Application	Measurements	Platform	Software	ADC resolution	Sampling interval	Data transmission	Data storage
1998	Mukaro et al. [29]	Solar radiation	Irradiance	ST62E20	Turbo C++	8-bit	10 min	Wired RS232	EEPROM
1998	M. Benghanem and A. Maafi [27]	PV Systems	Irradiance, ambient temperature, PV module voltage and currents, battery voltage, battery charge current, load current	Processor MC 68B09	-	-	-	Wired RS232C	-
2001	Wichert et al. [33]	RES system	Ambient temperature, irradiance, voltage, current and power	DataTaker DT50	Labview	-	5 min	Wired RS232	PC
2003	Koutroulis and Kalaitzakis [28]	RES system	Ambient temperature, irradiance, voltage, current and power	PCI-6024E	Labview	12-bit	1 min	Wired RS232	PC
2005	Papadakis et al. [34]	RES system	Ambient temperature, irradiance, wind, humidity, voltage, current and power	Commercial DAQ unit	VB, SQL Server 2000	-	1 min	RF	PC
2005	Forero et al [30]	Grid connected PV system	DC current, DC voltage, AC current, AC voltage, energy, power, ambient temperature, solar radiation, I–V curve	FP DAQ board	Labview	16-bit	30s	Wired RS232	PC
2008	Demirtas et al [32]	RES system	Wind speed, the panel positions of the solar module, the currents and the voltages of the solar and the wind systems	PIC 18F452 and PIC 18F2550	C#	10-bit	-	Wired RS485	PC
2011	Puwardi et al.[31]	PV LED Street Lighting	Daily energy, total energy used, charging or discharging status and failure condition	Atmel Atmega8	-	-	-	-	EEPROM
2011	Anwari [35]	Small PV installation	PV array voltage, PV array current, ambient temperature, solar irradiance	PIC16F877a microcontroller	Labview	8-bit	-	Wired RS232	-

Year	Author	Application	Measurements	Platform	Software	ADC resolution	Sampling interval	Data transmission	Data storage
2012	Mahjoubi [36]	PV water pump	water flow rate, ambient temperature, global irradiation (inclined and horizontal), voltages, currents	HOBO	HOBO	-	-	-	-
2012	Eke et al. [37]	PV module temperature	PV module temperature	PC	Qbasic routine on PC	12-bit	1 min	Wired RS232	PC
2012	Lopez et al. [38]	Grid connected PV system	Solar radiation, wind speed, voltage and current of PV modules	DSP	Labview, C	16-bit	-	ZigBee	PC
2014	Tina and Grasso [39]	SAPV system (fridge application)	Currents, voltages, temperatures of the fridge (internal and external), Temperatures of PV system, ambient temperature, humidity, irradiance	ET-7017 produced by ICPDAS	Matlab	-	-	Wired (Modbus protocol)	Database
2015	Devaraju et al. [40]	Weather station	Humidity, atmospheric temperature, wind speed, wind direction, rainfall, solar radiation, surface temperature, ambient temperature, atmospheric pressure	PIC16F887 microcontroller	Weather Monitoring Station (Embedded C language)	14 bit	30 s	ZigBee	MySQL server
2015	Shariff et al. [41]	Grid connected PV system	Solar radiation, ambient temperature, module temperature, PV voltage, PV current, grid voltage and grid current	PIC18F8720	C / Netbeans	12-bit	1min	Zigbee	EEPROM
2017	Villagrán et al. [42]	Environmental parameters	Temperature, humidity, wind	LP3500	Dynamic C	-	1min	GSM	SD
2017	Chao et al. [43]	Fault diagnosis	Temperatures, irradiance, voltages, currents and curves I-V/ P-V	PIC18F8720	Solar Pro software	12-bit	-	ZigBee	PC
2017	Rezk et al. [44]	SAPV system	Temperatures, irradiance, voltages, currents and curves I-V/ P-V	DAQ card NI USB-6009	Labview	12 bits	-	-	-

PTT (modem) and connection HF was also used. The use of this external hardware as well as the PC increased the price of the monitoring system. In 2003, E. Koutroulis and K. Kalaitzakis [28] presented an integrated data acquisition system for renewable energy sources. The system measured both meteorological (e.g. temperature, humidity etc.) and electrical parameters (photovoltaic voltage and current). The proposed datalogger used a data acquisition (DAQ) card installed in a PC with 16 single ended or eight differential analogue, an analogue-digital converter (ADC) with a 12-bit accuracy, 8 digital input/output channels and 2 up/down timer/counters. However, the use of commercial software for processing, displaying and storing the collected data and the dependence on a PC, increased the price of the system.

3.3.2. Dependence on a PC and external power supply

Aimed to monitor PV system in remote areas of developing countries with lack of electricity and wired telecommunication networks, the independence of the data acquisition system on an external source is vital. In 1998, one of the first attempts for solar radiation monitoring was developed by R. Mukaro et al. [29]. The monitoring system was low-cost, and it relied on an 8-bit microcontroller. With 4 analogue inputs, an ADC was used. Data was stored until uploaded to a portable computer. The sampling interval was 10 min, and between intervals, a low-power mode was implemented for minimizing power consumption. The results were compared against precision equipment and the error of measurement was studied. This system was suitable for monitoring climatic parameters at remote stations, especially in developing countries, but the connection of this system to PC was a disadvantage. N. Forero et al. [30] in 2006 proposed a system developed for monitoring PV solar plants using a novel procedure based on virtual instrumentation. The system was designed for collecting environmental data, as well as for monitoring the performance of a stand-alone PV solar plant, including the plant I–V curve. The datalogger was based on a high-speed data acquisition card. The process control, as well as the acquisition, processing, storing and reporting of all data, is achieved with the help of the graphic programming software. The requirement of a PC connection was the main inconvenience.

3.3.3. Compliance with international standards

One of the problems found in the review of the PV monitoring system was that usually, they were not evaluated in terms of quality of the measurements by comparing the results with calibrated equipment. Commonly, the errors were not bounded according to the international standards related to the monitoring of PV systems. In 2011, Purwadi et al. [31] developed a datalogger prototype based on a microcontroller, battery powered, and equipped with internal memory for data storage, Real Time Clock (RTC), and sensor. The datalogger was installed inside the PV light-emitting diode (LED) Street Lighting controller in a remote area of Jakarta province. The prototype was developed based on a low-cost solution using Atmel Atmega8 microcontroller, Dallas DS 1307 RTC and 64k serial Electrically Erasable Programmable Read-Only Memory (EEPROM) from microchip. The datalogger measured daily energy used, total energy used, charging or discharging status and failure condition. The system was low power consumption, low-cost, portable and easily embedded inside the PV LED Street Lighting controller. But measurements were not compared with another calibrated pattern and the error of measurements was not bounded. In 2008, Demirtas et al. [32] presented a low-cost and highly sensitive data acquisition system for renewable energy sources. The data acquisition system was successfully designed and implemented with a PIC 18F452, and an 18F2550 microcontroller. Then it was tested on a 2.5 kW solar panels and 2.5 kW wind turbine. It was low-power consumption and low-cost. A 10-bit A/D converter with up to 8 single-ended analogue inputs was used. Parameters of the solar and the wind sources such as the current, the voltage and the direction of wind could be illustrated on a Liquid Cristal Display (LCD) and displayed on a PC using the card developed. The main inconvenience was that the design did not follow any international standard and the accuracy of the system was not demonstrated by comparing with calibrated equipment.

3.4. Novel open-source and Internet of Things technologies for SHS monitoring

Microcontrollers are widely used in the majority of monitoring systems developed due to their ability to provide an inexpensive alternative in comparison with the rest of solutions. The selection of the microcontroller is a key point for designing a datalogger. Many of the conventional designs studied were based on commercial microcontrollers and the use of PICs was widely used as an inexpensive solution [28, 32, 43, 41, 40, 35]. Lately, the fast evolution of open source hardware that has been widely employed in the design of high-performance systems provided useful and low-cost solutions. As stated before, the IEC standard advises about synchronization processes. According to the IEC61724 the clocks should be synchronized preferably by an automated mechanism (GPS, NTP), requiring the connection to the Internet. Connectivity techniques employed can be classified into two types: wired and wireless data transmission techniques. Wireless technologies have been preferably used in the case of decentralized systems, although an Ethernet cable is also an alternative for centralized systems [45]. Conventional wired systems reviewed were mainly based on a RS232 cable [29, 27, 33, 30, 32, 35, 37, 40]. As usually SHSs are located in remote and inaccessible regions, in locations without access to traditional wired telecommunication networks, wireless technologies are most appropriate. Most of the conventional monitoring system reviewed used a PC [33, 28, 34, 30, 32, 37, 38, 43] as a data storage system; this was a disadvantage as the use of auxiliary equipment to store data (laptops…) increases the final cost. An interesting storage option widely used was the secure digital (SD) card [46, 47, 48, 49, 50, 42]. However, in the case of SHSs installed in isolated regions, the use of an SD card requires an operator for collecting data, and this increases the maintenance actions and costs. In addition, with the emergence of IoT and its application for modern designs, several open cloud platforms for IoT (or middleware) have proliferated. Modern monitoring systems have included a cloud service as a data storage technique. It provides the potential of IoT; each monitoring system is connected to the Internet and data can be monitored using computers or smartphones.

3.4.1. Hardware – Basic platforms

‘Open Source Hardware (OSHW) is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design’ as defined the Open Source Hardware Association [51]. Lately, OSHW has been widely used in the design of high-performance systems at low cost. Table III shows a review of the most popular open-source hardware platforms including the comparison between their main technical characteristics

Mostly, in the OSHW boards reviewed, the programming language is wiring-based (C++); Python is used to a lesser extent. Many of these projects have their own integrated development environment (IDE), which can be downloaded for free. Others use software tools such as Eclipse. The architecture of the simplest boards (Arduino^{TM}) is 8-bit.More advanced microprocessors are based on 32-bit architecture, with fewer restraints on resources, particularly on memory. In terms of speed, there are boards of up to 1 GHz. The numbers of inputs determine the maximum number of measurements [46]. Usually, there are two types of inputs: analogue and digital inputs (GPIO). The microcontroller memory sets the number of tasks that the datalogger can perform. It may also affect the storage of the measurements. In the specific case of SHSs’ monitoring, the operating temperature is a very important aspect as SHSs used to be located in very hot regions and often, dataloggers may be out in the open. The most commonly operating temperature range is 0 to +70 º C. The resolution of the ADC sets the precision of the measurements: the higher the resolution, the more accuracy. In some applications, the resolution of the measurement is not excessively important. However, in the case of the SHSs mass-scale monitoring, this point is vital as measurements must comply with the IEC standard precision requirements. As stated before, SHSs are located in remote and inaccessible regions, so often, wireless technologies are required. Lately, some OSHW boards include wireless potential. Although the OSHW platform does not have wireless, this capacity is usually added through an external board. At the time of selecting the OSHW platform for low-cost designs, the price of the platform is crucial because it is one of the biggest hardware expenses of the datalogger

Monitoring attempts for PV systems designed around OSHW platforms were found in the literature. In 2014, M. Fuentes et al. [46] developed a low-cost prototype based on the Arduino™ UNO board for monitoring PV systems (SAPV systems and a micro-grid-connected PV system), especially in remote areas or regions in developing countries. The datalogger accomplished the accuracy requirements of the IEC standards. The datalogger resolution was 18-bits, including 8 analogue inputs for measuring up to 8 PV modules parameters or weather sensors, 3 inputs for low-cost analogue temperature sensors and virtually unlimited inputs for digital temperature sensors. The datalogger was tested under the harsh environmental conditions of the summer and winter in Southern Spain. The results indicated that the data acquisition system was reliable and exhibited comparable performance to commercial systems, but it presented various shortcomings: meteorological parameters measured were insufficient (only temperatures and irradiance were measured, and input voltage range was quite limited). In 2015, Gad et al. [47] developed a new temperature data acquisition system for solar energy applications. The monitoring system consisted of four parts: a master control board, an Arduino™ MEGA board, the power supply unit and the sensors terminals unit. The datalogger stored data in a local memory until the system operator downloaded them to a computer. This is a disadvantage for the monitoring of SHSs located in isolated and inaccessible regions. In 2018, Pereira et al. [45] developed a monitoring system applied to real-time cloud monitoring of a decentralized photovoltaic (PV) plant based on the Raspberry PI (RPi) platform. RPi was chosen due to the small size and low-cost, plus zero cost of free Linux software. Climatic and electrical parameters were measured; the datalogger was tested in the Brazilian Northeast region. The biggest drawback of this datalogger was that, when the plant is remotely located, Wi-Fi signal must be available. Therefore, in decentralized plants a Wi-Fi modem or router is required, and as stated before, often this is not available in rural regions of developing countries.

TABLE III: OPEN HARDWARE PLATFORMS COMPARISON

	Arduino	Arduino	Arduino	Parallax Propeller	Netduino	Adafruit	Launchpad	Beagle Board	Raspberry PI	Intel Galileo	Cubieboard	APC Rock [60]	OlinuXino
Model	Uno [52]	Leonardo [52]	Yún [52]	PropStick USB [53]	Netduino 3 wi-fi [54]	Feather M0 Wi-Fi - ATSAMD21 + ATWINC1500 [55]	EK-TM4C123GXL [56]	Rev.C4 [57]	Model B [58]	Rev 2 [52]	1 [59]	-	A13-OLinuXino-WI-FI [61]
Dev.Environmment / IDE	Arduino IDE, Eclipse	Arduino IDE, Eclipse	Arduino IDE, Eclipse	Propeller / Spin	.NET MicroFramework., Netduino SDK	Arduino IDE	Energia IDE	Eclipse, Android ADK, Scratchbox	Open Embedded,QEMU, Scratchbox, Eclipse	The Arduino IDE. x86-based Linux	NF*	NF*	OLinuXino
Programming language	Wiring-based (C++)	Wiring-based (C++)	Wiring-based (C++)	Spin / Propeller Assembly	Wiring-based (C++)	Wiring-based (C++)	Wiring-based (C++)	Python, C, etc…	Python, C, basic	Wiring-based (C++)	NF*	NF*	Python
Architecture [bit]	8	8	8	32	32	32	32	32	32	32	32	32	32
Microcontroller/ Processor	ATMEGA328	ATmega32u4	ATmega32u4	P8X32A-M44	STMicro microcontroller. Cortex-M4	ATSAMD21G18 ARM Cortex M0 processor	ARM Cortex-M4 CPU	11DM3730 (ARM Cortex-A8)	BCM2835 (ARM)	Intel Quark X1000 – single core	ARM Cortex-A8	ARM Cortex-A9	ARM Cortex-A8
Speed [MHz]	16	16	16	12	168	48	80	720	700	400	1000	800	1000
RAM	2KB	2.5KB	2.5 KB	32kB	256KB	32KB SRAM	32KB	256MB	700MB	512KB on-chip SRAM & 256MB	1GB	512MB	512MB

	Arduino	Arduino	Arduino	Parallax Propeller	Netduino	Adafruit	Launchpad	Beagle Board	Raspberry PI	Intel Galileo	Cubieboa rd	APC Rock [60]	OlinuXino
										DRAM			
ROM	32KB	32 KB	32 KB	32 KB	2MB Flash	256KB Flash	2KB EEPROM/ 256KB Flash	256 MB Flash	SD	8MB NOR Flash	4GB NAND Flash	4GBNAN D Flash	4GB NAND Flash
ADC	10-bit	10-bit	10-bit	-	12-bit	12-bit	12-bit	12-bit	-	12-bit	NF*	NF*	NF*
Analogue Input / GPIO (I/O)	6/14	12/14	12/14	-/32	6/22	10/20	8/43	7/22	-/8	6/20	NF*/96	NF*/24	NF*/ 68
Operating Temperature [°C]	0 to +70	0 to +70	0 to +70	0 to +70	0 to + 70	NF*	-40 to 85	0 to + 70	0 to + 70	0 to +70	-25 to +85	5 to 45	0 to +70
Wireless	no	no	yes	NF*	yes	yes	no	no	no	no	no	no	yes
Price[€]	16.95	16.06	47.85	40.50	56.78	28.35	10.53	101.50	35.66 [62]	64.90	48.67 [63]	47.91	55.00

3.4.2. Connectivity challenges in remote monitoring

Remote monitoring is a necessity. SHSs are commonly located in isolated and inaccessible regions, often without access to electricity and wired telecommunication networks. The IEC61724 standard recommends the use of automated synchronization mechanisms so the connection to the Internet is required. Although the standard does not set any requirements related to the type of communication technology, in the specific case of decentralized systems, wireless technologies are most appropriate due to the remote locations of the SHSs. The communication system should allow the transmission of measured data anywhere; the location of the SHS does not interfere with the correct functioning of the monitoring system. The communication technique should be capable of operating autonomously, requiring no additional wired communications networks. In addition to obtain real-time monitoring, the delivery speed of the data transmission system should allow compliance with the sampling intervals established by the IEC61724 standard.

In recent years, several efforts have been made to monitor PV systems located in isolated areas remotely, mainly using dataloggers that send data through wireless technologies. Communication via satellite was used for the implementation of remote monitoring systems [64]. In areas without access to telephone communications, transmission via satellite is very useful. However, this data transmission technique was reported to be slow, taking around 10 min, and the initial cost for the transmitter was very high. Other technologies such as Zigbee or Bluetooth were also applied to the remote monitoring of PV systems, [65] but often the systems required a wired network due to these technologies only covering short distances. In decentralized PV systems, a disadvantage of Wi-Fi use is the need for a Wi-Fi modem or router [45]. Typical (2.4 GHz band) Wi-Fi Routers reach up to 92 m outdoors [66]; often in remote locations, a mechanism to increase Wi-Fi speed and range is needed. Monitoring systems based on mobile communications [67] were also employed for remote monitoring and they stood out over the rest due to the considerable advantages in transmitting the information at large distances in isolated areas. The monitoring systems were empirically tested receiving experimental data from remote stations located around a distance of 100 km. Table IV shows a comparison of connectivity technologies (non-exhaustive) focused on range, bandwidth and cost.

TABLE IV: CHARACTERISTIC OF WIRELESS CONNECTIVITY TECHNOLOGIES (SOURCE ITU [69])

Type	Technology	Maximum range	Maximum bandwidth	Module cost
Wireless Personal Area Network (WPAN)	ANT+	30 m	1 Mbps	$1 - $15
	Bluetooth 4.0 LE	50 m	24 Mbps	$1 - $15
	Radio Frequency Identification (RFID)	10 m (passive) 100 m (active)	100 kbps	<$1 - $15 (passive) $5 - $25 (passive)
	Near Field Communication (NFC)	10 cm	424 kbps	<$1
	802.15.4g	200 m	200 kbps	$1 - $15
	ZigBee	10 m -100 m	250 kbps	$1 - $15
Wide Area Network (WLAN)	Wi-Fi	300 m	250 Mbps (802.11n) 54 Mbps (802.11a/g) 11 Mbps (802.11b) 1 Gbps (802.11ac)	$10+
Wireless Wide Area Network (WWAN)	LoRa	2 – 10 km	200 kbps	$1 - $15
	Weighless	2 – 10 km	200 kbps	$1 - $15
	Dash 7	2 km	200 kbps	$1 - $15
	Worldwide Interoperability for Microwave Access (WiMax)	40 km	34 Mbps – 1Gbps	$1 - $15
	2G technologies: Global System for Mobile (GSM) General Packet Radio Service (GPRS) Enhanced Data Rates for GSM Evolution (EDGE)	35 km	9.6 kbps – 384kbps	$1 - $15
	3G technologies: Universal Mobile Telecommunications System (UMTS) High-Speed Packet Access (HSPA)	up to 100 km	384 kbps– 10 Mbps	$35 - $50
	Cellular 4G/ Long Term Evolution (LTE)	up to 100 km	3 Mbps – 100 Mbps	$80 - $120

As a result, the use of mobile communications (2G, 3G) ensures an affordable and stable long-distance data transfer. But the effectiveness of this technique is subject to the signal strength in the location of the SHS. The International Telecommunication Union (ITU) [68] in 2016 estimated that approximately seven billion people, 95% of the global population, live in an area that is covered by a mobile network. With regards to the mobile-broadband networks (3G or above), they reach 84% of the global population, 67% of the rural population.

According to a Groupe Speciale Mobile Association (GSMA) report [16] in 2014, 63% of Africans had access to improved water supply and 32 % to electricity, compared to 82 % who had access to GSM coverage. United Nations research in India [17] in 2008 showed nearly 366 million people (31% of the population) had access to improved sanitation. Meanwhile, 545 million mobile phones were connected to service. In most African countries access to Information and Communications Technologies (especially Mobile networks) is higher than the access to electricity. Fig. 12 shows that, in some sub-Saharan African countries more households have mobile phones than electricity access, as smartphones now account for more than a quarter of total connections [2].

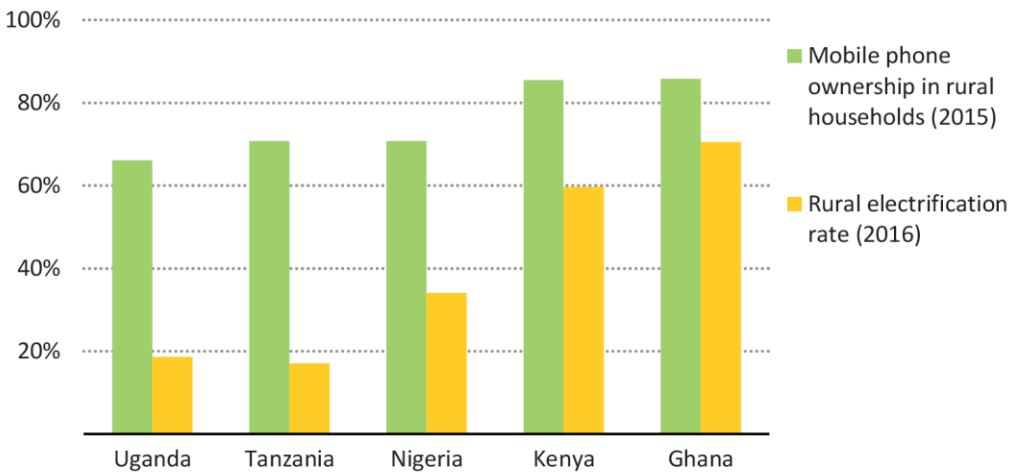


FIGURE 12: Mobile phone ownership and electricity access rates in rural areas in some sub-Saharian countries [2]. Source: IEA analysis; USAID (2017).

Therefore, the use of mobile communications is the most appropriate. This technology presents more advantages than the other communication techniques studied. Both industrialised and developing countries are covered by mobile communications networks, even reaching areas that lack access to electricity and improved water supply.

3.4.3. Internet of Things

The Recommendation ITU-T Y.2060 defined the IoT as ‘a global infrastructure for the information society enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies’ [18]. IoT envisions all objects around as part of the internet. It includes a variety of objects such as smart phones, tablets, sensors, etc. All of these devices are connected to each other, and increasingly they allow intelligent processes and services that support our basic needs, our economies, our environment and our health. This huge number of devices connected to the Internet offers many types of services and produces a large amount of data and information.

The combination of distributed power generation with IoT has recently gained greater recognition due to its potential to lead to more efficient and profitable infrastructures. This may have a transforming effect on the provision of energy to those living off the grid [70]. The ITU report ‘Harnessing the Internet of Things for Global Development’ [69] in 2016 presented conclusions on what is required for the IoT to reach billions of people living in the developing world. Also to accelerate income growth and social development as a result. The report highlighted IoT application for Energy as one of the specific instances where IoT interventions are helping to solve some of the most pressing issues of the world, collaborating to achieve the Sustainable Development Goal 7 (SDG7): ‘Affordable and Clean Energy goal’.

On the other hand, according to the United States National Institute for Standards and Technology [71] (NIST) ‘cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction’ . Cloud based platforms help to connect to the things around us, so that it is possible to access anything, at any time and any place in a user-friendly manner using customized portals and in-built applications; cloud acts as a front end to access IoT [72]. When choosing a cloud platform, many options should be considered; cloud platforms are categorized into private and public cloud models. The mass-scale implementation of smart energy systems has been cost-prohibitive, and thus at a premium for even the best of modern cities [73]. Over the past years, many projects focus on the development of open source multipurpose middleware IoT platforms and are presented as a solution to this problem. The most popular open IoT platforms have been reviewed.

Open source multipurpose middleware IoT platforms reviewed are based on public cloud technology, Some of these IoT platforms use an open application programming interface (API) that allows to manage the connected devices [73] collecting data, analyzing and performing in real-time [74] . The Software Development Kit (SDK) of these IoT platforms often helps to provide back-end functionality to operate mass-scale IoT solutions including security, interoperability, consistency and data management. Message Queue Telemetry Transport (MQTT), Advanced Message Queuing Protocol (AMQP), and Representational State Transfer (REST) communications are usually supported [75,76]. Usually, they provide data storage, visualization, monitoring and the integration of data with a wide variety of third-party platforms that include popular hardware platforms such as Arduino™ o Raspberry Pi, and Twitter amongst others. Open IoT supports REST and GSN (Global Sensor Networks) communications with their servers [77]

3.4.4. Current dataloggers using open-source and Internet of Things for monitoring

In recent years, the design of monitoring systems tends to use open source tools (software and hardware), and the integration of the IoT. Table V shows a review of the novel project for PV monitoring. Open source tools have undergone an exponential rise and have become a trend during the last decade. With the proliferation of open source hardware-based projects, novel OSHW platforms (See Section 3.4.1.) have been progressively incorporated in the design of precise and low-cost data acquisition systems. In the case of the PV application monitoring, OSHW platforms such as Arduino™ UNO [46], Arduino™ Mega [47, 50], PcDuino [48] or Raspberry PI [45, 79, 49] have been integrated.

With the emergence of IoT and its application for modern designs, final designs include a cloud service as a data storage technique. The application to the mass-scale monitoring of SHSs provide potential for the IoT. SHSs could be monitored in a remote way using computers or smartphones. In 2016, Friansa et al. [78] developed a battery datalogger to monitor the operation and performance of batteries in a smart microgrid system based on IoT. The embedded system utilized as an IoT was a RPi Model 2, where its primary function was to execute data acquisition, and as an internet gateway to the cloud server. The data acquisition was scheduled to execute every minute as mentioned in the IEC61724 standard. The data stored in the cloud system database was processed and analyzed to produce information that could be understood easily by users as it was displayed in human-machine interface (HMI) using ExtJS/HTML5 framework which can be accessed using a desktop or mobile device.

These novel monitoring systems need a connection to the Internet and, in general, modern dataloggers use wireless communications. A wide range of different wireless technologies (Table IV) can be used to provide full connectivity which may include: short-range radio protocols (such as ZigBee, Bluetooth and Wi-Fi); mobile networks; or longer-range radio protocols (such as Dash 7). In the monitoring systems reviewed, it was found that Zigbee (short range) technology was the most popular wireless communication transmission used [38, 41, 43, 65, 80]. However, as stated in Section 3.4.2., some wireless technologies are not applicable to the SHSs case because of the short reach of the communication technology, or the need of a backup wired network that is not available in many of the potential locations. In 2018, Lopez-Vargas et al. [80] developed a novel datalogger specifically designed for SAPV systems' monitoring installed in developing countries based on free software and hardware. It was based on an Arduino™ UNO board, and it was installed as an experimental prototype in multiple sites. The integration of IoT allowed remote monitoring, enhancing the performance and the maintenance of the PV system. The datalogger measured electric and climatic parameters with high accuracy. For the installation in developing countries, they selected 3G technology as a communication technique. The PV system could be monitored remotely via web or via mobile application.

Over the past 10 years, the tendency has been to integrate the use of cloud services as a preferred storage system as shown in Table V. The use of open cloud platforms allows the design of a monitoring system based completely on open source tools, reducing costs by the maximum. In the literature reviewed, the most used open cloud platform was ThingSpeak. In 2016, Touati et al. [79] used this open cloud service for storing data. They proposed a cost-effective PV monitoring system with ubiquitous access and processing of data through a local wireless system. The hardware components consisted of a microcontroller, 6 sensors with signal conditioning circuits, a DC-DC buck-boost converter and Zigbee modules. Some modern projects [80] rely on a web-based application, allowing the distribution of the data over the Internet to remote users and investigates novel control algorithm for the remote energy management of the PV system [81].

TABLE V: COMPARISON CHART OF MODERN PV MONITORING SYSTEM DEVELOPED

Year	Author	Application	Measurements	Platform	ADC resolution	Sampling interval	Data transmission	Data storage
2013	Papageorgas et al. [65]	Smart Solar Panels	Voltages, currents, temperature, humidity, irradiance	Arduino	10-bit	15 min	Zigbee	Open-source Cosm platform
2014	Fuentes et al.[46]	PV system	Temperatures, humidity, irradiance, voltage and current	Arduino UNO	18-bit	30s	-	SD
2015	Gad et al. [47]	PV module temperature	Module temperature	Arduino Mega	10-bit	5 min	-	SD
2016	Claros-Marfil et al. [50]	Solar research	Irradiance, temperature, water tank level, ambient light	Arduino Mega ADK	10-bit	5 min	-	SD
2016	A.J.Lewis et al.[49]	Environmental monitor	Air temperature, pressure and hummidity	RPi	-	1 min	-	SD
2016	Friansa et al.[78]	Battery Monitoring System in Smart Microgrid Based on IoT	batteryvoltage, current, and temperature	RPi	-	1 min	-	Cloud database
2016	Touati et al.[79]	Solar PV performance	Ambient temperature, relative humidity, PV module temperature, irradiance, dust, wind speed, maximum power	Atmega32	-	60 min	ZigBee	Open cloud platform (ThingSpeak)
2018	Erraissi et al. [48]	Grid connected PV system	Irradiance, ambient temperature, module temperature, current, voltages	PcDuino	15-bit / 16-bit	1 min- 5 min	Ethernet cable	SD
2018	Pereira et al. [45]	Decentralized PV plant	Irradiance, voltages, currents, power, ambient temperature, humidity, PV module temperature	RPi	16-bit	10 min	Wi-Fi	Cloud
2019	López-Vargas [80]	SAPV systems	Temperatures, humidity, irradiance, voltage and current	Arduino Ethernet	18-bit	30 s	3G	Open cloud platform (ThingSpeak)

3.5. Discussion

International standards describe the general guidelines for the monitoring of SHSs. The IEC standard establishes the minimum number of meteorological and electrical measurements. Some of the projects studied, such as Gad et al. [47], Claros-Marfil et al. [50] and A.J. Lewis et al. [49], did not accomplish the requirements for the monitoring of SHSs since their designs did not include the measurement of electrical parameters (current, voltages, power).

Arduino™ and RPi boards were the most popular platforms used to design monitoring systems in the wide range of OSHW available in the market. After studying the technical characteristics of these boards, one of the main limitations found was the low resolution. Papageorgas et al [65], Gad et al. [47] and Claros-Marfil et al. [50] used the default ADC (10-bit), which can be insufficient to accomplish the accuracy requirements defined by the IEC61724 standard. In this respect, Fuentes et al [46] stands out over the rest of designs due to the use of an external ADC (18-bit). The IEC61724 standard also establishes the maximum sampling interval (see Section 3.2). Touati et al [79] selected a sampling interval of 60 min that exceeded the sampling interval required for Class B (medium accuracy) systems.

Among the monitoring systems studied, an SD card was a very popular data storage system. As already mentioned, (see Section 3.4), in the case of SHSs installed in isolated regions, the use of an SD card requires an operator for extracting data. Therefore, increasing the maintenance actions and costs plus the fact that for the SD extraction, the owner of the SHS must be available, and at home, when the operator visits to retrieve the data. This storage method does not allow to collect the measured data in real time, hindering a quick detection of events.

In order to obtain information in real time, data should be transmitted. Considering the specific case of SHSs monitoring, the transmission of data via wireless is the most advantageous method (see Section 3.4). Papageorgeas [65] and Touati et al [79] used Zigbee for transmitting data. Pereira et al [45] employed Wi-Fi. However, some wireless technologies are not applicable to the SHSs case because of the short reach of the communication technology, or the need of a backup wired network that is not available in many of the potential locations. In this regard, the Lopez-Vargas et al [80] system was better suited for monitoring PV systems located in isolated areas using mobile communications to transmit data. With regards to the data storage, the four studies used open cloud platforms, reducing costs and being able to access the measured data in real time.

3.6. Conclusions

Millions of SHSs have been installed mainly in rural areas of Asia, Africa and Latin America, and international studies support the idea that over the coming years, the installation of SHS for rural electrification will increase. The monitoring of SHSs has advantages such as knowing the performance of the system and detecting failures in its operation. Therefore, the study of the applicable technology for the monitoring of SHSs is particularly interesting.

The main disadvantages of conventional monitoring systems detected were, the cost, the dependency on external hardware (PC or external power supply) and the misalignment of measurements according to the international standards. The major challenge of the SHSs monitoring is to monitor SHSs accurately at a low-cost. The use of open source tools is presented as an optimal solution that allows the development of low-cost ad-hoc monitoring systems.

As the PV systems studied in this work are commonly located in isolated regions, often without access to an electrical grid and wired telecommunication networks, remote monitoring is a priority and the use of mobile communications would seem to be the most appropriate technology for transmitting data. The integration of IoT allows the remote monitorization of SHSs and the visualization of data measured by the datalogger using laptops or smartphones. The use of open IoT cloud platforms minimizes the cost of the monitoring systems. The application of IoT to distributed power generation has benefits on the provision of energy to those living off the grid, helping to resolve some of the most pressing problems in the world, and collaborating to achieve the SDG7.

3.7. References

[1] <http://www.un.org> (accessed 07.04.2018)

[2] "Energy Access Outlook 2017" report. International Energy Agency, 2017.

[3] "Off-grid solar market trends report 2016" report. World Bank Group, 2016.

[4] "World Energy Resources Solar 2016," World Energy Council, 2016.

[5] R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, "Off-Grid Renewable Energy Systems: Status and Methodological Issues," Irena, p. 29, 2015.

[6] T. Urmee, D. Harries, and A. Schlapfer, "Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific," Renew. Energy, vol. 34, no. 2, pp. 354–357, 2009.

[7] F. D. J. Nieuwenhout, A. Van Dijk, V. A. P. Van Dijk, D. Hirsch, P. E. Lasschuit, and G. Van Roekel, "Monitoring and evaluation of experiences with applications of solar PV for households in developing countries" September, 2000.

[8] < http://solarone.me/2016/07/27/living-in-the-sun-belt-the-solar-power-potential-for-the-middle-east/ > (accessed 07.04.2018)

[9] < http://www.meteonorm.com/ > (accessed 08.04.2018)

[10]V.Salas. "Stand-alone photovoltaic systems". In: The Performance of Photovoltaic (PV) Systems, 2016.

[11]C. Werner and A. Gerlach, "Global Installed Photovoltaic Capacity and Identification of Hidden Growth Markets," no. October, 2014.

[12] M. Moner-Girona, S. Szabo and S. Bhattacharyya, "Off-Grid Photovoltaic Technologies in the Solar Belt: Finance Mechanisms and Incentives, Reference Module in Earth Systems and Environmental Sciences", Elsevier, 2016.

[13] < https://www.lightingglobal.org/ > (accessed 09.02.2018)

[14] R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, "Off-Grid Renewable Energy Systems: Status and Methodological Issues", International Renewable Energy Agency, 2015.

[15] < http://www.irena.org/ > (accessed 04.03.2018).

[16] "The Synergies between Mobile, Energy and Water Access: Africa". Groupe Speciale Mobile Association (GSMA), 2014.

[17] < https://unu.edu > (accessed 08.01.2018).

[18] Recommendation ITU-T Y.2060

[19] < http://kerea.org > (accessed 08.01.2018).

[20] < http://www.worldbank.org > (accessed 08.01.2018).

[21] < https://www.acciona.com/es/ > (accessed 10.02.2018).

[22] Jäger-Waldau, "PV status report 2014", JRC Science and Policy Reports, 2014.

[23] N.J. Williams, E. Ernest van Dyk, F.J. Vorster, "Monitoring solar home systems with pulse width modulation charge control". J Sol Energy Eng 2011.

[24] F. D. J. Nieuwenhout, A. Van Dijk, P. E. Lasschuit, G. Van Roekel, and V. A. P. Van Dijk, "Experience with Solar Home Systems in Developing Countries : A Review", Progress in photovoltaics: Research and applications, vol. 474, no. June, pp. 455–474, 2001.

[25] M.Fuentes, M. Vivar, H. Hosein, J. Aguilera, E. Muñoz-Cerón, ‘Lessons learned from the field analysis of PV installations in the Saharawi refugee camps after 10 years of operation’, Renewable and Sustainable Energy Reviews, Vol 93, pp.100-109, 2018..

[26] IEC61724-1. Photovoltaic System Performance- Part 1: Monitoring. 1st Ed., IEC, Switzerland, Geneva, 2017.

[27] Benghanem, M., Maafi, A., “Data acquisition system for photovoltaic system performance monitoring, 1998 IEEE Transaction on Instrumentation and Measurement, vol.47, pp.30-33

[28] E. Koutroulis and K. Kalaitzakis, “Development of an integrated data-acquisition system for renewable energy sources systems monitoring”, Renew. Energy, vol. 28, no. 1, pp. 139–152, 2003.

[29] R. Mukaro, X. Carelse, and L. Olumekor, “First performance analysis of a silicon-cell microcontroller-based solar radiation monitoring system”, Sol. Energy, vol. 63, no. 5, pp. 313–321, Nov. 1998.

[30] N. Forero, J. Hernández, and G. Gordillo, “Development of a monitoring system for a PV solar plant”, Energy Convers. Manag., vol. 47, pp. 2329–2336, 2006.

[31] A. Purwadi, Y. Haroen, F. Y. Ali, N. Heryana, D. Nurafiat, and A. Assegaf, Prototype development of a Low Cost data logger for PV based LED Street Lighting System, Proc. 2011 Int. Conf. Electr. Eng. Informatics, no. July, pp. 1–5, 2011.

[32] M. Demirtas, I. Sefa, E. Irmak, I. Colak, Low-cost and high sensitive microcontroller based data acquisition system for renewable energy sources, in: Int. Symp. Power Electron. Electr. Drives, Autom. Motion SPEEDAM, 2008, pp. 196–199.

[33] B. Wichert, M. Dymond, W. Lawrance, T. Friese, “Development of a test facility for photovoltaic-diesel hybrid energy systems”, Renew. Energy 22 (2001) 311–319.

[34] K. Papadakis, E. Koutroulis, K. Kalaitzakis, “A server database system for remote monitoring and operational evaluation of renewable energy sources plants”, Renew. Energy 30 (2005) 1649–1669.

[35] M. Anwari, M. Dom, and M. I. M. Rashid, “Small Scale PV Monitoring System Software Design” Energy Procedia, vol. 12, pp. 586–592, 2011.

[36] A. Mahjoubi, R.F. Mechlouch, A. Ben Brahim, “Data acquisition system for photovoltaic water pumping system in the desert of Tunisia”, Procedia Engineering. 33 (2012)268–277.

[37] R. Eke, A. Sertap Kavasoglu, N. Kavasoglu, “Design and implementation of a low-cost multi-channel temperature measurement system for photovoltaic modules”, Measurement 45 (2012) 1499–1509.

[38] M.E.A. López, F.J.G. Mantiñan, M.G. Molina, “Implementation of wireless remote monitoring and control of solar photovoltaic (PV) system”, in: Transm. Distrib. Lat. Am. Conf. Expo., 2012, pp. 1–6.

[39] G. M. Tina and A. D. Grasso, “Remote monitoring system for stand-alone photovoltaic power plants: The case study of a PV-powered outdoor refrigerator”, Energy Convers. Manag, vol. 78, pp. 862–871, 2014.

[40] J.T. Devaraju, K.R. Suhas, H.K. Mohana, V.A. Patil, “Wireless portable microcontroller based weather monitoring station”, Measurement 76 (2015) 189–200.

[41] F. Shariff, N.A. Rahim, W.P. Hew, “Zigbee-based data acquisition system for online monitoring of grid-connected photovoltaic system”, Expert Syst. Appl. 42 (2015) 1730–1742.

[42] V. Villagrán, A. Montecinos, C. Franco, R.C. Muñoz, “Environmental monitoring network along a mountain valley using embedded controllers”, Measurement 106 (2017) 221–235.

[43] K.H. Chao, C.T. Chen, “A remote supervision fault diagnosis meter for photovoltaic power generation systems”, Measurement 104 (2017) 93–104.

[44] H. Rezk, I. Tyukhov, M. Al-Dhaifallah, A. Tikhonov, "Performance of data acquisition system for monitoring PV system parameters", Measurement 104 (2017) 204–211.

[45] R. I. S. Pereira, I. M. Dupont, P. C. M. Carvalho, and S. C. S. Jucá, "IoT embedded linux system based on Raspberry Pi applied to real-time cloud monitoring of a decentralized photovoltaic plant", Measurement, vol. 114, no. August 2017, pp. 286–297, 2018.

[46] M. Fuentes, M. Vivar, J. M. Burgos, J. Aguilera, and J. A. Vacas, "Design of an accurate, low-cost autonomous datalogger for PV system monitoring using ArduinoTM that complies with IEC standards", Sol. Energy Mater. Sol. Cells, vol. 130, pp. 529–543, Nov. 2014.

[47] H.E. Gad, H.E. Gad, "Development of a new temperature data acquisition system for solar energy applications", Renew. Energy 74 (2015) 337–343.

[48] N. Erraissi, M. Raou, N. Aarich, M. Akhsassi, and A. Bennouna, "Implementation of a low-cost data acquisition system for ' PROPRE . MA ' project", vol. 117, no. November 2017, pp. 21–40, 2018.

[49] A. J. Lewis, M. Campbell, and P. Stavroulakis, "Performance evaluation of a cheap, open source , digital environmental monitor based on the Raspberry Pi", Measurement, vol. 87, pp. 228–235, 2016.

[50] L. J. Claros-Marfil, J. F. Padial, and B. Lauret, "A new and inexpensive open source data acquisition and controller for solar research: Application to a water- flow glazing", Renewable Energy, vol. 92, pp. 450–461, 2016.

[51] Open Source Hardware Association, "Open Source Hardware (OSHW) Statement of Principles and Definition," 2017. [Online]. Available: <http://www.oshwa.org/definition/>

[52] < https://www.arduino.cc/ > (accessed 09.04.2018)

[53] < https://www.parallax.com > (accessed 09.04.2018)

[54] < http://www.wildernesslabs.co/ > (accessed 09.04.2018)

[55] < https://www.adafruit.com/ > (accessed 09.04.2018)

[56] < http://www.ti.com > (accessed 09.04.2018)

[57] < https://beagleboard.org/ > (accessed 09.04.2018)

[58] < https://www.raspberrypi.org/ > (accessed 09.04.2018)

[59] < http://cubieboard.org/ > (accessed 09.04.2018)

[60] < https://apc.io/products/rock/ > (accessed 09.04.2018)

[61] < https://www.olimex.com > (accessed 09.04.2018)

[62] < https://es.rs-online.com > (accessed 09.04.2018)

[63] <http://www.geeetech.com > (accessed 09.04.2018)

[64] S. C. W. Krauter and T. Depping, "Remote PV-system monitored via satellite", Sol. Energy Mater. Sol. Cells, vol. 82, pp. 139–150, 2004.

[65] P. Papageorgas, D. Piromalis, K. Antonakoglou, G. Vokas, D. Tseles, and K. G. Arvanitis, "Smart solar panels: In-situ monitoring of photovoltaic panels based on wired and wireless sensor networks", Energy Procedia, vol. 36, pp. 535–545, 2013.

[66] B. Mitchell, "What is the Range of a Typical Wi-Fi Network?" 2016. < https://www.lifewire.com/range-of-typical-wifi-network-816564 > (Accessed January 31, 2017).

[67] S. Rosiek and F. J. Batlles,"A microcontroller-based data-acquisition system for meteorological station monitoring", Energy Convers. Manag., vol. 49, no. 12, pp. 3746–3754, 2008.

[68] ICT facts and Figures 2016, International Telecommunication Union <https://www.itu.int> (accessed 08.01.2018).

[69] “Harnessing the Internet of Things for Global Development” report. ITU, 2016.

[70] “Sub-Saharan Africa Power Trends Power disruption in Africa” report, Deloitte, 2017

[71] < https://www.nist.gov/ > (accessed 10.04.2018).

[72] B. Prahlada Rao , B, P. Saluja, N. Sharma, A. Mittal, and S. V. Sharma, “Cloud Computing for Internet of Things & Sensing Based Applications”, 2012 Sixth International Conference on Sensing Technology (ICST), pp. 374–380, 2012.

[73] < http://www.kaaproject.org > (accessed 08.04.2018).

[74] < https://thingspeak.com > (accessed 08.04.2018).

[75] < http://www.sitewhere.org/ > (accessed 08.04.2018).

[76] < https://devicehive.com/#connect > (accessed 08.04.2018).

[77] < http://www.openiot.eu/?page_id=32 > (accessed 08.04.2018).

[78] K. Friansa, I. N. Haq, B. M. Santi, D. Kurniadi, and E. Leksono, “Development of Battery Monitoring System in Smart Microgrid Based on Internet of Things (IoT),” Procedia Engineering., vol. 170, pp. 482–487, 2017.

[79] F. Touati, M. A. Al-Hitmi, N. A. Chowdhury, J. A. Hamad, and A. J. R. San Pedro Gonzales, “Investigation of solar PV performance under Doha weather using a customized measurement and monitoring system”, Renew. Energy, vol. 89, pp. 564–577, 2016.

[80] A. López-Vargas, M. Fuentes and M. Vivar, "IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino™ With 3G Connectivity," in IEEE Sensors Journal, vol. 19, no. 2, pp. 679-691, 15 Jan.15, 2019.

Chapter 4

Low-cost Datalogger Intended for Remote Monitoring of Solar Photovoltaic Stand-Alone Systems Based on Arduino™

A. López-Vargas, M. Fuentes, M. V. García and F. J. Muñoz-Rodríguez, "Low-Cost Datalogger Intended for Remote Monitoring of Solar Photovoltaic Stand-Alone Systems Based on Arduino™," in IEEE Sensors Journal, vol. 19, no. 11, pp. 4308-4320, 1 June1, 2019. Impact factor (2018): 3.076. Instruments & Instrumentation (2018): 13/61 (Q1).

4.1. Introduction

In recent years, the fast evolution of renewable energies and, particularly, solar PV technology, has led to a proliferation of PV installations throughout the world. PV systems can be categorized into two types: grid-connected PV systems and stand-alone PV systems. Grid-connected PV systems usually have high budgets, and the associated data acquisition devices, commonly known as dataloggers, allow to measure the main parameters to carry out the necessary corrective and maintenance actions without a high impact on the total installation cost. However, in the case of stand-alone PV systems, the installations are limited by size and cost factors. Most of these systems are located in remote locations, commonly in developing countries: large programmes have installed thousands of SAPV systems in rural areas of Asia, Africa, and Latin America. Unfortunately, it is very difficult to track the functioning of this type of systems mainly because the required dataloggers are too expensive in comparison with the total system cost, demand special software and usually require a power supply or a PC to be connected all of the time. But it is necessary to monitor SAPV systems accurately and at low cost because the impossibility of detecting operation and maintenance problems, can lead to a dramatic shortening of the useful life of the PV systems. The cost of commercial dataloggers has decreased in recent years, although it is still too high, in some cases even surpassing the price of the complete stand-alone PV system. As a result, further development of data acquisition systems is required to monitor SAPV systems under operation, under the premise of obtaining the measured parameters using accurate, autonomous and low-cost systems.

Analytical monitoring has been gradually applied to small PV installations because the prices for data acquisition hardware have decreased more rapidly than the prices of PV systems; the monitoring of SAPV systems is of special interest for both solar energy research and applications in developing countries The literature includes various reports of PV data acquisition systems during the last several years. One of the first low-cost systems designed for solar radiation monitoring was developed by R.Mukaro et al. [1] in 1998. The monitoring system was based on an 8-bit microcontroller. With 4 analogue inputs, an analogue-digital converter (ADC) was used and data was stored until uploaded to a portable computer. Sampling interval was 10 minutes and low-power mode was implemented between intervals minimizing power consumption. This system was suitable for monitoring of meteorological parameters at remote stations, especially in developing countries, but the need to connect this system to a computer proofed to be a disadvantage. Another integrated data acquisition system for renewable energy sources was reported by E. Koutroulis and K. Kalaitzakis [2] in 2003. The datalogger uses a data acquisition card installed in a PC with 16 single ended or eight differential analog, an ADC converter with a 12-bit accuracy, 8 digital input/output channels and 2 up/down timer/counters. However, the use of commercial software and the dependence on a PC, increased the price of the system. A dedicated data acquisition system for remote monitoring the operation of a stand-alone PV appliance was developed by G. M. Tina and A. D. Grasso [3] in 2014. The system adopted low-cost commercial sensors and components to measure electrical and environmental parameters. The data acquisition board comprised 20 analog inputs. The information provided by the data acquisition board was acquired by a web-based application. However, measurements were not compared with another calibrated data acquisition system and the error of measurements was not bounded. F. Touati et al. [4] in 2016 proposed a cost-effective PV monitoring system with ubiquitous access and processing of data through a local wireless system. The hardware components consisted of a microcontroller, 6 sensors with signal conditioning circuits, a DC-DC buck-boost converter and XBee modules. The main disadvantage of this system was the requirement of a Labview™ based monitoring and recording station. Other designs found in the literature depend on a PC [5-8], commercial software [9] or do not follow international standards of accuracy [10, 11].

M. Fuentes et al. [12] in 2014 developed a low-cost prototype based on open source and open source hardware technologies for monitoring PV systems, especially in remote areas or regions in developing countries. The datalogger accomplished the accuracy requirements of the IEC standards for PV systems. The datalogger resolution was 18-bits, including 8 analogue inputs for measuring up to 8 PV modules parameters or weather sensors, 3 inputs for low-cost analogue temperature sensors and virtually unlimited inputs for digital temperature sensors. The datalogger was tested during summer and winter in Southern Spain. The datalogger monitored a stand-alone PV system and a micro-grid-connected PV system. The results indicated that the data acquisition system was reliable and exhibited comparable performance to commercial systems. However, the datalogger presented various shortcomings: (a) it would need to minimize power consumptions, (b) it presented a low input voltage range and (c) it did not have a user-friendly interface.

The ultimate goal of this work has been to develop an improved and extended version of this low-cost datalogger in order to overcome the shortcomings mentioned above. The new prototype has been specifically designed for stand-alone PV systems located in remote areas. Main new datalogger characteristics are: (a) low-cost, employing open source software and hardware, (b) autonomous operation, independently of a computer, (c) high accuracy, meeting the IEC standard requirements, (d) robustness in outdoor, (e) low power consumption, using software and hardware techniques, (f) flexibility to be adapted to different stand-alone PV systems, (g) user-friendly interface and (h) data storage , allowing the installation of the system in areas deprived of telecommunications networks, requiring minimal maintenance.

4.2. SAPV systems in developing countries

As this work aims to develop a datalogger intended for SAPV systems in developing countries, the main characteristics of this type of applications have been reviewed including the typical daily energy consumption, the corresponding load profile and the most common characteristics of the SAPV systems used in developing countries.

For this review, studies focusing on rural electrification in developing countries [13-16] and renewable-based initiatives energy programs [17] have been used.

4.2.1. Typical stand-alone PV system in rural applications in developing countries

Large programmes have installed thousands of SHS (Solar Home Systems) in rural areas of Asia, Africa, and Latin America. For this review, the most significant programmes (grouped by continent) are:

a) In Asia, more than 6 million SHS are in operation, of which 3 million are installed in Bangladesh [17]. These systems are usually composed by a solar module of 10-350Wp, a 12V 15-130Ah deep cycle tubular battery and a charge controller, as given by Grameen Shakti Corporation [18]. On the other hand, thousands [19] of SHS have been installed in India under the National Solar Mission [20], and one of the main goals is to promote programmes for off grid applications. The capacities covered under the Indian programme are from 10W to 200W. However, three configurations have been commonly used in India as reported by Thrive™ Solar Energy Private Limited Corporation [21]: 110Wp solar modules and 12V 75Ah batteries, 250Wp solar modules and 12V 100Ah batteries, and 300Wp solar modules and 12V 120Ah batteries.

b) In Africa, an estimated 300,000 rural households in Kenya have SHS according to Kenya Renewable Energy Association [22]. In general, systems are composed by a module of 20-120Wp, a battery of 12V 30-100Ah and a charge controller. In Tanzania, SHS constitute around 75% of the installed solar PV capacity as indicated by U. E. Hansen et al. in 2014 [23]. These systems include a solar module of 80-200Wp, a battery and a charge controller.

c) Going to Latin America, the SHS program in Peru uses a crystalline module of 60-80Wp, a 12V 100Ah gel sealed lead-acid battery and a 10A charge controller. 3,000 SHS have been installed in Peru and 2,400 systems operate using 80Wp according to Acciona Microenergía Corporation [24].

Coming to the main components of an SHS, in general, all these initiatives use crystalline-silicon PV modules. Regarding the other key component of a SAPV system, the battery, in the SHS initiatives reviewed, lead-acid has been the type of battery technology widely used. The performance reliability of a SAPV system is determined by the long-term performance of its battery. Finally, SHS programmes have included a charge controller. Charge controllers present special features in order to enhance the battery lifetime (boost charging and pulsed charging) and to improve charging efficiency. The most common approaches for charge controllers are the shunt, series, pulse width modulation (PWM) and Maximum Power Point Tracking (MPPT) charge controllers [25]. Most small SHS employ charge controllers using PWM to regulate the charge current to the battery as reported by N.J.

Williams et al. [26] in 2011. The charge controller makes up only a small fraction (5% approximately) of the complete cost of a SHS [27].

4.2.2. Daily energy consumption and typical load profile in rural applications in developing countries

To estimate the daily energy consumption in a household, it is required to identify all the appliances in terms of power (W) and their daily usage in terms of hours per day. For example, T. Kulworawanichpong and J.J. Mwambeleko in 2015 [13] estimated the average daily energy consumption of a typical rural household in Tanzania, showing the power consumption per appliance / lighting. The lighting load of these typical rural households consisted of 12 VDC LED lamps, with an average daily usage of 4 hours. Regarding daily usage profile, A. El Fathi et al. in 2014 [14] measured typical load curves of 16 households located in the remote rural village of Elkaria (province of Essaouira in Morocco) and they showed that most of the consumption occurs after 6:00 PM (lights and TVs are on) although some smaller peaks are observed around 8:00 AM and around noon.

In another study, D.O.Akinyele and R.K.Rayudu in 2016 [15] showed the maximum load demand of 24 houses located in a remote community in Abuja, Nigeria. Most of the consumption occurred around 8:00 PM (lights and TVs are on) and smaller peaks were observed around 7:00 AM and 4:00 PM.

In general, a typical home in a developing country will have several lamps for lighting and it might have a TV, fans, phone charger or a small refrigerator. Typical configurations have been widely identified in the literature (Table VI).

TABLE VI: POWER GENERATION OF THE SYSTEM AND TYPICAL LOAD CONFIGURATION USED IN SHS PROGRAMMES

Country	PV power generation range	Load system
Bangladesh	10-350Wp	Basic LED tube lighting, fans and LCD/LED TVs [18]
India	10-200Wp	Compact fluorescent lamps, fans and TV [20]
Kenya	20-120Wp	Lights and TV/radio [28]
Tanzania	80-200Wp	LED lights, radios, mobile phones, TVs [23]
Peru	60-80Wp	Energy efficient lamps, cell phone charger, TV/radio [24]

4.3. Requirements for the SAPV system monitoring

International standards set the parameters that must be measured and monitored in photovoltaic systems [29, 30]. The IEC61724 standard [29] titled "Photovoltaic system performance" describes the general guidelines for the monitoring and analysis of the electrical performance of photovoltaic systems (stand-alone and grid connected). In Table VII a summary of such parameters is presented.

TABLE VII: PARAMETERS TO BE MONITORED IN REAL TIME PV SYSTEMS

General parameters	Specific parameters	Symbol
Meteorology	Total irradiance, in the plane of the array	G_i
	Ambient temperature in a radiation shield	T_{amb}
	Wind speed (optional)	-
	Rainfall (optional)	-
	Humidity (optional)	-
PVarray	Output voltage	V_A
	Output current	I_A
	Output power	P_A
	PV module temperature	T_{mod}
Energy storage	Operating voltage	V_S
	Current to storage[a]	I_{TS}
	Current from storage[a]	I_{FS}
	Power to storage[a]	P_{TS}
	Power from storage[a]	P_{FS}
Load	Load voltage	V_L
	Load current	I_L
	Load power	P_L
Utility grid	Utility voltage	V_U
	Current to utility grid[a]	I_{TU}
	Current from utility grid[a]	I_{FU}
	Power to utility grid[a]	P_{TU}
	Power from utility grid[a]	P_{FU}
Back-up sources	Output voltage	V_{BU}
	Output current	I_{BU}
	Output power	P_{BU}

Photovoltaic (PV) has become a practical technology for remote areas, especially stand-alone PV systems because of electric grid connection is not required. For characterizing SAPV systems, the measurement of electrical properties and atmospheric conditions is essential. An example of the IEC61724 standard appliance for SAPV systems is shown in Fig. 13.

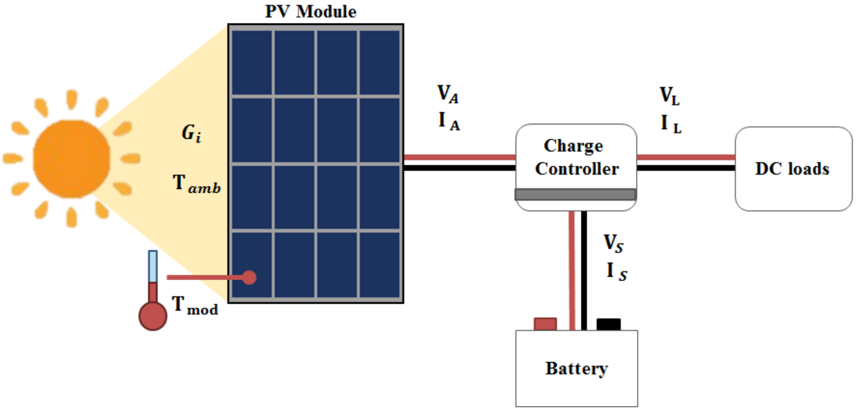


FIGURE 13: Diagram of the parameters measured in real time for SAPV systems.

4.3.1. Electrical parameters

The number of parameters to be measured (Table VII) determines the number of inputs and therefore it is an important starting point of the datalogger design. In the specific case of electrical measurements, if the current sensor can distinguish the direction of the current, the number of parameters to be monitored can be reduced.

According to IEC61724 standard, the accuracy of the voltage, current and power measurements, including signal conditioning, must be better than 2% of the reading (high accuracy class).

4.3.2. Meteorological data

With the aim to satisfy the IEC61724 standard, climatic parameters must be measured at a location that is representative of the SAPV system conditions and all of them, optional and mandatory parameters (Table VII), must comply the standard requirements of accuracy. The accuracy of PV module temperature measurements must be better than ±2 ºC, the accuracy of ambient temperature measures must be better than ±1 ºC of and the accuracy of irradiance measures must be better than 8% of the reading from 100 W·m-2 to 1,500 W·m-2 (including signal conditioning). The measurement of optional parameters such as wind speed, also must comply the standard requirements of accuracy: ≤ 0. 5 m·s-1 for wind speeds ≤ 5 m·s-1, and ≤ 10 % of the reading for wind speeds greater than 5 m·s-1.

4.3.3. Data storage

Data storage is an important process for carrying out any monitoring or performance analysis. The SAPV system was specifically designed for being installed in developing countries and sending data may not always be possible due to the lack of coverage in rural areas [31]. Hence, the method of data storage selected should ensure to keep collected data and to work autonomously, requiring minimal maintenance. According to IEC61724, it is necessary to keep all of the data collected in files organised by dates.

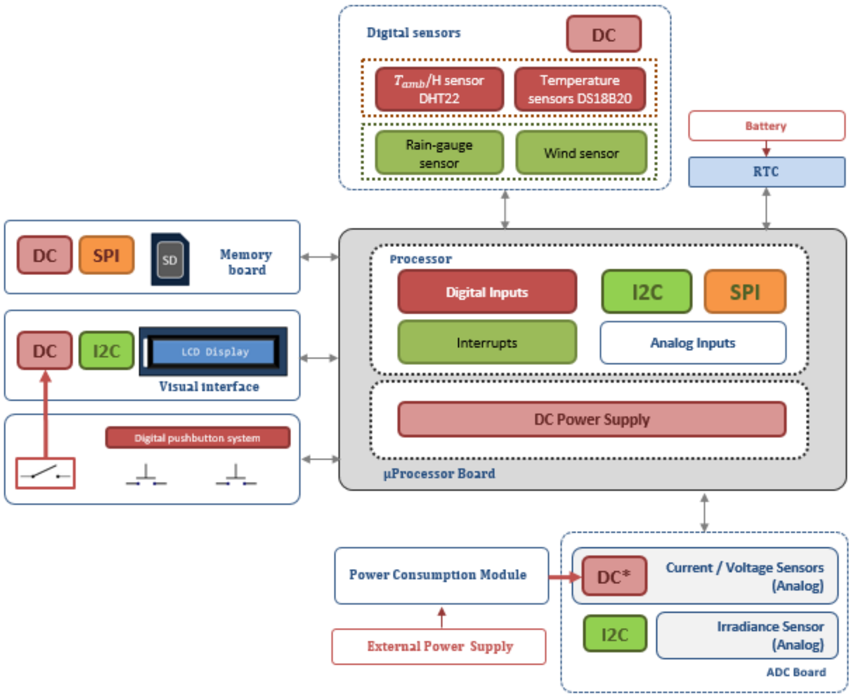


FIGURE 14: Diagram of the new prototype including improved modules (analog and digital sensors modules, ADC board) and new modules (visual interface, digital pushbutton system and power consumption module).

4.4. Design of the new datalogger

In this section, the new low-cost datalogger is presented, including both hardware and software. The microprocessor manages all the modules using appropriate communications protocols that will be detailed next. Fig.14 shows a general view of the design of the new datalogger, including current and voltage sensors, ADC board, Real-Time Clock (RTC), digital sensors, memory board, visual interface, digital pushbutton system and power consumption module.

4.4.1. Selection of microprocessor

The selection of the appropriate hardware was based on the use of open-sorce software and hardware that allows to achieve the low-cost objective of the final system. Within the numerous platforms based on open-source hardware available in the market, Arduino™ UNO stands out in comparison with the others due to its flexibility, cost and developer community [12]. The hardware is based on the ATmega328 microcontroller and it has 14 digital input/output pins, 6 analogue inputs, a power jack and a USB connection. The board contains everything required to support the microcontroller and it can operate using an external supply.

This microcontroller is comparable in price to the lowest cost options, but its flexibility to adapt any design poses an additional advantage over the other low cost platforms. The software can be downloaded for free and the hardware reference designs are available under an open-source license, and the users are free to adapt them to their needs. Another key advantage of Arduino™ is its developer community. A worldwide community of developers has gathered around this open-source platform and support is available in numerous webpages, being examples and libraries. Regarding the operating temperature, the ATmega328P microcontroller operates effectively within the range of temperature from -40 ºC to 125ºC.

On the other hand, one of the main weaknesses of Arduino™ UNO is the internal memory limitation. Arduino™ UNO has 32K bytes of Flash Memory (program space) and 2K bytes of SRAM (Static Random Access Memory) [32]. Due to these memory limitations, the optimization of the program is an essential task. Another disadvantage of Arduino™ UNO is the resolution. The board has 6 analogue inputs with an ADC of 10-bit resolution. This resolution is not sufficient for meeting all of the requirements of the IEC61724 standard because there are some sensors, such as the irradiance sensors for example, that have amplitudes in the range of hundreds of microvolts and need at least 16-bit resolution or amplifier systems to improve the measurement range.

4.4.2. Hardware improvement

Due to the basic Arduino™ UNO hardware limitations explained previously that hinders the possibility of meeting the IEC61724 standard requirements, hardware enhancements were required. To overcome the main limitations, all the new hardware designs were integrated in an ad-hoc PCB (Printed Circuit Board). The main hardware improvements were:

a) An I2C™ bus was integrated in the PCB using the pins A5 and A4 of Arduino™ UNO. An I2C™ connector and an additional reset button were also included.

b) A RTC for tracking time and ensuring the precise synchronization of the measurements was included. The selected external clock was the DS1307 serial RTC from Maxim Integrated™. DS1307 uses the I2C™ bus and operates under its particular battery independently of the board power supply.

c) Two external ADCs MCP3424 of 18-bits resolution from Microchip™ were also integrated to overcome the resolution limitation of Arduino™ UNO to accomplish the IEC61724 accuracy requirements. These ADCs have four differential channels with an input range of ±2.048V for monitoring up to 8 analogue inputs with high accuracy. PGA (Programmable-Gain Amplifier) gain of x1, x2, x4, or x8, before the analog-to-digital conversion takes place, can be selected by the user via software. The error introduced in this process is negligible compared to the error introduced by the sensors. MCP3424 uses the I2C™ bus. Regarding operating temperatures, these ADCs can work in the temperature range -40°C to +125°C.

d) A SD flash memory was employed to overcome the memory limitations of the Arduino™ UNO board. This data storage method is characterized by its high storage density, rapid speeds of reading and writing, and its low price. Due to the small size of the daily data files (plain text archives, written in single-byte ASCII code), using a 4GB SD card, there is available space for up to 10 years of measurements. The communication with the SD card was bas ed on SPI (Serial Peripheral Interface) [33].

e) A visual interface based on a display and a pushbutton system was added to communicate with the system. An LCD (Liquid Crystal Display) module was employed as a user interface. The connection of this shield requires only two digital pins since it uses the I2C™ bus to communicate with the Arduino™ board. The backlight can be set via software. At each iteration, the 16 x 2 LCD screen switches on showing the information measured by sensors.

f) A power consumption module was implemented with a bipolar transistor to power active sensors only in the timeframe necessary. In this way, the power consumption will be minimized. As results, voltage and current sensors only were enabled 3.4 seconds per cycle of 30 seconds of duration, with a power reduction of 88.6 % (of the total sensors consumption).

4.4.3. Selection of meteorological sensors

The first prototype of the new portable datalogger [12] covered the measurement of only irradiance and ambient temperature parameters. Employing exclusively low-cost sensors, the new extended and specific version for stand-alone PV systems includes a wide range of climatic measurements: irradiance, ambient temperature, humidity, wind velocity and rainfall.

4.4.3.1. Irradiance

The IEC standards IEC60904-2 [34] and IEC60904-6 [35] give the requirements for photovoltaic reference systems. It covers a variety of devices used as reference sensors, such as single photovoltaic cells or small modules. With the aim of reducing costs, calibrated PV cells were used to measure the solar irradiance, concretely 2.2W mono-crystalline cells from Nousol [12].

4.4.3.2. Ambient temperature and humidity

The DHT22 sensor from Aosong was selected for measuring both relative humidity and ambient temperature. This sensor provides a precision of ±0.5℃, measuring ambient temperature in the range of -40℃ to +80℃. Additionally, the DHT22 sensor allows to measure the relative humidity in the range of 0%RH to 100%RH, measuring the relative humidity with a precision of ±3%RH.

4.4.3.3. Wind

An anemometer sensor from Thies Clima was used to acquire the horizontal wind velocity. The microcontroller was configured to count clicks (as external interrupts) which are caused due to anemometer magnetic reed switch pulses, so the number of pulses is proportional to the wind speed. This sensor operates in the range of 0.9 m/s to 40 m/s with an accuracy of ± 0.5 m/s.

4.4.3.4. Precipitation

The rain gauge sensor measures the amount of rainfall in a given surface within a specific time interval. The Rain-O-Matic Small sensor from Pronamic™ was selected. This sensor measures the rainfall by means of a funnel which leads the water down into the self-emptying tipping bucket, held in place by a hard ferrite magnet [36]. The output of this sensor was also declared as a microcontroller interrupt by software. The number of clicks within a specific time interval (30 seconds in this case) is the proportional to precipitation. The sensor interrupts the microcontroller each time the click occurs and the number of clicks is registered.

4.4.4. Selection of SAPV system parameter sensors

This section presents the improvements on sensing methods with respect to the first prototype of the low-cost datalogger [12]. The SAPV system parameters measured and recorded by the monitoring system include voltages, currents and temperatures that have been empirically validated in alignment with the IEC61724 standard accuracy requirements.

4.4.4.1. Temperatures

DS18B20 temperature sensors from Maxim Integrated™ [37] were used to acquire PV module and PV battery temperatures. DS18B20 sensors use the 1-Wire bus: a communications protocol that has a single bus master and one or more slaves.

DS18B20 sensors have a 9 to 12 bit selectable resolution. In accordance with IEC61724 standard, the accuracy of these temperature sensors must be better than ±2ºC, so the highest resolution was selected. The operating temperature range of these sensors is -55°C to 125°C, but the manufacturer ensures a ±0.5°C accuracy from the operating temperature range of -10°C to +85°C. To avoid moisture and water-related problems, the waterproof version of the sensor was selected.

4.4.4.2. Electrical parameters: Voltage measurement

The voltage parameters measured and recorded by the new low-cost monitoring system include the PV generator output voltage (V_A), battery voltage (V_S) and load voltage (V_L). For this purpose, individual low-cost voltage sensors were developed.

Voltage dividers that increase the ADC input range from ±2.048V were used. Additionally, three common-mode voltage amplifiers were also used to allow measuring differential signals in presence of high common-mode voltage range accurately. The output of these dividers provided voltage level to measurable range without risk of damage. PV generator output voltage (V_A) sensor was scaled down by V_{OUT}/V_{IN}=1/76. Battery output voltage (V_S) and load voltage (V_L) sensors dividers were based on V_{OUT}/V_{IN}=1/51 proportion.

4.4.4.3. Electrical parameters: Current measurement

The current parameters measured and recorded by the new datalogger include PV generator output current (I_A), battery current (I_S) and load current (I_L). Three types of current sensors based on two different technologies: precision resistors (shunts) and Hall effect, were developed and tested in order to select the most adequate one for the SAPV system monitoring.Current sensors were empirically validated by comparing the results obtained with a high precision datalogger (22-bit resolution). After a full campaign of experiments, the best results in terms of accuracy were offered by the LTS sensors. The main advantage of these Hall Effect sensors over resistive shunts was a minimum power loss. A further advantage of employing this technique is that these Hall Effect sensors are fully non-invasive current sensors.

4.4.5. Software

The algorithm has been coded in the Arduino™ [32] C/C++ subset language, its own open source programing language, using the Arduino™ IDE. As the IEC61724 standard [1] advises sampling intervals below 1min for parameters related to irradiance, 30s has been the interval chosen, and data are recorded. Every day a new file is created, and these files are recorded and organized by date in the SD memory.

Fig. 15 shows the flow diagram of the process followed by the microprocessor. Every minute, at second 0 and second 30, parameters are measured. First, the most variable parameters are measured, and later, parameters with low instantaneous fluctuations. Thus, electrical parameters are measured and later, meteorological parameters. A green LED switches on for a few seconds in a cyclical way every time the parameters are measured, indicating that the software runs correctly. In addition, after measuring, data is stored in the SD card and the results are shown on the LCD screen.

Software improvements have been developed and new processes have been included:

a) An interactive system based on the display and a pushbutton system allows the user to control internal processes. After initializing, the display provides information about the SD data extraction. A message is displayed advising the user that data can be extracted from the SD of safely. The monitoring system stays in standby mode until the user extracts data from the SD card and the pushbutton is pressed (specified by the display). If after 10 minutes the button is not pressed, the next code is executed, preventing failures in the case of an unexpected restart (e.g. because of a power failure event).

b) A synchronization option has been included to account for potential drifts of the RTC during the operation of the system (usually a few seconds per week): the display shows detailed steps about the synchronization process, and time (hour, minute and second) can be selected by the user.

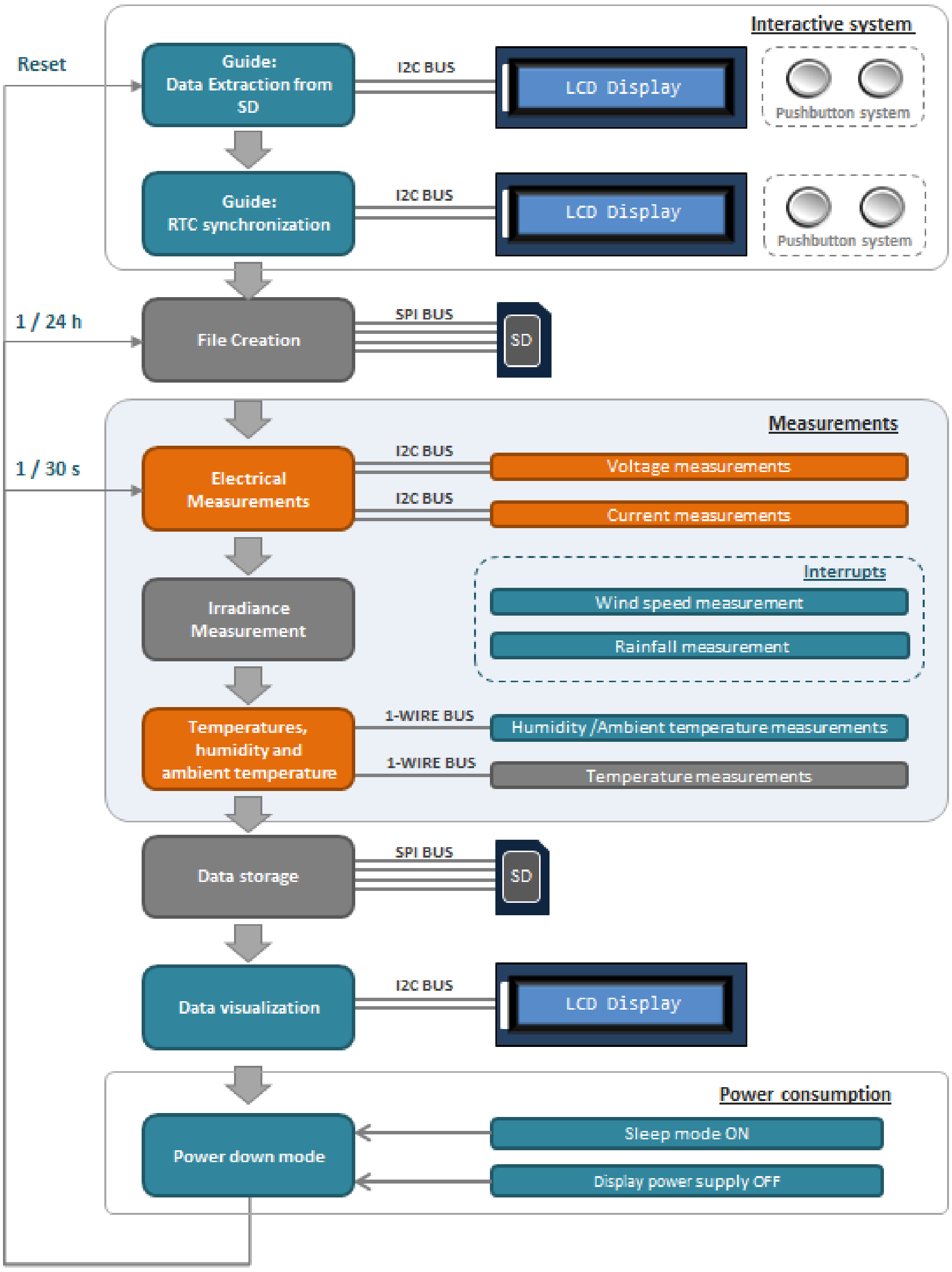


FIGURE 15: Diagram for the routine executed by each iteration: sequence of processes and communications. New processes (blue) and improved processes (orange) over the first prototype of the low-cost datalogger [2] are shown.

c) New climatic measurements have been included: horizontal wind speed and rainfall measurements have been implemented as external interrupts, and the measurement of relative humidity.

d) The process of measuring voltage and current parameters has been improved. The order of magnitude of voltage measurements is greater than the order of magnitude of current measurements. The PGA gain of each one of the ADCs has been configured via software in order to increase the resolution of the current measurements, optimizing the ADCs performance and reducing errors.

Several software strategies have been followed to reduce the power consumption:

a) In order to minimize power consumption via software, the decreasing of clock speed [32] was employed. Clock frequency was set to 1MHz during inactive periods of the microcontroller and default clock frequency, 8MHz, was maintained in the process of measurements. The application of this technique resulted in a power consumption reduction of 10mA (microcontroller), a reduction of 13.85%.

b) Sleep modes [38] were also employed for reducing power consumption: these techniques put the device in a low power state disabling functions in periods of inactivity. The sleep mode was implemented using libraries that disabled the onboard ADC of the Arduino™ UNO and Brown-Out Detection (BOD) by software, saving 23mA of the power consumption (microcontroller), a reduction of 35.38%.

c) Individual techniques based on the management of the LCD power supply were developed. After showing the information, the display was disabled until next cycle for reducing power consumption. A pushbutton connected to D5 pin allowed to switch on /off the display by the user.

4.5. Experimental validation

To verify the correct performance of the new low-cost datalogger under real conditions, a real stand-alone PV system similar to those typically employed in developing countries was installed at the test facilities in IMDEA Water Institute (Madrid, Spain, latitude 40.51° N, longitude 3.34° W).

4.5.1. Experimental set-up

Studies on rural electrification in developing countries and renewable-based initiatives energy programs (see Section 4.2) were reviewed to design the real SAPV system. The final installed stand-alone PV system (Fig.16) included an 80W mono-crystalline module, a 12-V lead-acid battery (90Ah-C100) and a PWM serial charge controller.

FIGURE 16: SAPV system installation: PV mono-crystalline module (a), charge controller (b) and lead-acid battery (c).

Typical domestic energy consumption of a household in developing countries will usually have several lamps for lighting and it might also have a small household appliance (see literature review details in Section 4.2). All the commonly used appliances in terms of power and hours of usage per day were identified for estimating the daily energy consumption used in this work (Table VIII, from literature review).

TABLE VIII: DAILY ENERGY CONSUMPTION ESTIMATION OF A TYPICAL HOUSEHOLD IN DEVELOPING COUNTRIES

	No. Of lamps	Watt per lamp	Watt-lamp	Hours per day	Energy per day [Wh]
Bedroom1	2	3	6	2	12
Bedroom2	2	3	6	2	12
Kitchen	2	5	10	1.5	15
Living room	2	5	10	4	40
Total					**79**

The daily energy distribution in terms of hours per day provided information to estimate the load profile. The load system was composed by two 12-V luminaries of 3W and 50W, respectively. A load management system based on Arduino™ UNO was developed to automate the switching of the lights. An RTC DS1307 was integrated for carrying out the tracking of the time and a relay system composed by four relays allowed the load control.

Fig. 17 shows the final prototype of the new low-cost datalogger including current and voltage sensors.

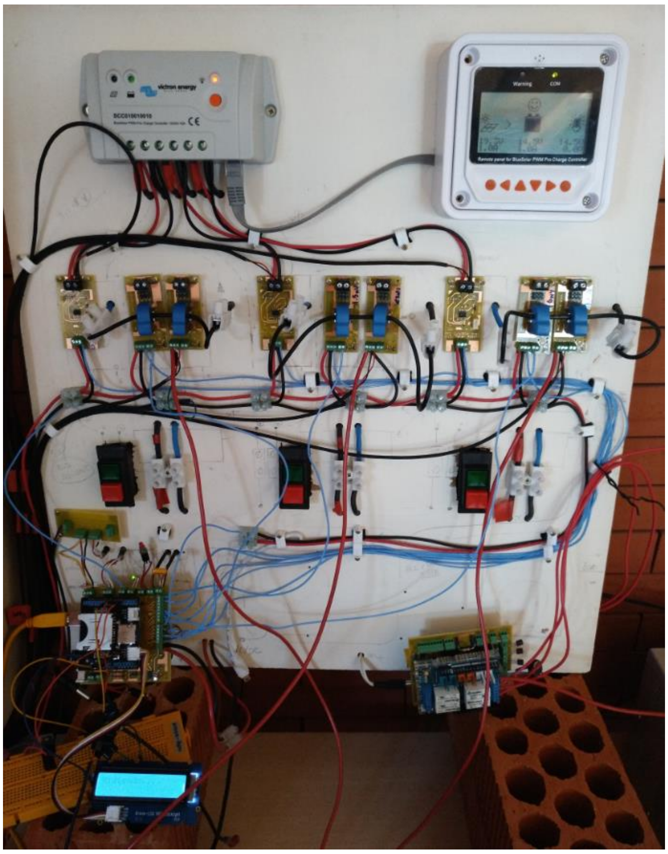


FIGURE 17: Final prototype assembly. The charge regulator uses a control panel for displaying real-time information on the SAPV system. The datalogger shows the information on a LCD display. The datalogger uses 9 small PCBs for electrical sensing (current and voltage measurements). The load control system includes an Arduino™ UNO board and a relay system.

4.5.2. Results

An experimental campaign at IMDEA Water Institute was performed to verify the correct performance of the new low-cost datalogger. The parameters measured by the new low-cost dataloger were compared with a commercial monitoring system that acted as a pattern. This pattern commercial monitoring system is an Agilent^{TM} 34972 datalogger of 22 bits with a voltage accuracy resolution of 0.004% that uses Labview^{TM}. Every 30 s, this datalogger measured and recorded the same parameters as the Arduino^{TM} datalogger.

4.5.2.1. <u>Meteorological data monitoring</u>

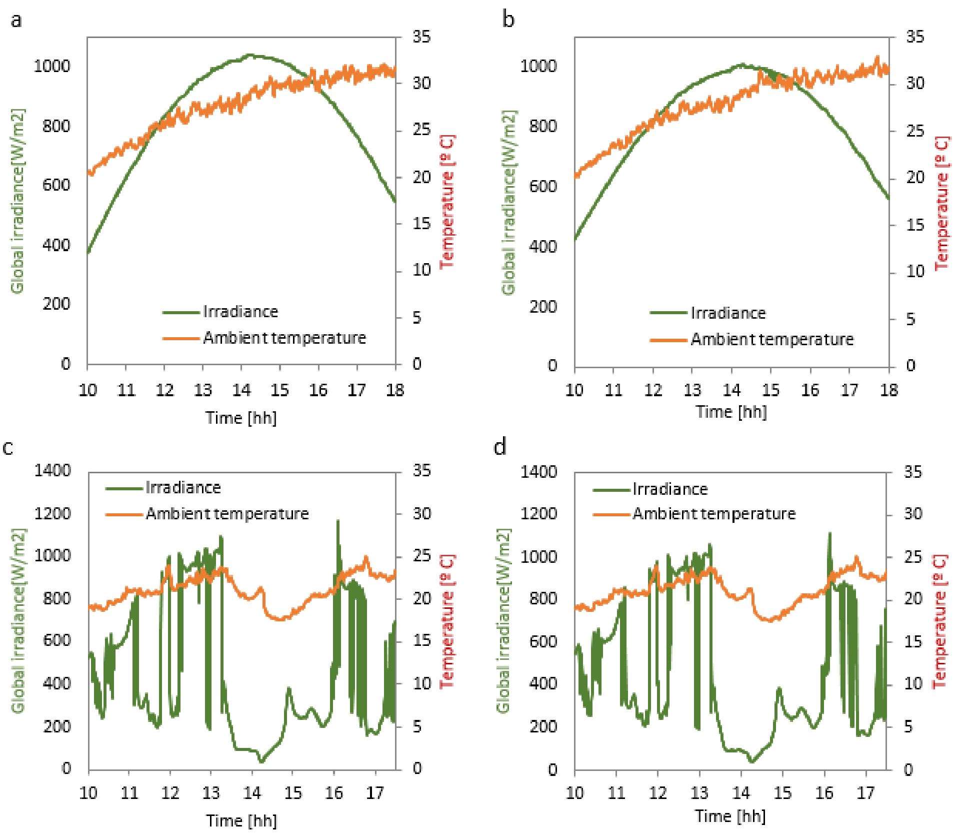


FIGURE 18: Comparison between the irradiance and ambient temperature measured by the Arduino^{TM} datalogger (a) and by the Agilent^{TM} datalogger (b) on 7/6/2017 (clear sky conditions, sunny day). Comparison between the irradiance together with the ambient temperature using the low-cost datalogger (c) and the Agilent^{TM} datalogger (d) on 8/7/2017 (cloudy day).

Climatic parameters measured by the low-cost datalogger were compared to another commercial weather station located at IMDEA Water Institute facilities (Madrid, Spain). The Agilent^{TM} datalogger measured the global solar irradiance using a pyranometer CMP21, Kipp and Zonen^{TM} and the ambient temperature using a PT100 with shield protector. Fig. 18 shows the daily profile of the irradiance and the ambient temperature monitored by the low-cost Arduino^{TM} datalogger and the commercial Agilent^{TM} datalogger. On the left we can observe the results for the low–cost monitoring system and on the right for the Agilent^{TM} datalogger. The irradiance and the ambient temperature measured by the Arduino^{TM} datalogger using low-cost sensors under clear sky conditions (Fig.18a) reveal a good fitting of these parameters with the measurements of the Agilent^{TM} datalogger (Fig. 18b). The Arduino^{TM} datalogger works well under adverse climatic conditions (Fig. 18c) regarding the measurements of the Agilent^{TM} datalogger (Fig. 18d).

Table IX shows the statistical parameters of the root mean square error (RMSE) and the mean bias error (MBE) [12]. Irradiance and ambient temperature measured by the new low-cost datalogger and the commercial datalogger are also compared in cloudy and sunny conditions. The uncertainly of irradiance measures was below the 8% required by the standard. According to IEC standard, the accuracy of ambient temperature measures must be better than ±1 ºC: the mean absolute errors [39] of measured ambient temperatures were 0.02 ºC (clear sky conditions) and 0.015 ºC (cloudy day).

TABLE IX: RESULTS OF THE COMPARISON BETWEEN IRRADIANCE AND AMBIENT TEMPERATURE MEASURED BY THE LOW-COST DATALOGGER AND THE COMMERCIAL DATALOGGER UNDER DIFFERENT CLIMATIC CONDITIONS

	Sunny day		Cloudy day	
	RMSE (%)	MBE (%)	RMSE (%)	MBE (%)
Irradiance	3.038	1.608	4.288	-0.422
Ambient temperature	1.241	-0.440	2.978	-0.334

4.5.2.2. SAPV system parameters monitoring

The electrical data were processed to analyse the performance of the SAPV system. Due to the use of a PWM charge controller, it was convenient to operate with charge parameters instead of energy parameters [40].

Fig. 19 shows the voltages monitored by the low-cost datalogger and the Agilent^{TM} datalogger. It shows the measurements of the PV generator output voltage, the battery voltage and the load voltage. Battery voltage line and load voltage line overlap. Both the voltages measured by the Arduino™ datalogger using low-cost sensors under c lear sky conditions (Fig.19a) and under adverse climatic conditions (Fig. 19c) exhibit a good fit regarding these voltage parameters with the Agilent™ datalogger measurements (Fig. 19b and Fig. 19d respectively), demonstrating the correct functioning of the Arduino™ datalogger under different climatic conditions.

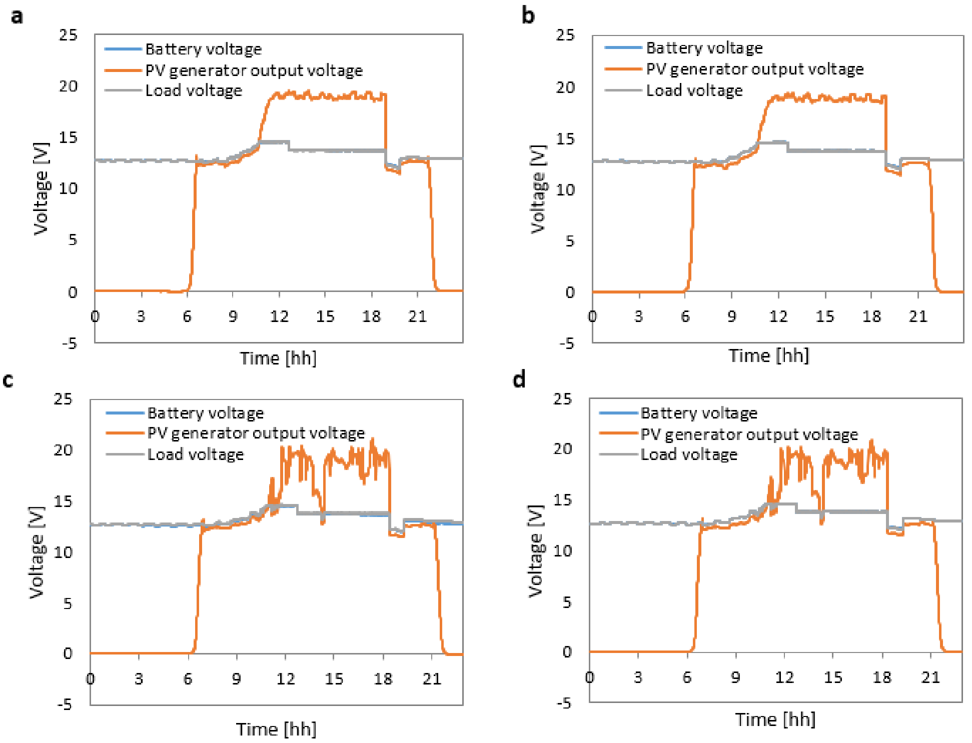


FIGURE 19: Comparison between the voltages measured by the low-cost datalogger (a) and the Agilent™ datalogger (b) on 7/6/2017 (clear sky conditions, sunny day). Comparison between the voltages measured by the Arduino™ datalogger (c) and the Agilent™ datalogger (d) on 8/7/2017 (cloudy day).

Fig.20 shows the measurements of the PV generator out current, the battery current and the load current. Negative values of currents mean the supply of power. Positive values mean the consumption of power. The data taken by the Arduino™ datalogger under clear sky conditions (Fig. 20a) show the good fitting of the current parameters with the measurements of the Agilent™ datalogger (Fig. 20b). The data taken by the Arduino™ datalogger (Fig. 20c) also reveal a good fit regarding these current parameters with the Agilent™ datalogger measurements (Fig.20d) under adverse climatic conditions.

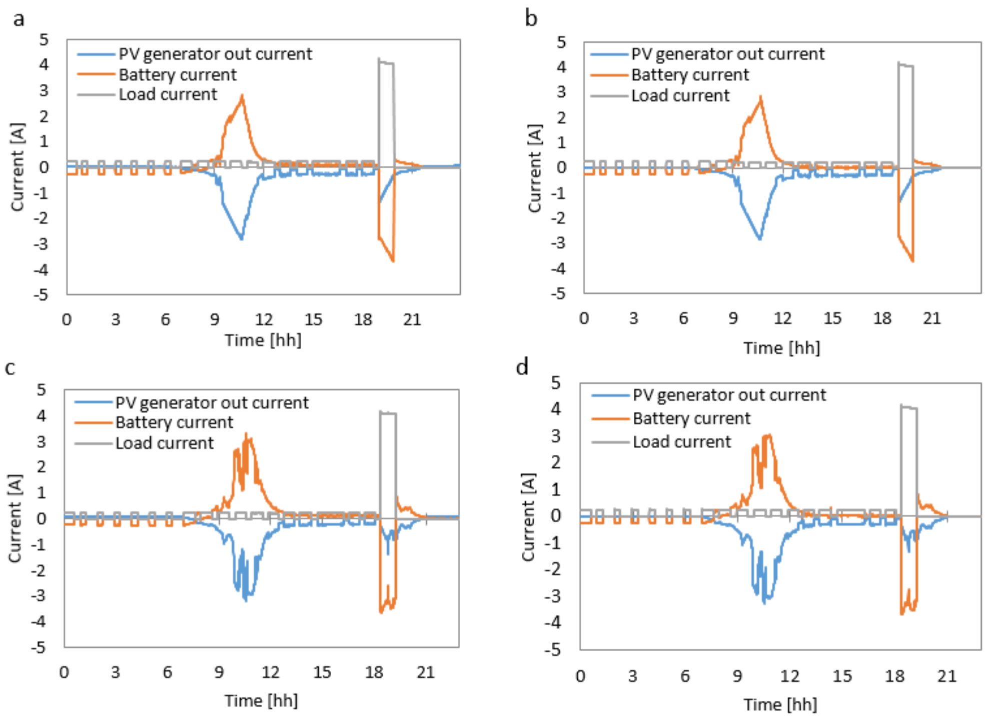


FIGURE 20: Comparison between the currents measured by the low-cost datalogger (a) and the Agilent™ datalogger (b) on 7/6/2017 (sunny day). Comparison between the currents measured by the low-cost datalogger (c) and the Agilent™ datalogger (d) on 8/7/2017 (cloudy day).

Table X shows the statistical parameters of the normalized root mean squared error (NMRSE), which provide a global error measure during the entire forecasting period [39] for electrical measurements.

TABLE X: RESULTS OF THE COMPARISON BETWEEN THE ELECTRICAL PARAMETERS MEASURED BY THE LOW-COST DATALOGGER AND THE COMMERCIAL DATALOGGER. THE UNCERTAINLY WAS BELOW THE 2% REQUIRED BY THE STANDARD

	NRMSE (%) in a sunny day	NMRSE (%) in a cloudy day
PV generator output voltage	0.139	0.889
Battery voltage	0.033	0.639
Load voltage	0.049	0.083
PV generator out current	0.161	0.566
Battery current	0.299	0.805
Load current	0.038	0.758

The battery temperature, the module temperature and the ambient temperature monitored by the low-cost datalogger (a, c) and the Agilent™ datalogger (b, d) are shown in Fig. 21. Back module temperature and battery temperature were measured by the Agilent™ datalogger using flat PT100 sensors located at their back part. Temperatures measured by the Arduino™

datalogger using low-cost sensors under clear sky conditions (Fig.21a) and under adverse climatic conditions (Fig. 21c) show a good fit regarding these temperature parameters with the Agilent^{TM} datalogger measurements (Fig. 21b and Fig.21d respectively). It demonstrates the correct functioning of the Arduino^{TM} datalogger under different climatic conditions.

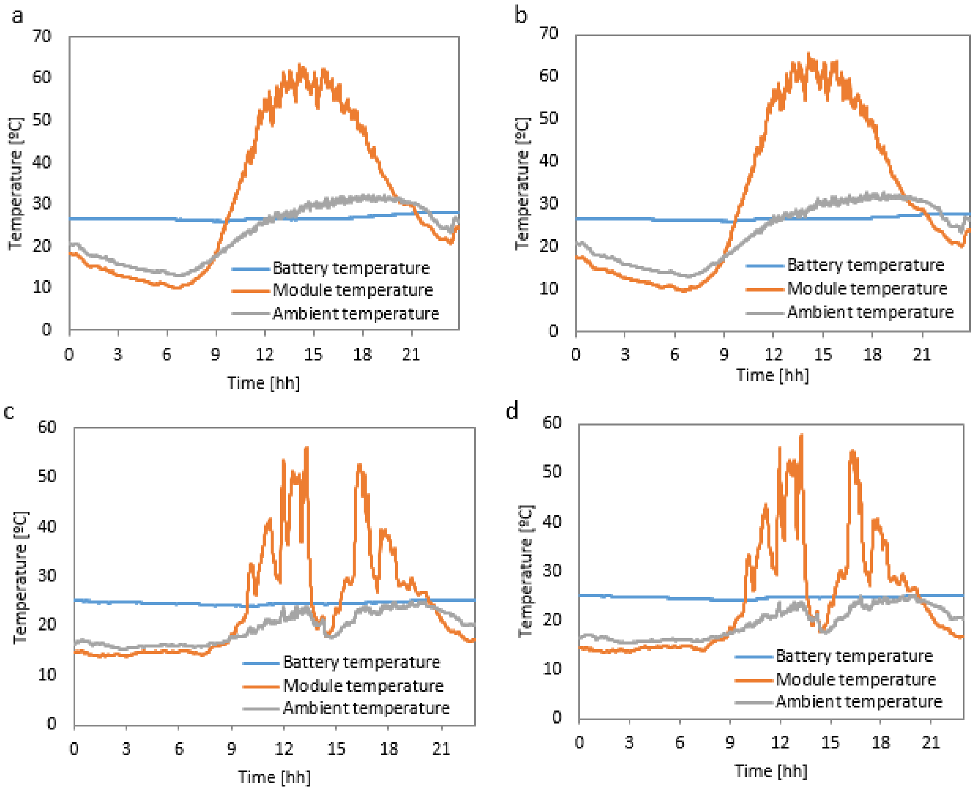


FIGURE 21: Comparison between temperatures (T_{mod}, T_{bat}, T_{amb}) measured by the low-cost datalogger (a) and the pattern commercial system (b) on 7/6/2017.This day was a sunny day. Comparison between temperatures (T_{mod}, T_{bat}, T_{amb}) measured by the low-cost datalogger (c) and the pattern commercial system (d) on 8/7/2017.This day was a cloudy day.

Table XI shows the statistical parameters of the root mean square error (RMSE) and the mean bias error (MBE) [12]. PV module temperature and battery temperature measured by the low-cost datalogger and the commercial datalogger are compared. According to IEC standard, the accuracy of PV module temperature measures must be better than ±2 ºC: the mean absolute errors of measured PV module temperatures were 0.781 ºC (clear sky conditions) and 0.295 ºC (cloudy day). The mean absolute errors of measured battery temperatures were 0.225 ºC (sunny day) and 0.016 ºC (cloudy day).

TABLE XI: RESULTS OF THE COMPARISON BETWEEN THE ELECTRICAL PARAMETERS MEASURED BY THE LOW-COST DATALOGGER AND THE COMMERCIAL DATALOGGER. THE UNCERTAINLY WAS BELOW THE 2% REQUIRED BY THE STANDARD.

	Sunny day		Cloudy day	
	RMSE (%)	MBE (%)	RMSE (%)	MBE (%)
Battery temperature	0.642	0.435	2.808	-0.038
PV module temperature	3.323	-0.266	3.498	-0.479

4.6. Costs

The aim of this work was to develop a new prototype of a datalogger that is low-cost, accurate and autonomous. The budget of the monitoring system is described in Table XII. The final cost of the new prototype, including high voltage and current sensing, was approximately 81€.

TABLE XII: BUDGET FOR THE NEW LOW-COST DATALOGGER .

	Components	Price[€]
Arduino™ UNO	Stocked board	17.95
Memory board	Stocked board	1.55
	SD memory card	3.96
Visualization module	LCD 16x2	3.46
ADC Board	2 MCP3424	6.84
	RTC DS1307	1.58
	Precision resistors, Capacitors	1.80
	Wires, connectors	0.70
Pushbutton System	Switch	0.32
	2 Pushbuttons	0.40
Power consumption	NPN transistor	0.29
Adaptor for high current sensing	3 LTS-15NP LEM	18.86
	9 Resistors SMD	5.40
	3 Voltage reference	2.79
Adaptor for high voltage sensing	3 Differential Amplifiers	11.31
	6 Resistors SMD	3.60
	TOTAL	**80.81**

Table XIII shows the budget for the low cost sensors. The budget of low-cost sensors (including the low-cost weather station) was approximately 268€. Total costs could be reduced considerably when mass produced and introduced in the market.

TABLE XIII: BUDGET FOR LOW COST SENSORS AND LOW-COST WEATHER STATION COMPONENTS

Components		Price[€]
3 Digital temperature sensors DS18B20		10.50
Irradiance sensor		39.90
Rain gauge sensor		35.20
Anemometer		120.00
Temperature and humidity sensor DHT22		2.69
Solar radiation shield for temperature sensor		59.88
	TOTAL	**268.17**

4.7. Conclusions

A new low-cost datalogger logger intended for stand-alone PV systems in developing countries meeting the accuracy requirements established by the IEC61724 standard related to photovoltaic monitoring system was presented. A real stand-alone PV system including the corresponding load system and the most common characteristics of the SAPV system used in developing countries was installed for testing and validating the new low-cost datalogger under real conditions.

The new prototype of the low-cost datalogger improved the measurement of climatic conditions and the measurement of SAPV system parameters employing exclusively low-cost sensors. The monitoring system included a wide range of climatic measures: irradiance, temperatures, humidity, horizontal wind speed and rainfall. Voltage and current parameters were monitored using improved amplifiers, voltage dividers, and Hall-Effect sensors to adapt the measurement to the designed monitoring system. The SD data storageallowed to keep collected data and to work autonomously in areas deprived of telecommunications networks, requiring minimal maintenance. In addition, measures were shown on a LCD screen and an interactive system based on a display and a pushbutton system allowed the user to control internal processes such as data extraction from SD card and RTC synchronization. Total power consumption of the datalogging system was minimized by applying specific techniques to reduce both sensors and microprocessor board power consumptions.

An outdoor campaign of over one month at IMDEA Water Institute, in Alcalá de Henares (Madrid, Spain), was performed to test the new low-cost datalogger. The comparison of the results with those of other monitoring systems demonstrated compliance with the IEC61724 standard, monitoring all of the requested parameters with high accuracy.

In addition, after demonstrating the good accuracy of the low-cost datalogger and sensors, a network using an expanded version of the presented monitoring system (wireless) was installed under outdoor conditions demonstraing the robutness and fiability [41].

4.8. References

[1] R. Mukaro, X. Carelse, and L. Olumekor, First performance analysis of a silicon-cell microcontroller-based solar radiation monitoring system, Sol. Energy, vol. 63, no. 5, pp. 313–321, Nov. 1998.

[2] E. Koutroulis and K. Kalaitzakis, Development of an integrated data-acquisition system for renewable energy sources systems monitoring, Renew. Energy, vol. 28, no. 1, pp. 139–152, 2003.

[3] G. M. Tina and A. D. Grasso, Remote monitoring system for stand-alone photovoltaic power plants: The case study of a PV-powered outdoor refrigerator, Energy Convers. Manag., vol. 78, pp. 862–871, 2014.

[4] F. Touati, M. A. Al-Hitmi, N. A. Chowdhury, J. A. Hamad, and A. J. R. San Pedro Gonzales, Investigation of solar PV performance under Doha weather using a customized measurement and monitoring system, Renew. Energy, vol. 89, pp. 564–577, 2016.

[5] M. Benghanem, Low cost management for photovoltaic systems in isolated site with new IV characterization model proposed, Energy Convers. Manag., vol. 50, no. 3, pp. 748–755, Mar. 2009.

[6] M. Demirtas, I. Sefa, E. Irmak, and I. Colak, Low-cost and high sensitive microcontroller based data acquisition system for renewable energy sources, 2008 Int. Symp. Power Electron. Electr. Drives, Autom. Motion, pp. 196–199, 2008.

[7] M. Benghanem and A. Maafi, Performance of stand-alone photovoltaic systems using measured meteorological data for Algiers, Renew. Energy, vol. 13, no. 4, pp. 495–504, Apr. 1998.

[8] M. Benghanem, A. H. Arab, and K. Mukadam, Data acquisition system for photovoltaic water pumps, Renew. Energy, vol. 17, no. 3, pp. 385–396, Jul. 1999.

[9] M. Benghanem, Measurement of meteorological data based on wireless data acquisition system monitoring, Appl. Energy, vol. 86, no. 12, pp. 2651–2660, Dec. 2009.

[10]A. Purwadi, Y. Haroen, F. Y. Ali, N. Heryana, D. Nurafiat, and A. Assegaf, Prototype development of a Low Cost data logger for PV based LED Street Lighting System, Proc. 2011 Int. Conf. Electr. Eng. Informatics, no. July, pp. 1–5, 2011.

[11]M. Ikhsan, A. Purwadi, N. Hariyanto, N. Heryana, and Y. Haroen, Study of Renewable Energy Sources Capacity and Loading Using Data Logger for Sizing of Solar-wind Hybrid Power System, Procedia Technol., vol. 11, no. Iceei, pp. 1048–1053, 2013.

[12]M. Fuentes, M. Vivar, J. M. Burgos, J. Aguilera, and J. A. Vacas, Design of an accurate, low-cost autonomous datalogger for PV system monitoring using ArduinoTM that complies with IEC standards, Sol. Energy Mater. Sol. Cells, vol. 130, pp. 529–543, Nov. 2014.

[13]T. Kulworawanichpong and J. J. Mwambeleko, Design and costing of a stand-alone solar photovoltaic system for a Tanzanian rural household, Sustain. Energy Technol. Assessments, vol. 12, pp. 53–59, 2015.

[14]A. El Fathi, L. Nkhaili, A. Bennouna, and A. Outzourhit, Performance parameters of a standalone PV plant, Energy Convers. Manag., vol. 86, pp. 490–495, 2014.

[15]D. O. Akinyele and R. K. Rayudu, Strategy for developing energy systems for remote communities: Insights to best practices and sustainability, Sustain. Energy Technol. Assessments, vol. 16, pp. 106–127, 2016.

[16]G. D. Kamalapur and R. Y. Udaykumar, Rural electrification in India and feasibility of Photovoltaic Solar Home Systems, Int. J. Electr. Power Energy Syst., vol. 33, no. 3, pp. 594–599, 2011.

[17]R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, Off-Grid Renewable Energy Systems: Status and Methodological Issues, International Renewable Energy Agency, 2015.

[18]< http://www.gshakti.org > (accessed 30.12.18).

[19] < http://anert.gov.in/index.php?option=com_content&view=article&id=9&Itemid=4> (accessed 28.12.18).

[20] < http://mnre.gov.in > (accessed 28.12.18).

[21]<http://www.thriveenergy.co.in/subsidy-schemes/mnre-nabard-solar-home-lighting> (accessed 30.12.18).

[22] < http://kerea.org > (accessed 30.12.18).

[23]U.E. Hansen, M.B. Pedersen and I. Nygaard, Review of Solar PV Market Development in East Africa, UNEP Risø Centre UNEP Risø Cent. Work. Pap. Ser., no. 12, 2014.

[24]Luz en casa – Case study, Fundación ACCIONA ,2014 < http://www.accioname.org/ > (accessed 30.12.18).

[25]Y. E. Abu, N. H. Saad, and A. Zekry, Enhancing the design of battery charging controllers for photovoltaic systems, Renew. Sustain. Energy Rev., vol. 58, pp. 646–655, 2016.

[26]N.J. Williams, E. Ernest van Dyk, F.J. Vorster, Monitoring solar home systems with pulse width modulation charge control. J Sol Energy Eng 2011;133:021006- 1–021006-7.

[27]F. D. J. Nieuwenhout, A. Van Dijk, P. E. Lasschuit, G. Van Roekel, V. A. P. Van Dijk, D. Hirsch, H. Arriaza, M. Hankins, B. D. Sharma, and H. Wade, Experience with solar home systems in developing countries: A review, Prog. Photovoltaics Res. Appl., vol. 9, no. 6, pp. 455–474, 2001.

[28]< http://sollatek.co.ke/shop/solar-lighting/solarhomekit/ > (accessed 30.12.18).

[29]IEC61724-1. Photovoltaic System Performance- Part 1: Monitoring. 1st Ed., International Electrotechnical Commission (IEC), Switzerland, Geneva, 2017.

[30]Commission of the European Communities. Photovoltaic System Monitoring, Documents A & B, version 4.3 ed., Guidelines for the Assessment of Photovoltaic Plants; 1997.

[31]ICT facts and Figures 2016, International Telecommunication Union <https://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2016.pdf > (accessed 30.12.18).

[32] < https://www.arduino.cc > (accessed 30.12.18).

[33]K. M. Lynch, N. Marchuk, and M. L. Elwin, SPI Communication, Embed. Comput. Mechatronics with PIC32, pp. 177–190, 2016.

[34]IEC, Photovoltaic Devices: Requirements for Reference Solar Devices, 2nd Ed., International Electrotechnical Commission (IEC), Switzerland, Geneva, 2007 (60904-2).

[35]IEC, Photovoltaic Devices. Requirements for Reference Solar Modules, 1st Ed., International Electrotechnical Commission (IEC), Switzerland, Geneva (1994) 60904–60906.

[36] < http://pronamic.com/products/rain-o-matic-small > (accessed 30.12.18).

[37] < https://www.maximintegrated.com > (accessed 21.06.17).

[38]S. Monk, Programming Arduino Getting Start With Sketches, McGraw-Hill, 2011.

[39]J. Zhang, A. Florita, B. Hodge, S. Lu, H. F. Hamann, V. Banunarayanan, and A. M. Brockway, A suite of metrics for assessing the performance of solar power forecasting, Sol. Energy, vol. 111, pp. 157–175, 2015.

[40]F.J.Muñoz, G. Almonacid, G. Nofuentes, and F. Almonacid, A new method based on charge parameters to analyse the performance of stand-alone photovoltaic systems, Sol. Energy Mater. Sol. Cells, vol. 90, pp. 1750–1763, 2006.

[41]A. López-Vargas, M. Fuentes and M. Vivar, "IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino™ With 3G Connectivity," in IEEE Sensors Journal, vol. 19, no. 2, pp. 679-691, 15 Jan.15, 2019.

Chapter 5

IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino^{TM} with 3G Connectivity

A. López-Vargas, M. Fuentes and M. Vivar, "IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino™ With 3G Connectivity," in IEEE Sensors Journal, vol. 19, no. 2, pp. 679-691, 15 Jan.15, 2019. Impact factor (2018): 3.076. Instruments & Instrumentation (2018): 13/61 (Q1).

5.1. Introduction

An estimated 1.1 billion people currently lack electricity access [1], mainly residing in rural areas of sub-Saharan Africa and Southeast Asia, and, to a lesser extend in the Middle East, Central Asia and Latin America [2]. Due to the emergence of rural electrification programmes, thousands of Solar Home Systems (SHSs) [3] are installed in remote regions, commonly in locations with no electrical grid, no traditional wired telecommunication networks and often with difficult accessibility by common transport. SHSs are stand-alone PV (SAPV) systems. Typically, these installations use crystalline-silicon PV modules. Regarding the battery backup unit, the most commonly battery type installed is lead-acid and most small SHS employs charge controllers using PWM to regulate the charge current to the battery [4].

The absence of adequate monitoring of SHS and, therefore, the impossibility of detecting operation and maintenance problems, can lead to a dramatic shortening of the useful life of the PV systems or even to the withdrawal of their use. [5].In the case of grid-connected PV systems generally have high budgets, and the associated data acquisition systems allow to monitor the main parameters to conduct the necessary maintenance actions without impacting significantly in the total installation cost. However, it is very difficult to supervise the operation of SHSs due mainly to the fact that the required commercial dataloggers available in the market are very expensive compared to the total system cost, they require special software and they also generally demand an external power supply or a PC to be connected all of the time.

As a result, it is necessary to further develop data acquisition systems very accurate and independent of external sources, all at low cost. In recent years, analytical monitoring has been progressively applied to small PV systems.

5.2. Related works on dataloggers for PV monitoring

The literature includes numerous reports of PV monitoring systems during the last two decades. Mukaro et al. [6] in 1998 developed one of the first low-cost systems designed for solar radiation monitoring. With 4 analogue inputs, this monitoring system was based on an 8-bit microcontroller. This datalogger was suitable for monitoring of meteorological parameters at remote stations, especially in developing countries. The main disadvantage of this work was the connection of the datalogger to PC. Koutroulis and Kalaitzakis [7] in 2003 reported another monitoring system for renewable energy sources. With 16 single ended (eight differential analog) input channels, the datalogger used a DAQ card installed in a PC and a 12-bit accuracy ADC converter. As a disadvantage, the dependence on a PC and the use of commercial software increased the final cost of the system. Forero et al. [8] in 2006 proposed a system for monitoring a stand-alone PV plant. The system was designed for measuring environmental variables, as well as for monitoring the performance of a stand-alone PV solar plant. The datalogger was based on precision electronic modular field point I/O devices and a high speed data acquisition card. The main inconveniences were the use of a graphical environment based on the Labview™ program and the requirement of a PC connection. Tina and Grasso [9] in 2014 proposed a dedicated data acquisition system for remote monitoring the operation of a stand-alone PV appliance. With 20 analog inputs, the monitoring system measured electrical and climatic parameters using low-cost commercial sensors. However, measurements were not compared with another calibrated datalogger and the errors were not weighted. After reviewing the published literature, it was identified that it is difficult to track the functioning of these SAPV systems with conventional dataloggers mainly due to various limitations:: external source dependency [10-13], requirement of commercial software [14, 15] and in numerous designs the measurement of errors were not bounded following international standards of accuracy [16, 17].

To solve the former technical and economic issues, a low-cost prototype based on open source and free hardware technologies (Arduino™) for monitoring PV systems was proposed by M. Fuentes et al. [18] in 2014. With 8 analogue inputs for measuring up to 8 electrical/meteorological parameters and 3 inputs for low-cost analogue temperature sensors, the resolution of the datalogger was 18-bits. Virtually unlimited inputs for digital temperature sensors were available. The datalogger was especially designed for installing in remote areas or regions in developing countries. The datalogger was tested under the harsh environmental conditions of the summer and winter in Southern Spain and it accomplished the accuracy requirements of the IEC standards for PV systems. Later on, López-Vargas et al. [19] in 2018 developed an improved version of this low-cost datalogger in order to overcome several of the shortcomings of the solar Arduino™ datalogger, and so the power consumption was minimized, the number of meteorological parameters measured was increased, the electrical measurements were improved and a user-friendly interface was integrated. The new prototype was specifically designed for SAPV systems located in remote areas. The new datalogger was empirically tested measuring a real stand-alone system. The results indicated that the datalogger provided high accuracy, and it was autonomous, low-cost and robust in harsh environments. Data was stored in

SD card, allowing the installation of the system in isolated areas, requiring minimal maintenance. But this minimal maintenance of the novel datalogger was based on a manual procedure requiring human operator intervention for collecting data, which can be an inconvenient at locations that are difficult to access as well as it increases the maintenance costs and operation.

TABLE XIV: PARAMETERS TO BE MONITORED IN REAL TIME PV SYSTEMS

General parameters	Specific parameters	Symbol
Meteorology	Total irradiance, in the plane of the array	G_i
	Ambient temperature in a radiation shield	T_{amb}
	Wind speed (optional)	-
	Rainfall (optional)	-
	Humidity (optional)	-
PV array	Output voltage	V_A
	Output current	I_A
	Output power	P_A
	PV module temperature	T_{mod}
Energy storage	Operating voltage	V_S
	Current to storage[a]	I_{TS}
	Current from storage[a]	I_{FS}
	Power to storage[a]	P_{TS}
	Power from storage[a]	P_{FS}
Load	Load voltage	V_L
	Load current	I_L
	Load power	P_L
Utility grid	Utility voltage	V_U
	Current to utility grid[a]	I_{TU}
	Current from utility grid[a]	I_{FU}
	Power to utility grid[a]	P_{TU}
	Power from utility grid[a]	P_{FU}
Back-up sources	Output voltage	V_{BU}
	Output current	I_{BU}
	Output power	P_{BU}

The objective of this new work has been to develop a novel and improved version of this solar Arduino^{TM} low-cost datalogger based on the application of IoT (Internet of the Things), adding internet connectivity and allowing the

SAPV system to be monitored remotely via web or via mobile application, which means that not only data of the long-term system performance is retrieved but also that instantaneous information is received and so the problems related to the operation and maintenance of the stand-alone PV system can be rapidly detected and solved. Additionally, another novelty of this work lies in designing, manufacturing and testing the prototype under real (electrical and environmental) working conditions.

5.3. Requirements for the SAPV electrical performance monitoring system

The IEC61724 standard [20] entitled "Photovoltaic system performance" describes the general guidelines for the monitoring and analysis of the electrical performance of photovoltaic systems (stand-alone and grid connected). In Table XIV, a summary of parameters to be monitored in real time PV systems is presented.

The standard defines three classes of monitoring systems, corresponding to different levels of accuracy and different intended applications: Class A (high accuracy), Class B (medium accuracy) and Class C (basic accuracy). The accuracy classification and the suggested applications are presented in Table XV.

TABLE XV: MONITORING SYSTEM CLASSIFICATION AND SUGGESTED APPLICATIONS

Typical applications	Class A: High accuracy	Class B: Medium accuracy	Class C:Basic accuracy
Basic system performance assessment	x	x	x
Documentation of a performance guarantee	x	x	
System losses analysis	x	x	
Electricity network interaction assessment	x		
Fault localization	x		
PV technology assessment	x		
Precise PV system degradation measurement	x		

According to IEC61724 standard, Class B or Class C would be most appropriate for small systems, such as smaller commercial and residential installations. An example of the IEC61724 standard appliance for SAPV systems is shown in Fig.22.

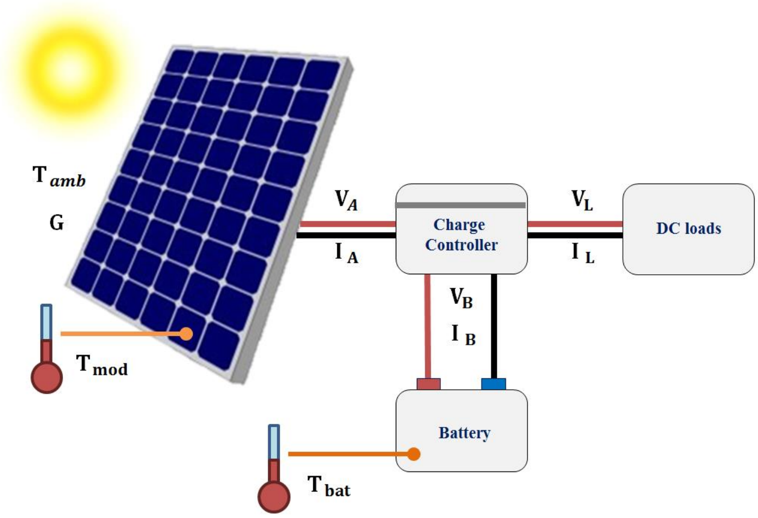


FIGURE 22: Example of application of the IEC61724 standard: SAPV system.

5.3.1. Electrical and climatic parameters

The measurements of electrical parameters provide information on the consumption and the efficiency of SAPV systems. According to IEC61724 standard, the accuracy (the most restrictive case, high accuracy class) of the voltage, current and power measurements, including signal conditioning, must be better than 2% of the reading. IEC61724 standard indicates that climatic parameters must be measured at a location that is representative of the SAPV system conditions. The accuracy of temperature measures must be better than ±1 ºC and the accuracy of irradiance measures must be better than 8% of the reading from 100 W·m^{-2} to 1,500 W·m^{-2} (including signal conditioning). The measurement of optional parameters such as wind speed, also must comply the standard requirements of accuracy: ≤ 0. 5 m·s-1 for wind speeds ≤ 5 m·s-1, and ≤ 10 % of the reading for wind speeds greater than 5 m·s-1. According to the results obtained by López-Vargas et al. in 2018 [19], the previous version of the datalogger [19] met all the precision requirements established by the IEC61724 standard mentioned above.

5.3.2. Monitoring requirements

According to IEC61724 standard, for medium and basic accuracy systems (Class B and Class C, as indicated earlier), the maximum sampling interval should be 1 min and maximum recording interval should be 15 min (medium accuracy) and 60 min (basic accuracy). The recording interval should be an integer multiple of the sampling interval, and an integer number of recording intervals should fit within 1 h. Each record shall include a timestamp, and the time should refer either to local time (not daylight saving time) or universal time, to avoid winter/summer time changes. When multiple data acquisition units are involved that each independently apply timestamps, the clocks of the units must be synchronized, preferably by an automated mechanism such as global positioning system (GPS) or network time protocol (NTP).

To be able to apply the automated synchronization mechanisms advised by the IEC61724 standard, the connection to the Internet is required. To access the Internet, the standard does not set any requirements concerning the type of communication method. However, in the case of decentralized systems, wireless technologies are most appropriate: commonly SAPV systems are located in remote and inaccessible regions, in locations without access to traditional wired telecommunication networks. The datalogger should be able to transmit the measured data anywhere; the location of the SAPV system should not act to the detriment of the correct functioning of the monitoring system. The communication technology should be capable of operating autonomously, without requiring additional wired communications networks. To obtain real-time monitoring, the delivery speed of the data transmission system should allow compliance with the sampling intervals established by the IEC61724 standard.

5.4. SAPV monitoring system connectivity

Among all the different standards deployed in the market [21], usually distributed in different frequency bands and using multiple communication protocols, selecting the most suitable connectivity technology for an IoT application can be a challenge. Wireless technologies have been widely used in the case of decentralized systems, although Ethernet cable is also an alternative for centralized systems [22]. As there are different options to add wireless connectivity to the Arduino™ solar datalogger, previous PV monitoring wireless systems according to their data transmission techniques have been reviewed. The connectivity requirements of different types of IoT networks vary widely, depending on their purpose and resource constraints. Relevant wireless communications techniques have been studied: Table XVI [23] shows a wireless connectivity technologies (non-exhaustive) comparison focused on range, bandwidth and cost.

TABLE XVI: CHARACTERISTIC OF WIRELESS CONNECTIVITY TECHNOLOGIES (DATA SOURCE ITU [23])

Type	Technology	Maximum range	Maximum bandwidth	Module cost
WPAN	ANT+	30 m	1 Mbps	$1 - $15
	Bluetooth 4.0 LE	50 m	24 Mbps	$1 - $15
	RFID	10 m (passive) 100 m (active)	100 kbps	<$1 - $15 (passive) $5 - $25 (passive)
	NFC	10 cm	424 kbps	<$1
	802.15.4g	200 m	200 kbps	$1 - $15
	ZigBee	10 m -100 m	250 kbps	$1 - $15
WLAN	Wi-Fi	300 m	250 Mbps (802.11n) 54 Mbps (802.11a/g) 11 Mbps (802.11b) 1 Gbps (802.11ac)	$10+
WWAN	LoRa	2 – 10 km	200 kbps	$1 - $15
	Weighless	2 – 10 km	200 kbps	$1 - $15
	Dash 7	2 km	200 kbps	$1 - $15
	WiMax	40 km	34 Mbps – 1Gbps	$1 - $15
	2G (GSM, GPRS, EDGE)	35 km	9,6 kbps – 384kbps	$1 - $15
	3G (UMTS, HSPA)	up to 100 km	384 kbps– 10 Mbps	$35 - $50
	Cellular 4G/LTE	up to 100 km	3 Mbps – 100 Mbps	$80 - $120

A remote PV-system monitored via satellite was developed by Krauter and Depping [24] in 2004, where irradiance and electrical parameters were collected and sent to the ARGOS-SCD satellite. The satellite data was transferred from the receiving ground station to the Internet, providing worldwide access via WWW. Data transmission via satellite is very useful in regions without access to telephone communications. But this data transmission was reported to be slow, taking around 8 to 12 min, and the initial cost for the transmitter was very high.

Papageorgas et al. [25] in 2013 reported a solar panel monitoring system based on Zigbee. The system measured data for each solar panel of a solar park installation and allowed the optimization of electric power production through a web-based application. The client-server-web-publishing software was based on an open-source platform. The integrated Zigbee communication technology was based on a Zigbee RF modem available from ATMEL. However, the system required a wired network due to this technology only covers short distances. The same applies to the Bluetooth technologies that support simple wireless networking but only cover short distances (100 m is the maximum range without repeaters [26]) as reported by Hua et al. [27] in 2009: typically up to 10 m for Bluetooth class 2 and 100 m for Bluetooth class 1. A series of novel wireless portable systems including calibration, monitoring and ISP systems were implemented for fuel cell city buses, using Bluetooth for transmitting data.

Rosiek and Batlles [28] in 2008 developed a system for the data acquisition from remote meteorological stations located in the north side of the Natural Park of Sierra Nevada (Granada, Spain). The system was based on an ATmega16 microcontroller and they compared this system against two other commercial acquisition systems obtaining an error in the order of 1 %. They used mobile communications due to the considerable advantages in transmitting the information at big distances in isolated areas. The experimental data was received from the remote stations network, located about 100 km of distance.

Due to the location of PV systems in isolated regions, the study of communication techniques focused on technologies that provide greater ranges (WWAN). The use of mobile communications (2G, 3G) ensures an affordable and stable long-distance data transfer, but the effectiveness of this technique is subject to the signal strength in the location of the stand-alone PV system. The International Telecommunication Union (ITU) [29] in 2016 estimated that approximately seven billion people, the 95 % of the global population, live in an area that is covered by a mobile network. Regarding the mobile-broadband networks (3G or above) they reach 84 % of the global population, 67 % of the rural population [29].

On the other hand, a clear signal of the global mobile penetration rate is that in developing countries, there are more households that own a mobile phone that have access to electricity or drinking water: roughly 70 % of the bottom fifth of the population in developing countries own a cell phone, as reported by the World Bank's World Development Report for 2016 [30]. According to a Groupe Speciale Mobile Association (GSMA) report [31], in 2014, more than a half of all global mobile money deployments were carried out in sub-Saharan Africa. The 63 % of Africans had access to improved water supply and 32 % to electricity, compared to 82 % who had access to GSM coverage. A United Nations research in India [32], in 2008, showed nearly 366 million people (31 % of the population) had access to improved sanitation, meanwhile, 545 million mobile phones were connected to service.

After studying the available wireless techniques, the use of mobile communications was selected for adding wireless connectivity to the Arduino™ datalogger, since this technology presents more advantages than the other communication techniques studied and both, industrialized countries and developing countries, are covered by mobile communications networks, even reaching areas where the electric grid and the water supply network do not. In addition, other studies endorse the use of mobile communications for this specific application. In 2014, R. Tejwani et al. [33] presented the advantages and disadvantages of several monitoring systems for rural application based on different techniques of communication. After discussing, they proposed remote monitoring using mobile communications. In 2017, V. Villagrán et al. [34] presented the design and implementation of monitoring system to study down-slope winds in the Laja River Valley, southern-central Chile. They used mobile communications because of the continued growth of the mobile telecommunication industry, its coverage has also expanded in Chile, even in remote areas inhabited by small communities.

5.5. Design of the 3G datalogger for solar photovoltaic monitoring

5.5.1. General description

Fig.23 shows the diagram of the new wireless monitoring system as well as the basic distribution of environmental and electrical sensors for monitoring the SAPV system. The new datalogger measures meteorological and electrical parameters; data is sent via 3G and information is stored in two different servers: a dedicated server (located in the University of Jaén) and a cloud server (free storage platform). The connection to the internet allows to monitor the SAPV system from any device or computer.

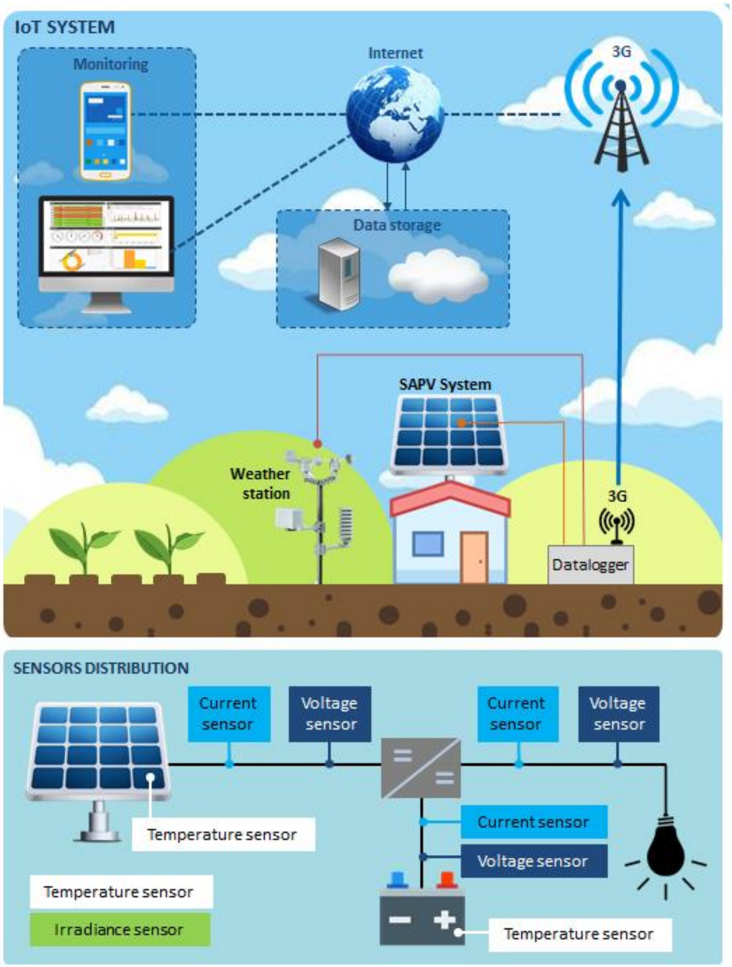


FIGURE 23: Final remote datalogger diagram

5.5.2. Hardware

The previous datalogger was designed around the Arduino™ UNO board as it stands out in comparison with the other open-source platforms due to its robustness, cost and developer community [18]. However, it did not cover all the functionalities for PV monitoring itself, so hardware enhancement was integrated by López-Vargas et al. [19] integrated in an ad-hoc PCB (Printed Circuit Board): (a) a bi-directional I2C™ bus, (b) sensors signal conditioning including the integration of electronic elements for filtering undesirable signals, (c) a RTC for tracking time and ensuring the precise synchronization of the measurements, (d) two external ADCs of 18-bits resolution for accomplishing the IEC61724 accuracy requirements and (e) a specific module to reduce the energy consumption.

When designing the new datalogger with connectivity features, it was found that Arduino™ UNO would not allow to connect directly the board to the internet (it would require an extra shield board). The 3G shields compatible with Arduino™ found in the market that met the requirements of transmission were extremely expensive so the use of these shields was discarded. As a low-cost alternative, an Ethernet board with a nanorouter could perform the same connectivity functions.

TABLE XVII: ARDUINO™ UNO AND ARDUINO™ ETHERNET COMPARISON

Component	UNO	Ethernet
Processor	ATmega328P	ATmega328P
Operating/Input Voltage	5 V / 7-12 V	5 V / 7-12 V
CPU Speed	16 MHz	16 MHz
Analog In/Out	6/0	6/0
Digital IO/PWM	14/6	14/4
EEPROM [kB]	1	1
SRAM [kB]	2	2
Flash [kB]	32	32
USB	Regular	Regular
UART	1	-

Therefore, Arduino^{TM} Ethernet (Rev 3) was selected as it has connectivity functions and similar characteristics integrated all in a single board. Table XVII shows the comparison between Arduino^{TM} Ethernet and Arduino^{TM} UNO boards. The use of an Arduino^{TM} UNO with an Ethernet shield stacked on top could be also considered as an alternative option as the price is comparable to that of the Arduino^{TM} Ethernet board.

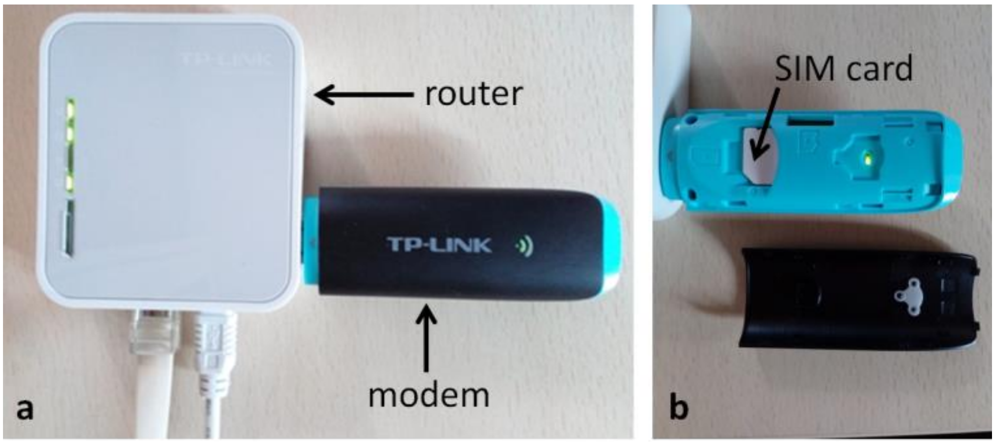


FIGURE 24: Connectivity system: router and modem (a) and SIM card into the modem adapter (b).

Regarding connectivity itself, studies based on PV system monitoring were reviewed (see Section 5.4) to select a suitable data transmission technique. The use of mobile communications, concretely 3G, offers the most significant advantages. Main advantages of the 3G prototype are flexibility and unlimited reach, although the latter is restricted by the 3G mobile penetration rate. The system based on 3G does not require the installation of additional networks and this flexibility makes the 3G system more suitable for the monitoring of SAPV systems located in remote areas, especially in developing countries. Among the numerous options to connect Arduino^{TM} to the internet using 3G, the TL-MR3020 router from TP-LINK (Fig.24a) stands out over the rest because it offers the potential to configure Wi-Fi and 3G transmission systems at a low price. This device requires an external 5VDC/1A power supply and it operates over a temperature range from 10 ºC to 60 ºC and relative humidity conditions in the humidity range of 10 % RH to 90 % RH (non-condensing).

As the router has an on-board interface USB 2.0 port, the 3G operating mode can be configured providing internet connection through a 3G USB stick modem (Fig. 24b). For this purpose, MA260 modem from TP-LINK was selected. This modem allows to acquire 3G mobile broadband access by inserting a SIM card into the adapter. It supports 3G HSPA+ technology, which provides improved data transfer rates. The USB modem operating temperature range is 0 °C to 40 °C. Thus, the operating temperature of the entire system (router and modem) is limited by the most restricted values: 10 ºC - 40 ºC. This is particularly important since, depending on the location of the system, temperature evacuation systems (fans, heat sinks…) may be required.

The novel datalogger was developed ad-hoc for the monitoring of SAPV systems that in most cases are isolated systems, so an individual data transmission system was the most appropriate option. However, in the case of finding several SAPV systems installed close enough, the monitoring system was designed to provide scalability. The novel monitoring system stands out due to its stackable hardware design. By adding boards with the hardware improvements, the number of analog or digital inputs can be expanded, and various SAPV systems can be monitoring using a single datalogger. To do this, only it would be necessary to extend the number of parameters transmitted in each cycle by SW, achieving scalability at a reduced cost.

5.5.3. Meteorological and SAPV sensors

Sensor characteristics for measuring both electrical and meteorological system parameters were previously detailed by López-Vargas et al. [19] in their work on the Arduino™ basic datalogger. Employing exclusively low-cost sensors, the prototype for measuring SAPV systems includes a wide range of climatic measures: irradiance (G_i), ambient temperature (T_{amb}), humidity (H), wind velocity (W) and rainfall (R). DS18B20 temperature sensors from Maxim Integrated™ were used to acquire PV module temperature (T_{mod}) and PV battery temperature (T_{bat}). The electrical parameters measured by the low-cost datalogger include the PV generator output voltage (V_A), battery voltage (V_S), load voltage (V_L), PV generator output current (I_A), battery current (I_S) and load current (I_L). Based on voltage divider circuits, low-cost voltage sensors that increase the ADC input range were developed and three common-mode voltage amplifiers were also used to allow measuring differential signals in presence of high common-mode voltage range accurately. Hall Effect sensors, LTS 15-NP from LEM™, were used for current measurements. These sensors presented a level of accuracy from ± 0.2 % to ± 0.7% (operating with internal measuring resistance at 25 ºC). Fig. 25 shows both voltage and current sensors developed.

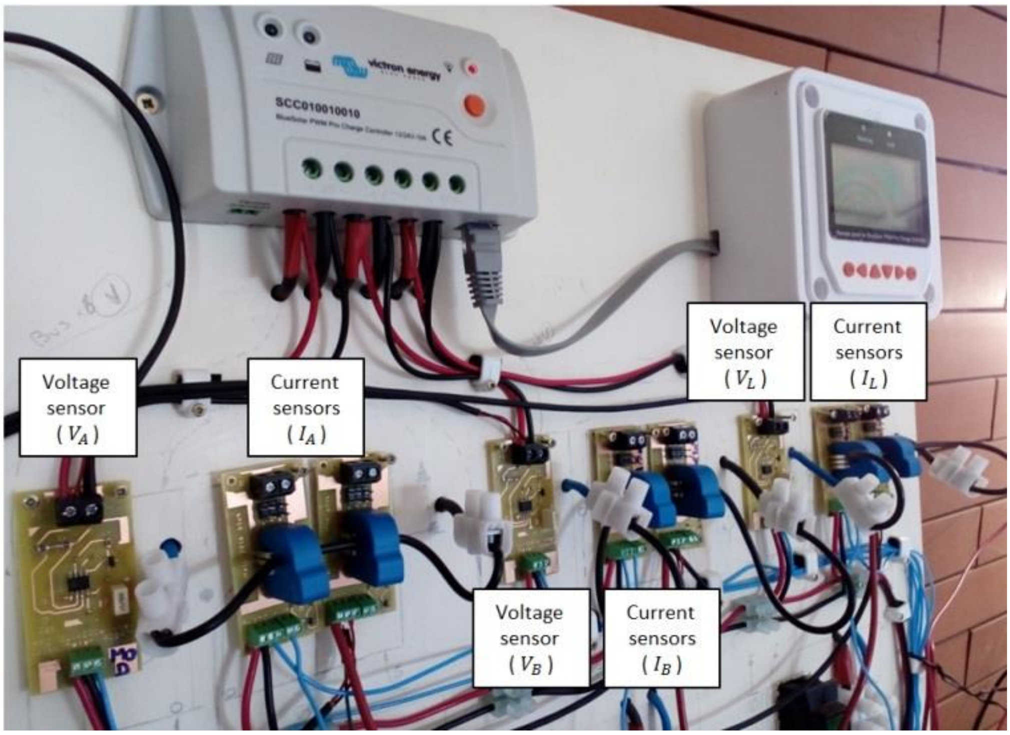


FIGURE 25: Development of PV output generation, battery and load current and voltage sensors.

5.5.4. Software

Fig. 26 shows the flow diagram of the process followed by the microprocessor. At start, the internet connection is established and the RTC is synchronized: these processes run every time the routine is initialized or the reset button is pressed. In addition, once per day, at 00 AM, the RTC is synchronized to avoid drifts. Every minute, in second 0 and second 30, parameters are measured; data transmission and data storage processes are carried out. Software improvements have been developed and new processes have been included:

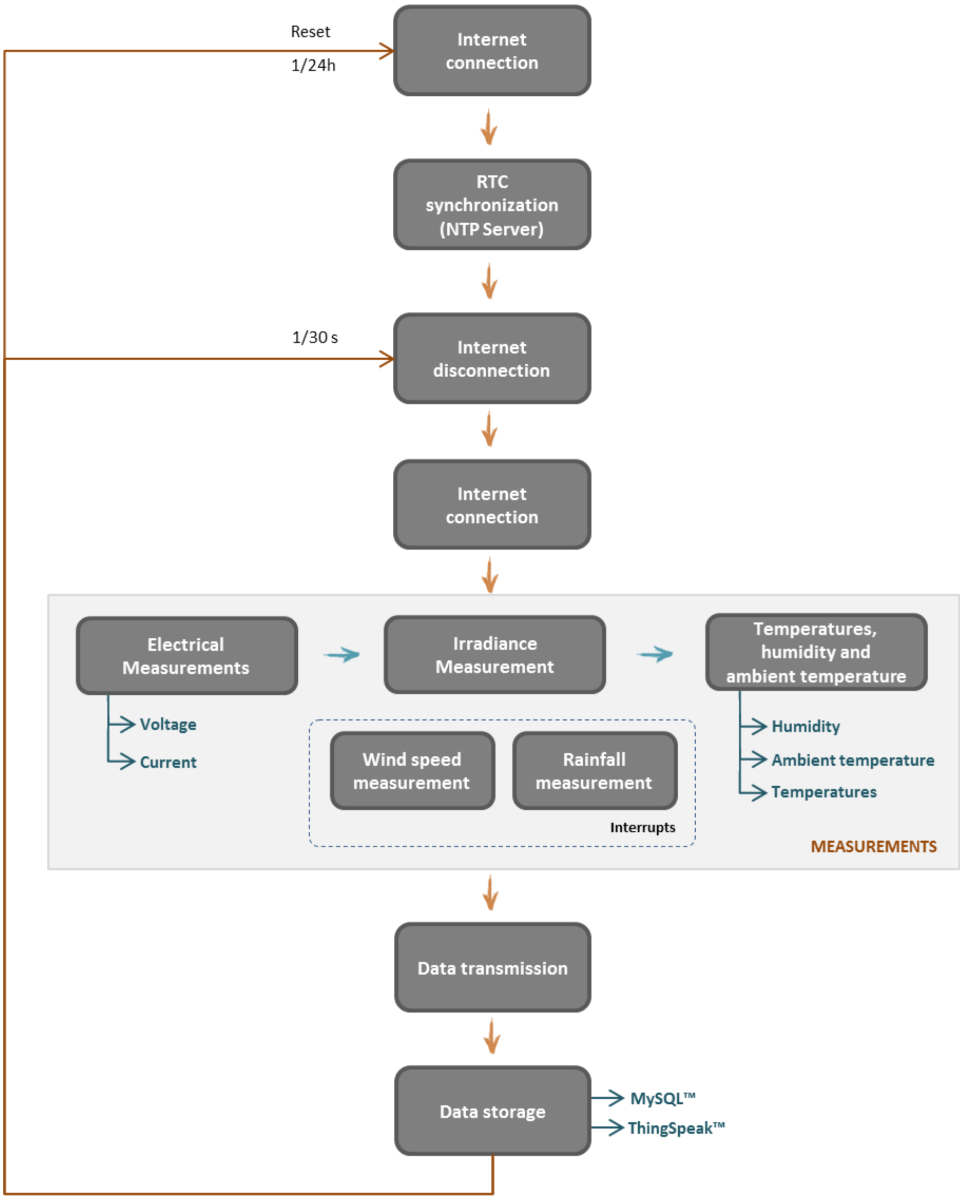


FIGURE 26: Diagram for the routine executed by each iteration: sequence of processes and communications.

a) The internet access provides the possibility of synchronizing the RTC using a NTP server. The clock is synchronized at the start of the program or in case of reset. As the drift of the RTC is a few seconds per week, to synchronize once a day (at 00 AM) is enough.

b) The connection between the microcontroller and the server is established by a Hypertext Transfer Protocol (HTTP) petition. After establishing the connection between datalogger and server, the process of data transferring starts.

c) The information is stored in a MySQL™ database hosted in a server, located in the University of Jaén, with a specific order and format.

d) Additionally, data is sent to ThingSpeak™, an open source Internet of Thing analytics platform service that allows inserting, visualizing and analyzing live data streams in the cloud.

Two types of data storage were implemented: a dedicated server (conventional method) and a cloud service platform (novel application of IoT). Both alternatives of storage allow to monitor the system in a remote way. The use of free cloud service platforms allows to obtain a highly accessibility and cost-effective monitoring system based entirely on free SW and HW.

In the first option (conventional), the measured data is stored in the main base PC (located in the University of Jaén) which serves as the server for the website, such that users can retrieve data from any previous date within the monitoring period. The web-based monitoring feature was included for adding value to the global monitoring system. The website allows users to observe the monitored parameters and statistical data, as well as other information: daily production, charge of battery or consumptions. The website was developed in HTML language while the table and graph were created by integrating PHP code and library from Highcharts. The parameters monitored are processed and analyzed to produce information that can be understood easily by users; data is protected by password and the information is represented in graphs. The website is accessible using the following link: http://energiaagua.ujaen.es/FVMonitor/.

On the other hand, a second option was also developed, as the advantages of open cloud systems are really interesting for this type of applications: they provide large data storage, high reliability and low-cost. Cloud systems reduce the cost of data storage facilities and extra maintenance to keep or maintain the data. Open cloud-based IoT platforms and services were reviewed [35]. ThingSpeak™, an open IoT data platform based on public cloud technology was selected mainly due to its variety of third party platforms that include Arduino and Twitter amongst others. ThingSpeak™

platform stores and retrieves data from things using HTTP over internet. ThingSpeak™ allows to analyze data using MATLAB without requiring the purchase of a license from Mathworks™. Each monitoring system sends data to an individual channel. These channels can be configured as a public or a private channel (protected by password). In addition, mobile applications allow to monitor ThingSpeak™ channels using a smartphone. Free users are limited to 10 million messages (3+ years at minimum update interval, 15s) and 8 fields per channel. Irradiance (G_i), ambient temperature (T_{amb}), PV module temperature (T_{mod}), PV generator output voltage (V_A), battery voltage (V_S), PV generator output current (I_A), battery current (I_S) and load current (I_L) parameters were selected for monitoring.

FIGURE 27: SAPV system installed at IMDEA Water Institute facilities: PV mono-crystalline module (a), charge controller (b) and lead-acid battery (c).

5.6. Experimental set-up

Studies on rural electrification in developing countries and renewable-based initiatives energy programs were previously reviewed by López-Vargas et al. [19]. Two real SAPV systems, similar to those typically employed in developing countries, were installed in different locations to verify the proper functioning of the monitoring system under real conditions:

Alcalá SAPV system: The SAPV system (Fig. 27) was located at the test facilities in IMDEA Water Institute (Alcalá de Henares, Madrid, Spain, latitude 40.513° N, longitude 3.339° E). The PV system included an 80W mono-crystalline module, a 12 V lead-acid battery (90Ah-C100) and a PWM serial charge controller.

FIGURE 28: SAPV system installed at University of Linares facilities: PV mono-crystalline module (a), charge controller (b) and lead-acid battery (c).

Linares SAPV system: The SAPV system was composed by a 100W mono-crystalline module, a 12 V lead-acid battery (90Ah-C100) and a PWM serial charge controller. The real SAPV system (Fig.28) was installed at the test facilities in the University of Jaén, in the Linares School of Engineering (Linares, Jaén, Spain, latitude 38,085ºN, longitude 3,646ºW).

Another version of the Arduino™ solar datalogger was installed in the School of Science of the University Benito Juarez of Oaxaca (Oaxaca, Mexico, latitude 17.047° N, longitude 96.712° W). This datalogger was connected directly to the Internet via cable, using the Ethernet input of the board. In this case, the datalogger measures meteorological parameters; data is sent to the Linares server.

Typical domestic energy consumption of a household in developing countries will usually have several lamps for lighting and it might also have a small household appliance. A real load profile was designed by López-Vargas et al. [19] identifying all the commonly used appliances in terms of power and hours of usage per day for estimating the daily energy consumption used in this work. The load system was composed by two 12 V luminaries of 3 W and 50 W, respectively. The total daily energy consumption of the designed load profile was 79 Wh.

Each SAPV system had also their own low-cost modular weather station (Fig. 29), including a calibrated solar cell from Nousol™ to measure solar global irradiance in the same plane of the PV mono-crystalline module (G_i), a DHT22 digital sensor with shield protector to monitor ambient temperature (T_{amb}) and relativity humidity (H), a Small Wind Transmitter sensor from Thies Clima to measure horizontal wind speed (W) and a rain gauge sensor from Pronamic™ to measure rainfall (R).

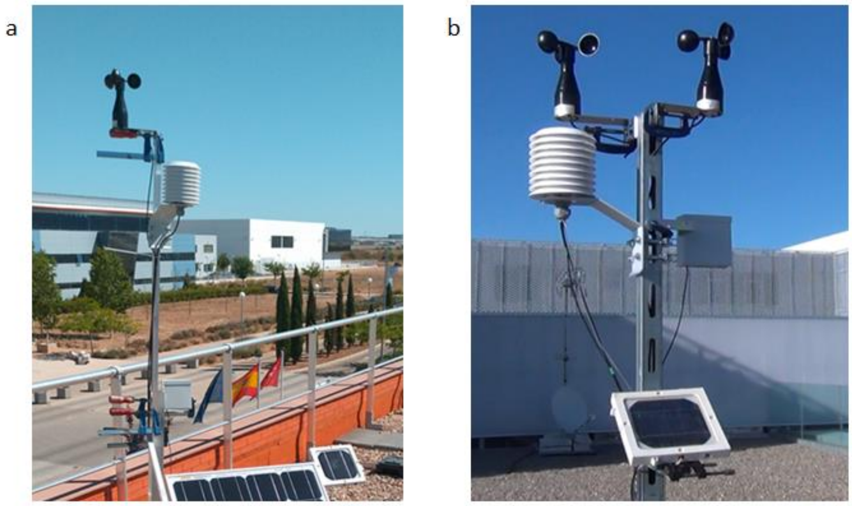


FIGURE 29: Weather stations installed in Alcalá de Henares (a) and Linares (b).

5.7. Experimental results

Fig. 30 shows the final prototype of the new low-cost datalogger installed in Alcalá de Henares (Fig.30a) and Linares (Fig.30b). At both sites, the results from the testing period indicated how the new 3G datalogger monitored and sent the data correctly for the complete period of time.

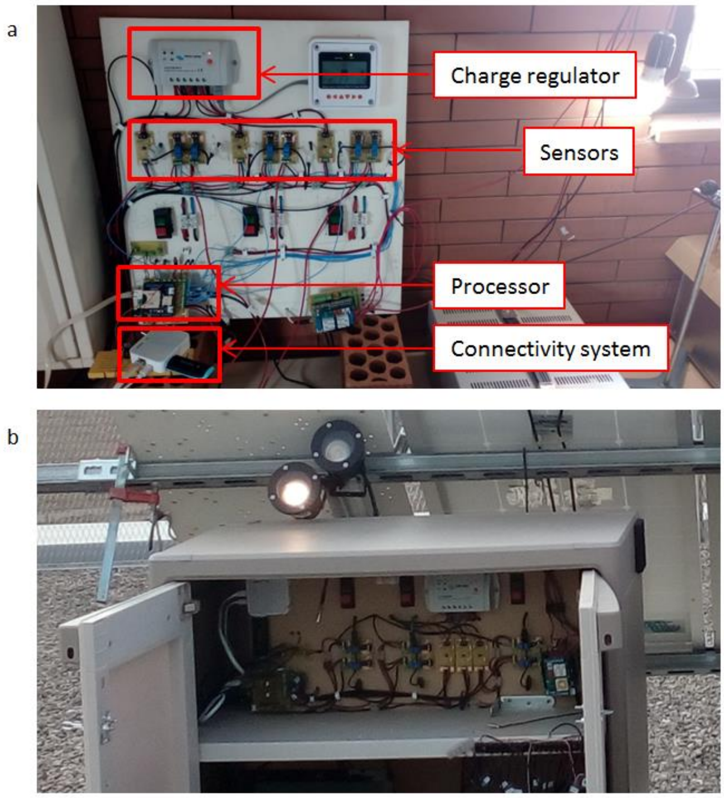


FIGURE 30: Final prototype assembly. Datalogger installed in Alcalá de Henares (a) and datalogger installed in Linares (b). The datalogger uses 9 small PCBs for electrical sensing (current and voltage measurements). The load control system includes an Arduino™ UNO board and a relay system.

The measurements were compared with a commercial monitoring system that acted as a pattern. This pattern commercial monitoring system was an Agilent^{TM} 34972 datalogger of 22 bits with a voltage accuracy resolution of 0.004% that uses Labview^{TM}. Every 30 s, this datalogger measured and recorded the same parameters as the Arduino^{TM} datalogger.

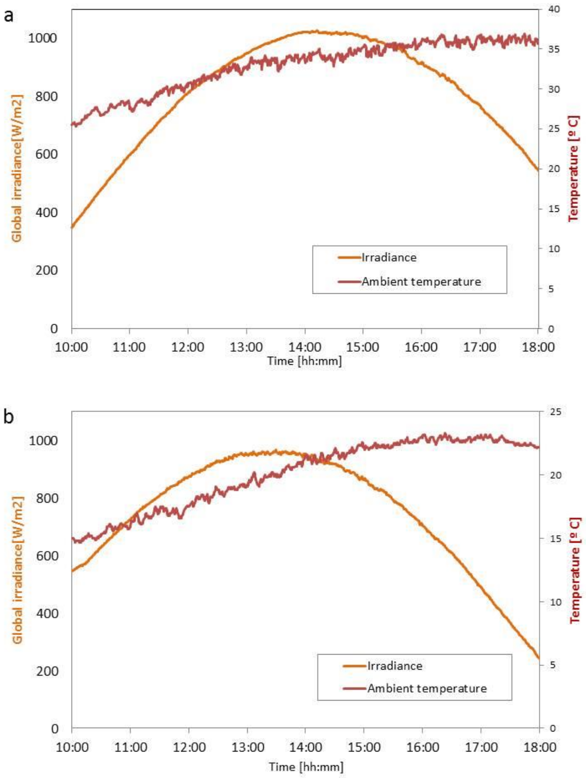


FIGURE 31: Irradiance and ambient temperatures measured in Alcalá de Henares (27/07/2017) and Linares (20/03/2017) sites under clean sky conditions.

5.7.1. Electrical and meteorological parameters monitoring: comparison with commercial datalogger

Lopez-Vargas et al. demonstrated in 2018 that the Arduino^{TM} datalogger works well under adverse climatic conditions [19]. As expected, the new datalogger continued to measure correctly both the meteorological and electrical parameters, always complying with the IEC standard. Fig.31 shows an example of the daily variations of the solar irradiance and the ambient temperature monitored by the low-cost Arduino^{TM} datalogger and the commercial Agilent^{TM} datalogger in Alcalá de Henares (Fig.31a) and Linares (Fig. 31b), revealing the correct functioning of the Arduino^{TM} datalogger: the uncertainly of irradiance measures was below the 8 % required by the standard and the mean absolute errors of measured ambient temperatures were better than the ±1 °C required.

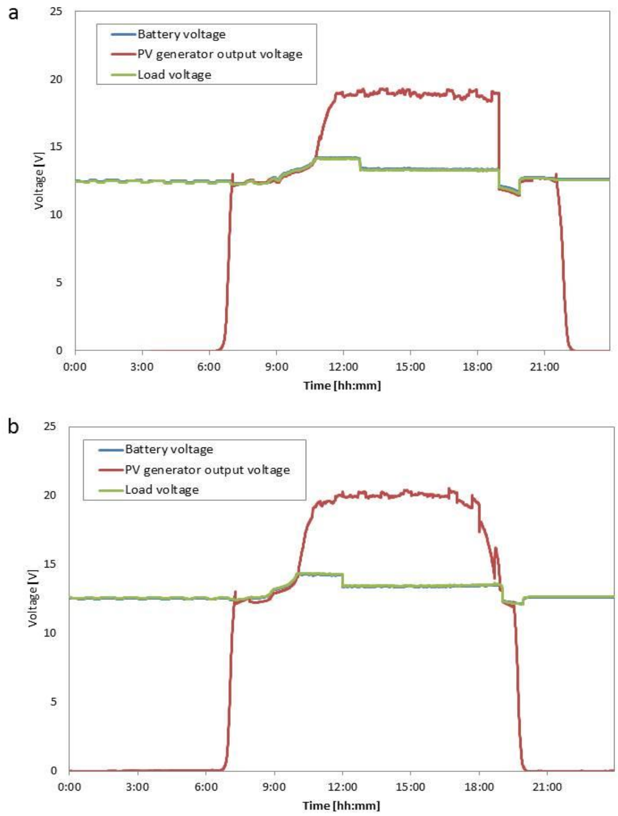


FIGURE 32: Voltages measured in Alcalá de Henares (27/07/2017) and Linares (20/03/2017) sites under clean sky conditions.

Regarding electrical parameters, Fig. 32 shows an example of the daily variations of the PV generator output voltage, the battery voltage and the load voltage monitored by the low-cost Arduino™ datalogger in Alcalá de Henares (Fig. 32a) and Linares (Fig. 32b) sites. Battery voltage line and load voltage line overlap. The voltages measured by the Arduino™ datalogger using low-cost sensors under clear sky conditions shown in the Fig. 32 demonstrate the correct functioning of the Arduino™ datalogger. The uncertainly of electrical measures was below the 2% required by the standard.

5.7.2. System reliability

During the experimental period, it has been verified that all the installed dataloggers send data correctly and that the quality of the data is excellent (meteorological and electrical) as indicated previously. All the dataloggers have been intensively tested over a period of 12 months, identifying the performance of the datalogger when a failure occurred. The dataloggers only failed in 4 occasions over the year, due to different reasons. One of these errors was an access failure (to the server installed in Linares). The datalogger located in Oaxaca registered 1 error as a result of a network outage. The datalogger installed in Alcalá de Henares failed in 1 occasion due to a power shortage. An equipment failure was detected in the datalogger installed in Linares. The experimental results showed that after 12 months under operation, taking into account the low number of failures and that the most of the failures are due to external factors, the datalogger is highly reliable. Details on the errors of different origin were registered:

a) Access failure: On 16/11/2017, it was detected an access failure to the server installed in Linares. This failure affected all three systems (dataloggers sent data to the same server). In the experimental phase, one of the problems encountered was the loss of data sent for brief periods of time. As previously stated, each datalogger sends the collected data to a dedicated server, located in the Superior School of Linares. Eventually, because of performing the maintenance activities by the university, the server installed in Linares was disconnected for short periods of time (it was beyond our scope of work: these maintenance works were carried out by the general university technical unit). In these periods, the datalogger could not establish the connection to the server and data was not received or stored. The server downtimes lead to observe the behavior of the datalogger under this condition: it was verified that as soon as the server functioned again, the monitoring system was reconnected and the data was sent again and stored as normal.

b) Power failure: Another data: in Alcalá de Henares, on 21/05/2017 a power failure was detected in the Alcalá de Henares site. Problems with Agilent™ pattern datalogger occurred due to power shortages that forced to initialize the software and perform maintenance. The Arduino™ datalogger was designed to start-up without external help after power shortages and it did not require any external initialization. This result is of special interest since the SAPV systems studied in this work are usually installed in isolated and inaccessible regions. The datalogger does not require external help to recover from a power failure; the datalogger does not need an external operator. In addition to providing the reliability to the system, it was empirically proved the proper functioning of the system without the need for maintenance, reducing the operational costs of the monitoring system to a minimum.

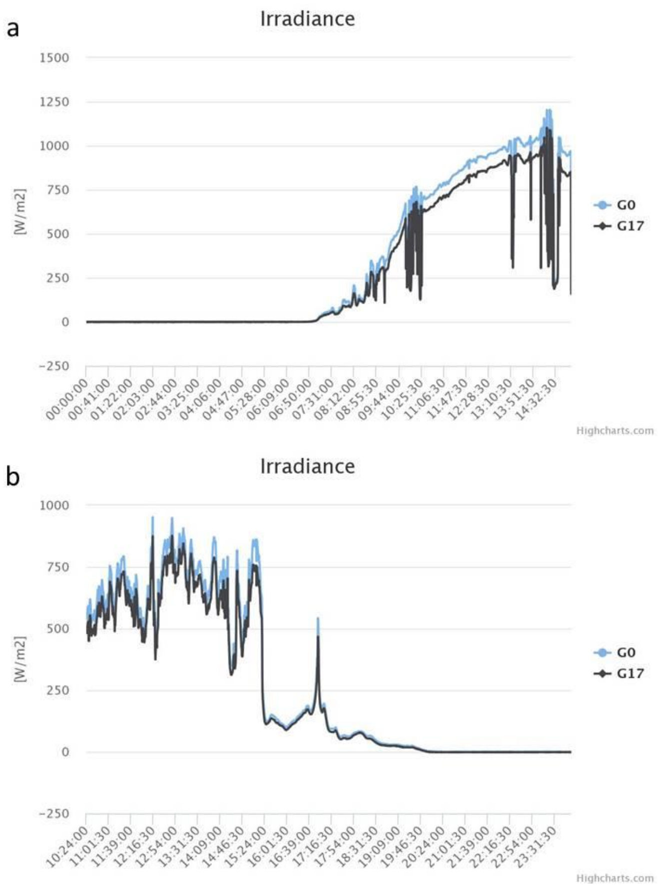


FIGURE 33: Global horizontal irradiance (G0) and in-plane irradiance (G17) data registered in the network failure period in Oaxaca. Data recorded on 17/6/2017 (a) and 19/6/2017 (b).

c) Network failure: The solar Arduino™ datalogger installed in Oaxaca provided information on how the new monitoring system responds to a network failure. Jointly with the Ardino datalogger, another commercial dataloggerr (LabJack™ U12 series) was installed. This commercial datalogger stored the data in a folder shared over the Internet. On 17/06/2017, the datalogger stopped sending data to the server as shown in Fig. 33a. It was observed that, the commercial datalogger, stopped sending data too. On 19/06/2017, the solar datalogger (Fig 33b) and the commercial datalogger started sending data again. As the commercial datalogger has to be initialized manually in case of power failure, the bug was registered as a network failure. The Arduino™ datalogger stopped sending data to the server due to a (WAN) network error. This failure served to verify empirically that after a network failure, the datalogger can re-hook and resend the data, as designed by the software. Subsequently, other networks failures were registered with a certain frequency in the Oaxaca site, and these failures have led to the loss of data in the fault period. It was found that, often in developing countries, due to the quality of the wired networks it is common to suffer successive Internet drops; it was empirically proved that the monitoring system based on transmission via mobile communications is more reliable than a data acquisition system that is wired network dependent.

TABLE XVIII: EXAMPLE OF EXTREME CONDITIONS RECORDED IN THE DAYS BEFORE THE FAILURE. DATA RECORDED ON 24/06/2017.

Parameter	Minimum value	Average value	Maximum value
Ambient Temperature [ºC]	21.4	31.61	40.7
Humidity [%]	14.3	21.46	36.3
Module Temperature [ºC]	19.5	38.29	67.5
Battery Temperature [ºC]	25.31	33.57	41.19
Electrical Cabinet Temperature [ºC]	22.44	35.25	47.63
Horizontal Wind Speed [m/s]	0	3.77	17.37
Irradiance [W/m^2]	0	259.29	903.37

d) Equipment failure: The datalogger installed in Linares recorded a fall on 29/06/2017. The system was completely inoperative; it stopped sending data to the server and the cloud. In Linares, the summer period usually contains some of the harshest environmental conditions for PV systems and electronic equipment, including temperatures up to 45º, dust storms (from winds from the Sahara Desert), and occasional electrical storms with high speeds and heavy rain. In the days before the failure, ambient temperatures (T_{amb}) were recorded above 40 degrees Celsius as shown in Fig. 34. Table XVIII includes a summary of the daily environmental parameters recorded on 24/06/2017 by the datalogger, including temperatures, irradiance, humidity and horizontal wind speed. Although a cooling system consisting of two fans was installed, in some instances, the T_{ec}, temperature measured inside the electrical cabinet (where the datalogger was located), exceeded the ambient temperature, reaching 47 degrees Celsius as shown in Table XVIII. The operating temperature of the entire connectivity system (router and modem) recommended by the manufacturer was 10 ºC - 40 ºC. As the maximum operative conditions of the system were reached, by all accounts, it was an equipment failure in the connectivity system due to the high temperatures. After inspecting the system it was found that, in effect, the data delivery system (consisted of the nanorouter and the modem) stopped working. The connectivity system was not broken, but it was necessary to reset the nanorouter and configure it again manually.

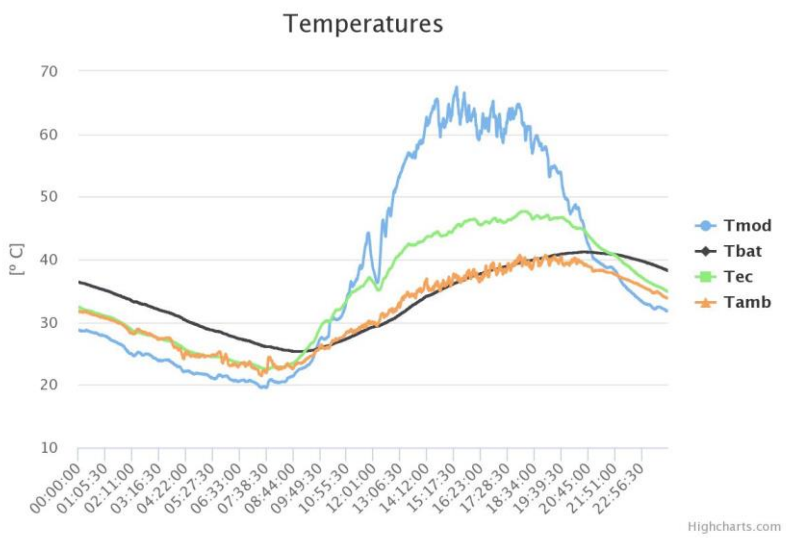


FIGURE 34: Temperatures recorded by the datalogger in Linares, a previous day before the failure (24/06/2017).

5.7.3. Data visualizations

As the main novelty of this work, the remote visualization of the data in real time via web or smartphone stands out, due to the incorporation of connectivity to the system via 3G. The parameters monitored are processed and analyzed to produce information that can be understood easily by users; the information is represented in graphs. Fig. 35 shows a view of the dynamic charts integrated in the website.

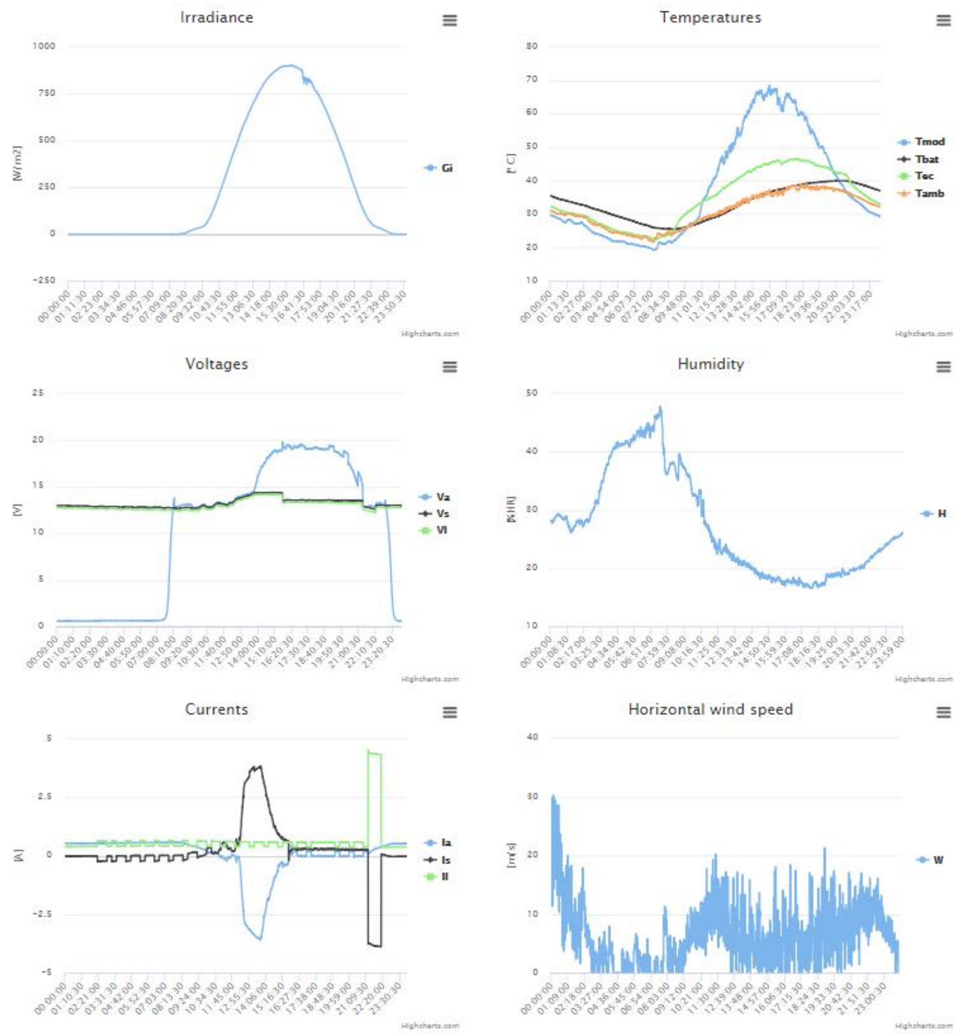


FIGURE 35: Online web-page view of data measured in the Linares site: graphs on 13/06/2017.

Fig. 36 shows the visualization of data measured and sent to the cloud on 23/01/2017 in Alcalá de Henares. The open cloud platform selected, ThingSpeak™, allows to monitor up to eight parameters and to locate the monitoring system on the map via www.

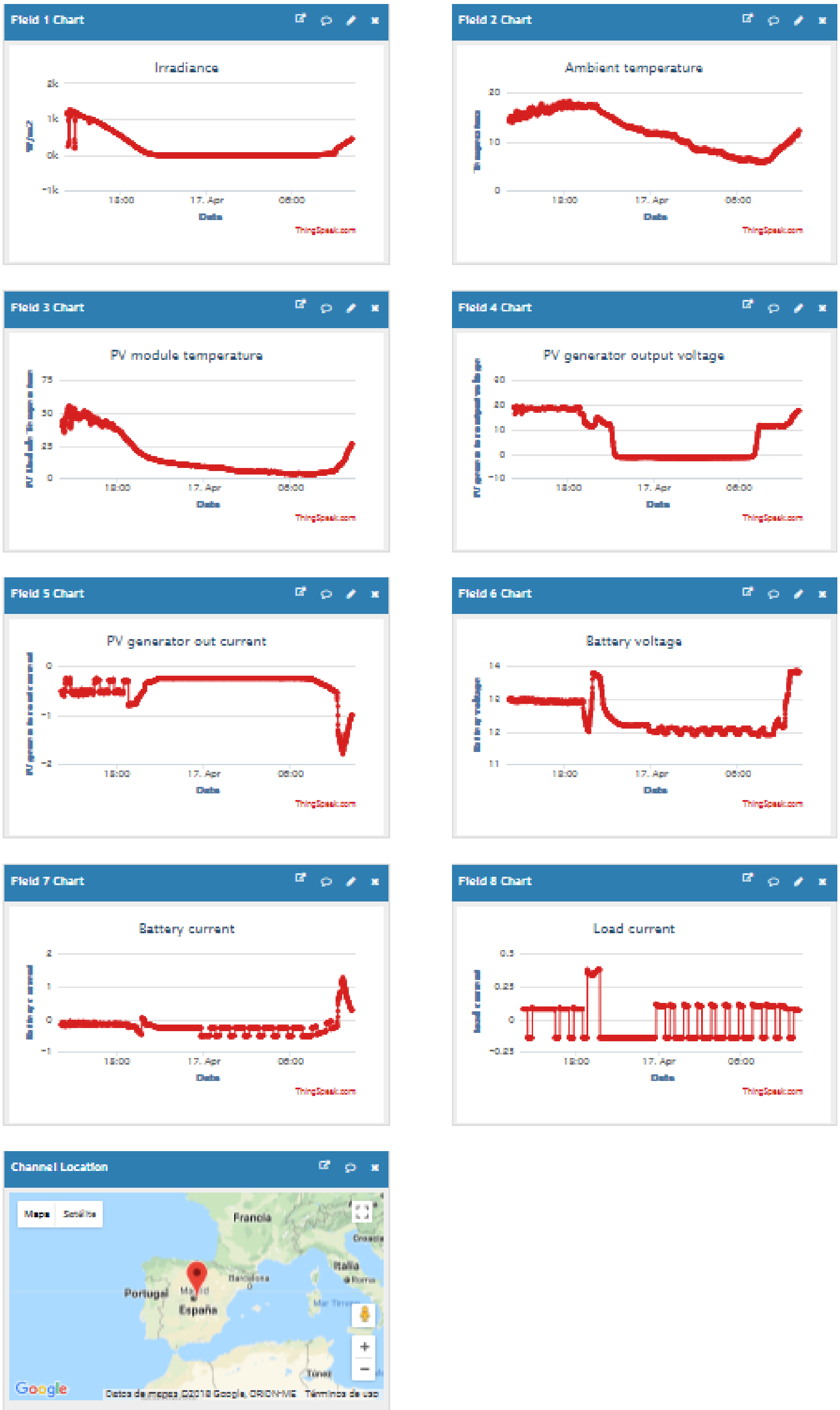


FIGURE 36: ThingSpeak™ visualization of parameters measured by the monitoring system located in Alcalá de Henares

Fig.37 shows the daily variations of the irradiance and the module temperature using the mobile application ThingView™.

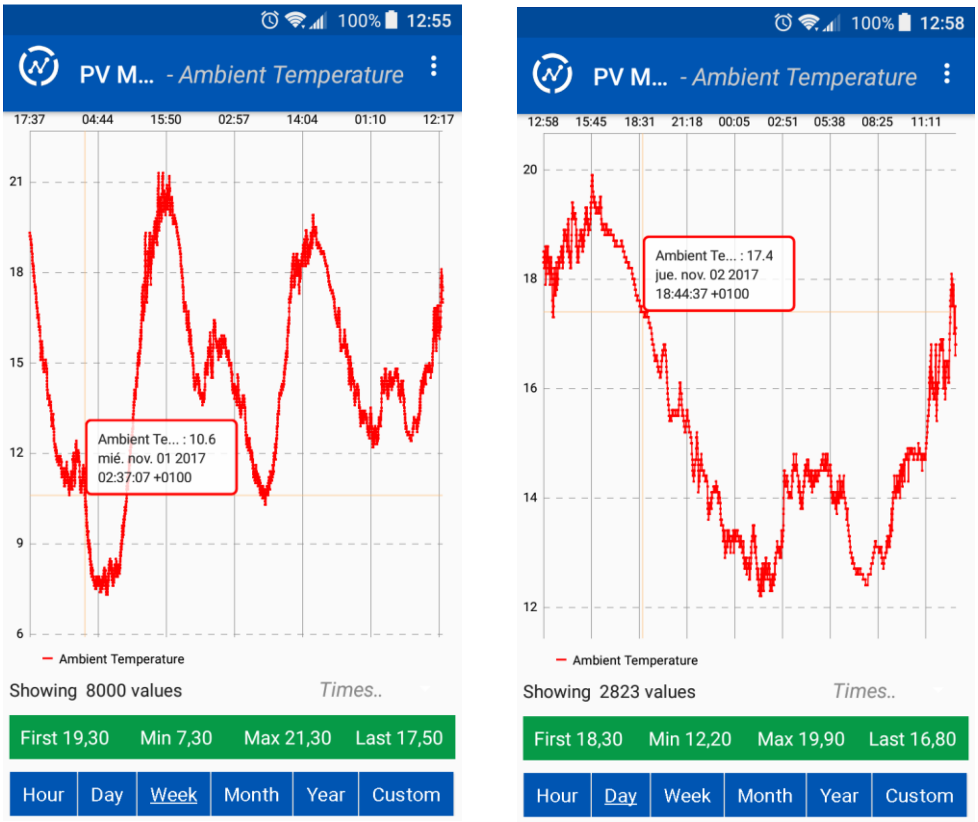


FIGURE 37: Screenshots on an Android smartphone using Thingview™ App: weekly (a) and daily (b) ambient temperature monitored by the datalogger located in Alcalá de Henares.

5.8. Cost estimation of the first prototypes

The ultimate goal of this work was to develop an IoT-based prototype of a datalogger that uses a mobile communication transmission system and is low-cost, accurate and autonomous. Table XIX describes the budget of the monitoring system. The final cost of the new prototype, including sensing and connectivity, was approximately 141 €. Table XX shows the budget for the low cost sensors. The budget of low-cost sensors (including the low-cost weather station) was approximately 268 €. Total costs could be reduced considerably when mass produced and introduced in the market.

This monitoring system has a maintenance cost due to the use of a 3G SIM card. This maintenance cost depends on the fee of the contracted telephone service. As the information transmitted is very low, with a cheap data plan should be sufficient, so this expense is not significant.

TABLE XIX: BUDGET FOR THE LOW-COST DATALOGGER

Board	Components	Price [€]
Arduino^{TM} UNO	Stocked board	17.95
Ethernet Shield	Ethernet Shield W5100 for Arduino^{TM} UNO	7.95
ADC Board	2 MCP3424	6.84
	RTC DS1307	1.58
	Precision resistors, Capacitors	1.80
	Wires, connectors	0.70
Power consumption	NPN transistor	0.29
Adaptor for high current sensing	3 LTS-15NP LEM	18.86
	9 Resistors SMD	5.40
	3 Voltage reference	2.79
Adaptor for high voltage sensing	3 Differential Amplifiers	11.31
	6 Resistors SMD	3.60
Connectivity system	TL-MR3020 router from TP-LINK	23.74
	MA260 modem from TP-LINK	37.9
	Total	**140,71**

TABLE XX: BUDGET FOR LOW COST SENSORS AND LOW-COST WEATHER STATION COMPONENTS

Components	Price [€]
3 Digital temperature sensors DS18B20	10.50
Irradiance sensor	39.90
Rain gauge sensor	35.20
Anemometer	120.00
Temperature and humidity sensor DHT22	2.69
Solar radiation shield for temperature sensor	59.88
Total	**268.17**

5.9. Conclusions

A novel datalogger for monitoring SAPV systems via website and mobile applications has been designed, built and tested incorporating wireless technology in it, concretely 3G, along with IoT. Two types of data storage were tested: a dedicated server (conventional method) and a cloud service platform (novel application of IoT). Both alternatives of storage allow to monitor the system in a remote way. The integration of an open cloud-based IoT platform allowed to monitor small stand-alone PV systems remotely in real time via web or mobile app at low cost.

The novel datalogger based on free software and hardware has been installed as an experimental prototype in multiple sites: Alcalá de Henares (Madrid, Spain), Linares (Jaén, Spain) and Oaxaca (Oaxaca, Mexico). The datalogger was tested under real and different conditions demonstrating the robustness of the system, working with 14 variables with low uncertainty. An outdoor campaign of over ten months was performed. Considering the low number of failures and their origin (the most of the failures were due to external factors), the experimental results showed that the datalogger is highly reliable. The cost of the monitoring system is considerably lower than commercial devices and allows high accurate remote monitoring.

The main novelty presented by this work is that the datalogger complies with the IEC standard accuracy requirements and it is designed based on wireless communications taking into account the limitations in rural areas of developing countries. The integrated solution has been tested and it works, so the datalogger could be installed solving the problem of monitoring of PV systems located in isolated regions, all at low cost.

As future works, to avoid the loss of information in case of failures (network, access…), a backup system based on a micro SD card would add value to the system; it would prevent the loss of data, storing the measured parameters in the disconnection period. In addition, it was proven that the connectivity system, working in extreme conditions (temperatures above 40 º C) fails. As a future line, another type of cooling system more effective and another 3G connectivity system that supports higher temperatures could be tested. To power the monitoring system using a solar cell could be another future improvement. Due to the stackable hardware design (by adding boards) several SAPV systems installed close enough can be monitoring using a single datalogger as a central node. The development of these networks is another future work.

5.10. References

[1] R. Mukaro, X. F. Carelse, and L. Olumekor, "First performance analysis of a silicon-cell microcontroller-based solar radiation monitoring system,"Sol. Energy, vol. 63, no. 5, pp. 313–321, Nov. 1998.

[2] E. Koutroulis and K. Kalaitzakis, "Development of an integrated data acquisition system for renewable energy sources systems monitoring," Renew. Energy, vol. 28, no. 1, pp. 139–152, 2003.

[3] G. M. Tina and A. D. Grasso, "Remote monitoring system for standalone photovoltaic power plants: The case study of a PV-powered outdoor refrigerator," Energy Convers. Manage., vol. 78, pp. 862–871, Feb. 2014

[4] F. Touati, M. A. Al-Hitmi, N. A. Chowdhury, J. A. Hamad, and A. J. R. San Pedro Gonzales, "Investigation of solar PV performance under Doha weather using a customized measurement and monitoring system," Renew. Energy, vol. 89, pp. 564–577, Apr. 2016.

[5] M. Benghanem, "Low cost management for photovoltaic systems in isolated site with new IV characterization model proposed," Energy Convers. Manage., vol. 50, no. 3, pp. 748–755, Mar. 2009.

[6] M. Demirtas, I. Sefa, E. Irmak, and I. Colak, "Low-cost and high sensitive microcontroller based data acquisition system for renewable energy sources," in Proc. Int. Symp. Power Electron., Elect. Drives, Automat. Motion, 2008, pp. 196–199.

[7] M. Benghanem and A. Maafi, "Performance of stand-alone photovoltaic systems using measured meteorological data for Algiers," Renew. Energy, vol. 13, no. 4, pp. 495–504, Apr. 1998.

[8] M. Benghanem, A. H. Arab, and K. Mukadam, "Data acquisition system for photovoltaic water pumps," Renew. Energy, vol. 17, no. 3, pp. 385–396, Jul. 1999.

[9] M. Benghanem, "Measurement of meteorological data based on wireless data acquisition system monitoring," Appl. Energy, vol. 86, no. 12, pp. 2651–2660, Dec. 2009.

[10] A. Purwadi, Y. Haroen, F. Y. Ali, N. Heryana, D. Nurafiat, and A. Assegaf, "Prototype development of a low cost data logger for PV based LED street lighting system," in Proc. Int. Conf. Elect. Eng. Inform., Jul. 2011, pp. 1–5.

[11] M. Ikhsan, A. Purwadi, N. Hariyanto, N. Heryana, and Y. Haroen, "Study of renewable energy sources capacity and loading using data logger for sizing of solar-wind hybrid power system," Procedia Technol, vol. 11, pp. 1048–1053, 2013. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S2212017313004477 >

[12] M. Fuentes, M. Vivar, J. M. Burgos, J. Aguilera, and J. A. Vacas,"Design of an accurate, low-cost autonomous data logger for PV system monitoring using Arduino^{TM} that complies with IEC standards," Sol. Energy Mater. Sol. Cells, vol. 130, pp. 529–543, Nov. 2014.

[13] T. Kulworawanichpong and J. J. Mwambeleko, "Design and costing of a stand-alone solar photovoltaic system for a Tanzanian rural household," Sustain. Energy Technol. Assessments, vol. 12, pp. 53–59, Dec. 2015.

[14] A. El Fathi, L. Nkhaili, A. Bennouna, and A. Outzourhit, “Performance parameters of a standalone PV plant,” Energy Convers. Manage., vol. 86, pp. 490–495, Oct. 2014. 4320 IEEE Sensors Journal, VOL. 19, NO. 11, JUNE 1, 2019

[15] D. O. Akinyele and R. K. Rayudu, “Strategy for developing energy systems for remote communities: Insights to best practices and sustainability,” Sustain. Energy Technol. Assessments, vol. 16, pp. 106–127, 2016.

[16] G. D. Kamalapur and R. Y. Udaykumar, “Rural electrification in India and feasibility of photovoltaic solar home systems,” Int. J. Elect. Power Energy Syst., vol. 33, no. 3, pp. 594–599, 2011.

[17] R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, “Off-grid renewable energy systems: Status and methodological issues,” Int. Renew. Energy Agency, White Report, 2015. [Online]. <https://www.irena.org/publications/2015/Feb/Offgrid-renewable-energy-systems-Status-and-methodological-issues > (accessed 29.07.2019).

[18] Grameen Shakti. [Online]. <http://www.gshakti.org> (accessed 29.07.2019).

[19] Agency for Non-Conventional Energy and Rural Technology. [Online]. <http://anert.gov.in/index.php?option=com_content&view=article&id=9&Itemid=4> (accessed 29.07.2019).

[20] MNRE [Online] <http://mnre.gov.in > (accessed 29.07.2019).

[21] Thrive Energy [Online] < http://www.thriveenergy.co.in/subsidy-schemes/mnre-nabard-solarhome-lighting > (accessed 29.07.2019).

[22] Kerea. [Online].< http://kerea.org > (accessed 29.07.2019).

[23] U. E. Hansen, M. B. Pedersen and I. Nygaard, “Review of solar PV market development in East Africa,” United Nations Environ. Programme, Nairobi, Kenya, Work Paper 12, 2014.

[24] (2014). Luz en Casa—Case study, Fundación ACCIONA. Accessed: Dec. 30, 2018. [Online]. Available: < http://www.accioname.org/ >

[25] Y. E. Abu, N. H. Saad, and A. Zekry, “Enhancing the design of battery charging controllers for photovoltaic systems,” Renew. Sustain. Energy Rev., vol. 58, pp. 646–655, May 2016.

[26] N. J. Williams, E. E. van Dyk, and F. J. Vorster, “Monitoring solar home systems with pulse width modulation charge control,” J. Sol. Energy Eng., vol. 133, no. 2, pp. 021006, 2011.

[27] F. D. J. Nieuwenhout et al., “Experience with solar home systems in developing countries: A review,” Prog. Photovolt., Res. Appl., vol. 9, no. 6, pp. 455–474, 2001.

[28] Sollatek http://sollatek.co.ke/shop/solar-lighting/solarhomekit/ (accessed 29.07.2019).

[29] Photovoltaic system performance—Part 1: Monitoring, 1st ed. Standard: IEC61724-1, International Electrotechnical Commission (IEC), Switzerland, Geneva, 2017.

[30] Commission of the European Communities, Photovoltaic System Monitoring, Documents A & B version 4.3, Guidelines for the Assessment of Photovoltaic Plants, 1997.

[31] ICT facts and Figures. (2016). International Telecommunication Union. [Online]. <https://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2016.pdf > (accessed 29.07.2019).

[32] Arduino [Online]< https://www.arduino.cc > (accessed 29.07.2019).

[33] K. M. Lynch, N. Marchuk, and M. L. Elwin. Embedded Computing and Mechatronics with the PIC32 Microcontroller. [Online]. Available: <http://hades.mech.northwestern.edu/images/e/e3/EmbeddedComputingMechatronicsSampleChapters.pdf>

[34] Photovoltaic Devices: Requirements for Reference Solar Devices, Standard IEC60904-2, 2nd ed., International Electrotechnical Commission

(IEC), Switzerland, Geneva, 2007.

[35] Requirements for Reference Solar Modules, Standard IEC60904-60906, 1st ed., International Electrotechnical Commission (IEC), Switzerland, Geneva, 1994.

[36] Pronamic. [Online]. <http://pronamic.com/products/rain-o-matic-small > (accessed 29.07.2019).

[37] Maxim Integrated. [Online]. <https://www.maximintegrated.com > (accessed 29.07.2019).

[38] S. Monk, Programming Arduino Getting Started with Sketches. New York, NY, USA: McGraw-Hill, 2011.

[39] J. Zhang et al., “A suite of metrics for assessing the performance of solar power forecasting, Sol. Energy, vol. 111, pp. 157–175, Jan. 2015.

[40] F. J. Muñoz, G. Almonacid, G. Nofuentes, and F. Almonacid, “A new method based on charge parameters to analyse the performance of standalone photovoltaic systems,” Sol. Energy Mater. Sol. Cells, vol. 90, pp. 1750–1763, Jul. 2006.

[41] A. López-Vargas, M. Fuentes, and M. Vivar, “IoT application for realtime monitoring of solar home systems based on Arduino™ with 3G connectivity,” IEEE Sensors J., vol. 19, no. 2, pp. 679–691, Jan. 2019.

Chapter 6

Evaluation of Long-Term Performance of a SHS Monitoring System on Harsh Environments

A. López-Vargas, M. Fuentes and M. Vivar; "Evaluation of long-term performance of a SHS monitoring system on harsh environments".

6.1. Introduction

Grid-connected photovoltaic (PV) systems often involve large budgets, and monitoring devices measure the main parameters to apply the necessary corrective and maintenance operations without strongly influencing the total cost of the installation. However size and cost aspects are decisive with Solar Home Systems (SHSs). SHSs lack appropriate monitoring and the impossibility of detecting operation and maintenance problems can drastically shorten systems' lifetime or even the withdrawal of their usage [1].

Millions of SHSs have been installed in remote locations, mainly in isolated regions of Asia, Africa, and Latin America thanks to electrification programs emerging. Monitoring these PV systems has been identified as one of the key agents that contributes to the success of rural electrification programs [2] as these actions extend the systems' lifetime and minimize operation failures. In addition, it has also been demonstrated [3] that lack of information about the performance of SHSs and projects slows down further development and successful dissemination. The cost of commercial dataloggers has decreased in recent years, but it remains too high, and frequently even surpasses the price of the complete stand-alone PV system. As a result, the further development of dataloggers has been required to monitor these PV systems.

For PV application monitoring, open-source platforms, such as Arduino [4, 5, 6, 7, 8] or Raspberry PI [9, 10, 11, 12], have been integrated to lower costs, using wireless technologies [13, 14, 15, 16] to transmit data. Dataloggers installed in rural regions of developing countries need to be autonomous and have good recording capacity because SHSs are commonly installed in locations where is neither an electrical grid nor traditional wired telecommunication networks, and they are often difficult to access by everyday transport. As for modern communications, due to the quality of wired networks in developing countries, Internet services frequently and successively drop. Dataloggers need to be robust as they may be exposed to harsh environmental conditions. N. Schelling et al [17] reported that one of the fundamental roadblocks to sustainable and scalable solar electrification is high maintenance costs induced by several factors: high equipment failure rates, poor maintenance/rough usage practices, high fixed maintenance costs due to travel, low user densities in sparsely populated areas, and the severe lack of accountability in the system. For equipment failures, these authors detected that an extremely hot, dry, and dusty climate can affect the PV system’s with additional wear and tear for equipment. This is an issue of special concern because the climate zones with the highest temperatures (in regions between latitudes 35°N and 35°S) are found in many developing countries in central Africa, the Americas and south Asia, and extreme climate conditions can affect the correct functioning of the dataloggers installed in rural areas of these countries.

In 2014, M. Fuentes et al. [18] proposed a low-cost monitoring system designed around open source and free hardware platforms (Arduino™) to monitor PV systems. It was designed especially for being installed in isolated regions or rural areas in developing countries. The datalogger measured up to

8 electrical/meteorological parameters and 3 analog temperatures with a resolution of 18 bits. The datalogger was empirically tested under real environmental conditions and accomplished the accuracy requirements of the IEC standards for PV systems. Later in 2018, an improved prototype of this low-cost monitoring system was developed by López-Vargas et al. [19]. Its main enhancements were: minimized power consumption, more meteorological parameters were measured, improved electrical measurements and a user-friendly interface was integrated. The new datalogger was designed specifically for SHSs located in remote regions. The prototype was empirically tested by measuring a real stand-alone PV system with very accurate results; the datalogger proved to be autonomous, low-cost and robust in harsh environments. The data storage system was based on an SD card that required a manual procedure involving a human operator to collect data. This circumstance can be an inconvenience at locations that are difficult to access, and increases maintenance and operating costs.

6.1.1. Failures detected in the previous system

In 2018, López-Vargas et al [20] developed a datalogger based on an IoT (Internet of Things) application. These authors stated that integrating IoT allows SHSs to be remotely monitored and the data measured by the datalogger to be visualized using laptops or smartphones. Moreover the use of open IoT cloud platforms minimizes the cost of monitoring systems. 3G Internet connectivity was added. Instantaneous information is received,so the operating and maintenance problems related to the of the stand-alone PV system can be rapidly detected and solved. Three of these dataloggers were installed at three different locations: Oaxaca (Oaxaca, Mexico), Alcalá de Henares (Madrid, Spain) and the EPS Linares (Jaén, Spain). The authors intensively tested the three dataloggers for a 12–months period to identify the datalogger’s performance when failure occurred. The experimental campaign demonstrated that the installed dataloggers were highly reliable as only 4 failures were recording over 1 year and the origin of most failures was external. They classified the failures found during the experimentation campaign as access failures, power failures, network failures and equipment failures. The origin of access, power or network failures is usually external and not linked to the datalogger. Equipment failures comprise the most hazardous failures because they refer to datalogger failures. Such failures include errors such as sensor breakage, errors in the connection system or even the complete breakdown of the monitoring system. While the other failures (access, power, network) do not have permanent consequences and only imply operation temporarily stopping, equipment failures can permanently affect some datalogger functionalities and can even render it inoperative. The datalogger located in Oaxaca recorded 1 error as a result of network outage. The datalogger installed in Alcalá de Henares failed on 1 occasion due to power shortage. The datalogger in Linares registered two errors: equipment failure and failed access to the server. The error detected in Alcala did not have any consequences as the datalogger was designed to re-hook and resend data after power shortage. However, the other recorded failures revealed that some system operation aspects can improve.

The equipment failure was recorded in the datalogger installed in Linares on 29/06/2017 and the system was rendered inoperable and stopped transmitting data. In Linares, PV systems and electronic equipment have to withstand very harsh environmental conditions in summer: temperatures up to 45°, dust storms, and occasional high-speed electrical storms and heavy rain. The ambient temperature recorded on the days before the error exceeded 40℃. A refrigeration system formed by two fans was installed, but was not enough: the Tec, temperature measured inside the electrical cabinet (where the datalogger was located), surpassed the ambient temperature and exceeded 47 ℃, which went well above the connectivity system's (router and modem) maximum operative conditions. After inspecting the system it was confirmed that, the data delivery system had stopped working. The connectivity system was not broken, but a manual re-configuration was necessary. So the failure was recorded as an equipment failure in the connectivity system due to extreme temperatures.

The other major detected problem was the loss of data due to network and access failures. Two monitoring systems were installed in Oaxaca: the

Arduino™ datalogger and a “LabJack™ U12 series” commercial datalogger. The commercial datalogger was configured for storing data in a folder shared over the internet. On 17/06/2017, a failure was detected: both the Arduino™ monitoring system and the commercial datalogger stopped sending data. On 19/06/2017, both the Arduino™ and the commercial dataloggers started sending data again. The error was classified as a network failure because the commercial datalogger had to be initialized manually to send data if power failure ocurred. Subsequently, frequently networks failures were recorded at the Oaxaca site, and these failures led to loss of data during fault periods. On 16/11/2017, an access failure to the server installed in Linares was recorded. As maintenance activities were performed, the server installed in Linares was disconnected for short periods of time which affected all three dataloggers. During these periods, the monitoring were unable to connect to the server and data were lost.

The ultimate goal of this work is to optimize the datalogger, by running the system at stream temperatures and reinforcing the data storage system. The thermal evaluation of the system to guarantee the reliability of the long-term datalogger was made by running an indoor campaign (temperature cycling tests) and evaluating of the dataloggers under real conditions for 3 years. Further main optimization strategies included designing, and testing a new backup storage system.

6.2. Indoor temperature stress tests

Figure 38 shows the configuration of the entire monitoring system by focusing on operating temperatures. Of the numerous options to connect the OSHW platform to the Internet using 3G, the TL-MR3020 router from TP-LINK was selected given its potential to configure Wi-Fi and 3G transmission systems at a low price. This device requires an external 5VDC/1A power supply and the temperature range operates at goes from 10 °C to 60 °C with relative humidity conditions within a range from 10% RH to 90% RH (non-condensing). As the router has an on-board interface USB 2.0 port, the 3G operating mode was configured by providing an Internet connection via a 3G USB stick modem. For this purpose, the MA260 modem from TP-LINK was selected. The USB modem operating temperature range is 0 °C to 40 °C. So, the operating temperature of the entire system (router and modem) is limited by the most restricted values: 10 °C - 40 °C. The operating temperature of the connectivity system is the most limited.

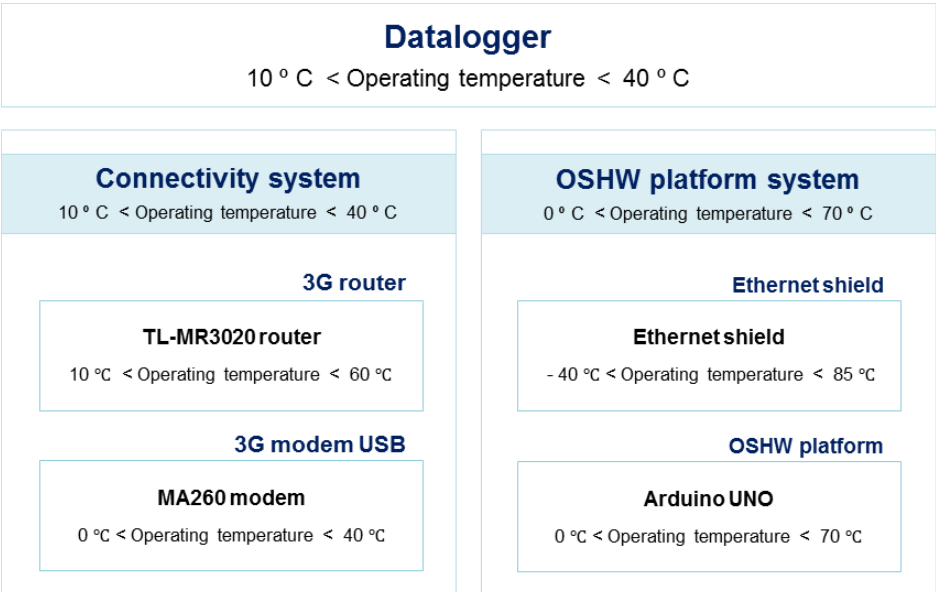


FIGURE 38: Global diagram of the monitoring system: operating temperatures.

As the system's maximum operative conditions were reached, by all accounts it would seem that an equipment failure in the connectivity system was due to high temperatures. After inspecting the system, it was found that, in fact, the data delivery system (consisting of the nanorouter and modem) stopped working. The connectivity system was not broken, but it was necessary to reset the nanorouter and reconfigure it manually.

6.2.1. Experimental evaluation of high temperature testing

A test campaign was designed to check the system's performance under adverse environmental conditions. The system's behavior at extreme temperatures to determine if that was the cause of failure. An experimental campaign that focused on the system's performance according to temperature and time was run. The objective of the test was to replicate the conditions that could have triggered the failure on 29/06/2017. Performing the text in a confined space allows to control times and experiment conditions.

International standard IEC60068 contains a collection of methods for the environmental testing of electronic equipment to assess its ability to perform under environmental conditions, including extreme cold and dry heat. IEC 60068-2-14 [21] provides a test to determine the ability of components, equipment or other articles to withstand rapid changes in ambient temperature (N test). As this involves the prototype level and the datalogger is not yet commercialized, the application of this standard is not required.

To design the experimental campaign, the data measured by the datalogger installed in Linares (Jaén, Spain) were used. The prototype specifically designed for measuring SHSs includes a wide range of climate measures: irradiance (G_i), ambient temperature (T_{amb}), humidity (H), wind velocity (W) and rainfall (R). DS18B20 temperature sensors from Maxim Integrated™ were used to acquire the PV module temperature (T_{mod}), the temperature measured inside the electrical cabinet (T_{ec}) and the PV battery temperature (T_{bat}). The electrical parameters measured by the low-cost datalogger included PV generator output voltage (V_A), battery voltage (V_S), load voltage (V_L), PV generator output current (I_A), battery current (I_S) and load current (I_L). The datalogger was installed inside an electrical cabinet.

6.2.1.1. Test design

To test design, an exhaustive study of the data collected in the month prior to the failure recorded in Linares on 28/6/2017 was conducted by paying special attention to the measured temperatures. Table XXI shows the minimum, maximum and average values of the ambient temperature (T_{amb}), the temperature inside the electrical cabinet (T_{ec}) and the humidity (H) recorded in Linares from 1/6/2017 to 28/6/2017.

TABLE XXI: CLIMATIC PARAMETERS MEASURED IN LINARES BETWEEN 1/6/2017 AND 28/6/2017

	Ambient Temperature [ºC]			Humidity [%]			Electrical Cabinet Temperature [ºC]		
Date	Minimum value	Average value	Maximum value	Minimum value	Average value	Maximum value	Minimum value	Average value	Maximum value
01/06/2017	19.3	27.18	36	14.2	32.87	55.9	20.62	31.35	42.63
02/06/2017	20.5	27.88	36.2	21.1	36.58	57.6	21.5	32.31	43.69
03/06/2017	20.7	26.82	32.8	12.4	35.56	59.1	21.5	31.02	39.75

	Ambient Temperature [ºC]			Humidity [%]			Electrical Cabinet Temperature [ºC]		
Date	Minimum value	Average value	Maximum value	Minimum value	Average value	Maximum value	Minimum value	Average value	Maximum value
04/06/2017	19.1	24.76	29.5	13.9	32.57	55	20	28.74	36.88
05/06/2017	15	23.33	30.1	19.1	34.91	59.3	16.5	27.71	37.44
06/06/2017	16.7	24.28	32.1	19.7	32.93	55.6	17.19	28.75	39.06
07/06/2017	18.4	27.64	36.7	15	26.63	41.3	19.62	31.49	43.94
08/06/2017	19.6	28.97	37.4	14.1	23.67	38	21	32.71	45
09/06/2017	21.5	27.51	34.3	16.4	31.45	49	22.5	31.6	41.81
10/06/2017	19.2	29.28	38.2	16.7	28.76	49.3	20.94	33.51	45.5
11/06/2017	21	30.56	39.1	15.9	28.41	49.6	22.12	34.5	45.06
12/06/2017	21.7	31.02	38.8	13.3	21.17	34.9	22.37	34.38	44.5
13/06/2017	21.6	30.89	39	16.6	27.2	47.8	22.5	34.82	46.56
14/06/2017	20.9	29.99	40.2	16	41.05	70	22	34.67	47.56
15/06/2017	22.7	30.77	41.3	17.1	39.37	64.9	23.81	35.27	48.69
16/06/2017	27.2	33.29	42	16.2	26.52	38.4	28.19	36.65	48.69
17/06/2017	24.9	32.59	41.5	15.5	27.32	42.8	25.5	36.76	49.31
18/06/2017	24.5	32.19	40.3	15.3	25.75	42.1	25.5	36.38	48.19
19/06/2017	22	30.43	39.1	15.7	31.5	57.7	22.87	34.05	47.69
20/06/2017	23.4	31.35	39.5	15.7	28.49	44.6	24.06	35.42	46.81
21/06/2017	23.4	31.08	39.9	14.5	29.95	42.5	24	35.42	47.75
22/06/2017	22.1	30.08	38	20.1	41.88	74.3	23.06	34.67	45.88
23/06/2017	22	30.22	38.1	6.1	31.26	58.9	22.69	34.49	45.44
24/06/2017	21.4	31.61	40.7	14.3	21.46	36.3	22.44	35.25	47.63
25/06/2017	24.2	30.34	37.4	18.6	26.32	36.5	26.19	32.71	43
26/06/2017	20	27.67	34.2	12.9	35.2	66.1	21.44	31.66	40.44
27/06/2017	18.6	24.69	30.8	17.3	34.17	61.7	19.69	28.44	36.63
28/06/2017	18.1	23.67	28.2	27.7	43.84	64.7	19.19	27.54	34

As shown in Table XXI, the electrical cabinet temperature was 6-9 ºC higher than the ambient temperature. So the electrical cabinet temperature will be used for the test design.

6.2.1.2. Selecting severities

The severities of the test comprises the maximum temperatures, the speed of variation of temperature selected, the time the datalogger was exposed and the number of cycles to which the datalogger was subjected to.

a) Selecting temperatures

Figure 39 shows the monthly variation in the maximum ambient temperature and maximum electrical cabinet temperature. The worst case was recorded on 17/06/2017, when the temperature inside the electrical cabinet reached 49º C (ambient temperature of 41º C,). For this reason, the temperature to which the datalogger was subjected had to be above 49º C. The minimum electrical cabinet temperature values fell within the range of 16º C - 27º C, so this parameter was not decisive in the test.

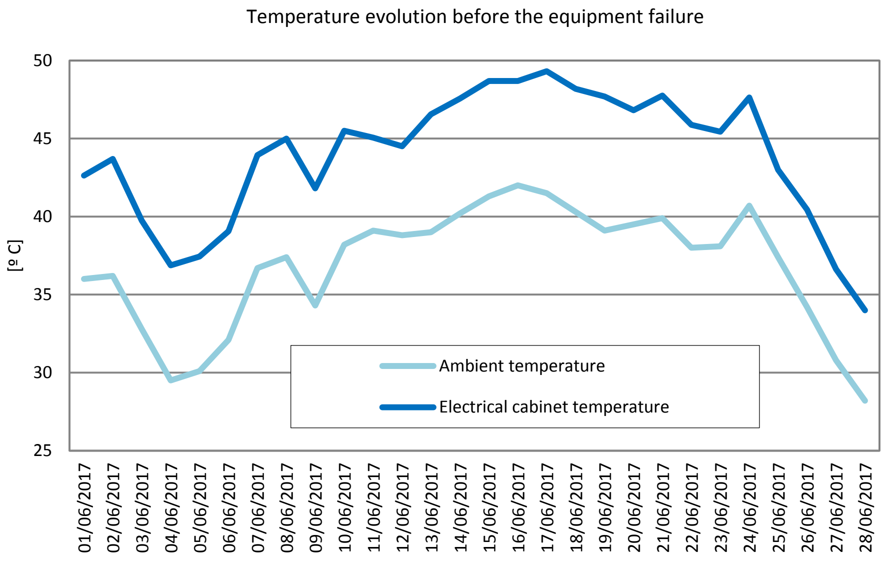


FIGURE 39: Maximum values of ambient temperature and electrical cabinet temperature measured in June 2017 by the prototype installed in Linares (Jaén, Spain).

b) Speed of variation temperature

To select the speed of variation temperature, the real data captured by dataloggers before the equipment failure occurred were used. The gradients of curves were studied. Figure 40 shows the worst case, with the most abrupt change in temperature in less time. This was recorded on 29/06/2017. A rise of approximately 0.09 ° C/min was recorded. This value corresponds to the maximum speed of recorded variation temperature.

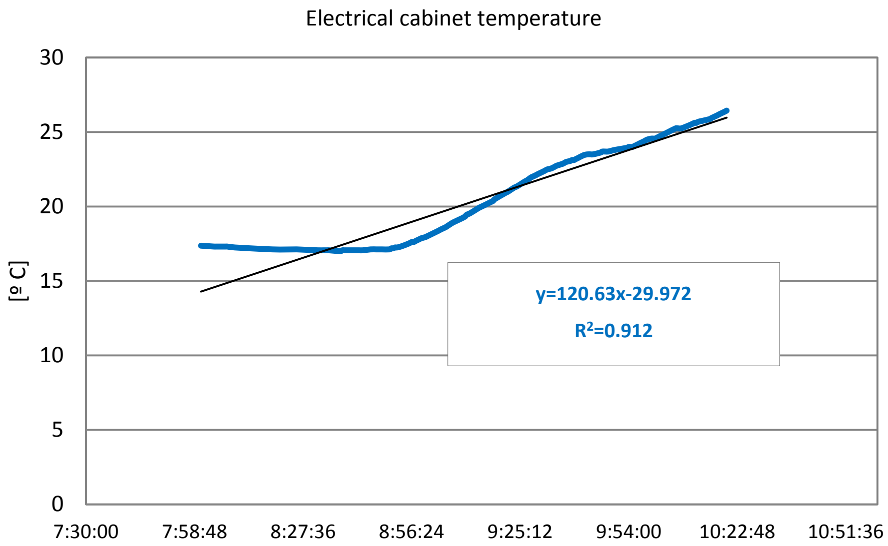


FIGURE 40: Worst case: speed of variation temperature. Measured in Linares on 29/6/2017.

c) Test exposure time

After studying the cycle of temperatures, the average duration of the cycle of the growing of the electrical cabinet temperature was 11hours (see Fig.41) which was taken as the exposure time selected for the test.

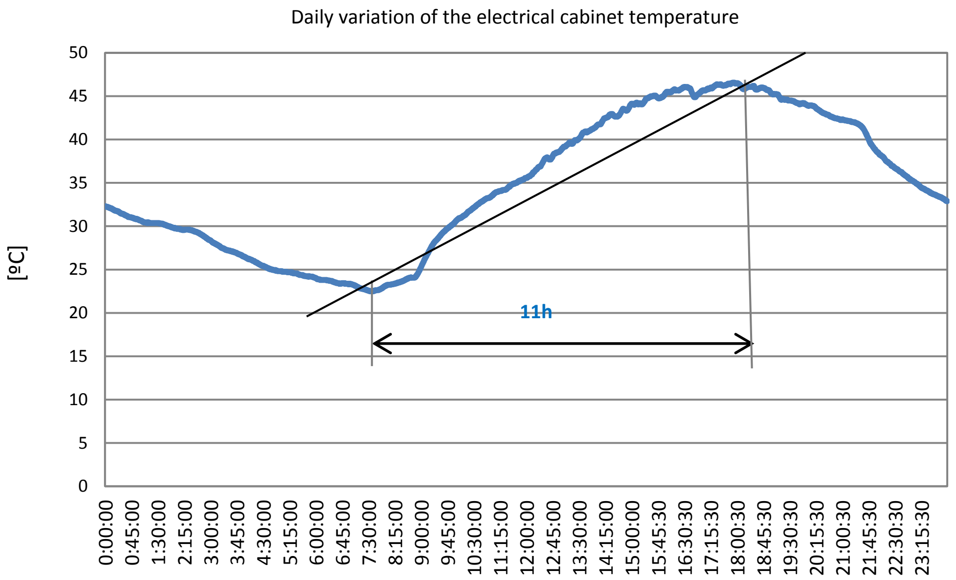


FIGURE 41: Data recorded in Linares on 13/6/2017.

d) Number of cycles

The number of days per year in which the ambient temperature reached 40ºC was limited (the electrical cabinet temperature is 6-9 ºC higher than the ambient temperature). In 2017, in Jaén (where the equipment failure occurredsee Table XXII), there were 13 days with a maximum temperature reached 40º C. Thus the number of cycles selected for the temperature test was 20 cycles.

TABLE XXII: EXTREME AMBIENT TEMPERATURE (>40 º C) MEASURED IN JAÉN IN 2017

Day	Month	Average Temperature [º C]	Maximum temperature [º C]	Minimum temperature [º C]
16	June	33.2	40.8	27.3
17	June	33.8	41.2	28.1
24	June	32.4	40.2	23.8
11	July	31.6	40.2	23.2
12	July	34.4	43.5	25.3
13	July	36.9	44.7	27.2
14	July	35.9	44.1	26.3
18	July	33.2	40.2	26.2
28	July	32.8	40	24.2
29	July	32.7	40.1	22.8
30	July	32.9	40.2	24.1
4	August	33.1	42.1	23.4
5	August	35	41.2	27.1
6	August	34.1	40.4	24.9
7	August	33.3	40.1	26.2
19	August	32.9	40.2	24.2
20	August	32.8	40.7	25.2
20	August	32.8	40.7	25.2

6.2.2. Temperature test in a confined space: Setup

A climate chamber (Binder EIW-179) was used for the temperature test. This climate chamber allows to select the set-point temperature as well as the speed of temperature variation till reaching it. The ambient temperature inside the climate chamber was measured by a DHT22 digital sensor. The DHT22 sensor measures temperature and relative humidity [22]. Prior to experimentation, individual test cycles were run to find that the relative humidity values recorded inside the climate chamber were appropriate, within the range of relative humidity values measured in Linares between 1/6/2017 and 28/6/2017 (Table XXI).

Table XXIII shows the final values selected to run the temperature test. The maximum recorded rise was approximately 0.09 ° C/min. Given the resolution of the employed chamber, the selected speed of temperature variation was 0.1 ºC /min. Figure 42 shows the block diagram of the entire experiment including Experiments 1 and 2. The process is composed of two experiments; each experiment comprised 10 cycles. The maximum temperature used in Experiment #1 was 50 ℃; the maximum temperature raised in Experiment #2 was 55 ℃. They were consecutive processes: to start the Experiment #2 the datalogger had to pass Experiment 1 before.

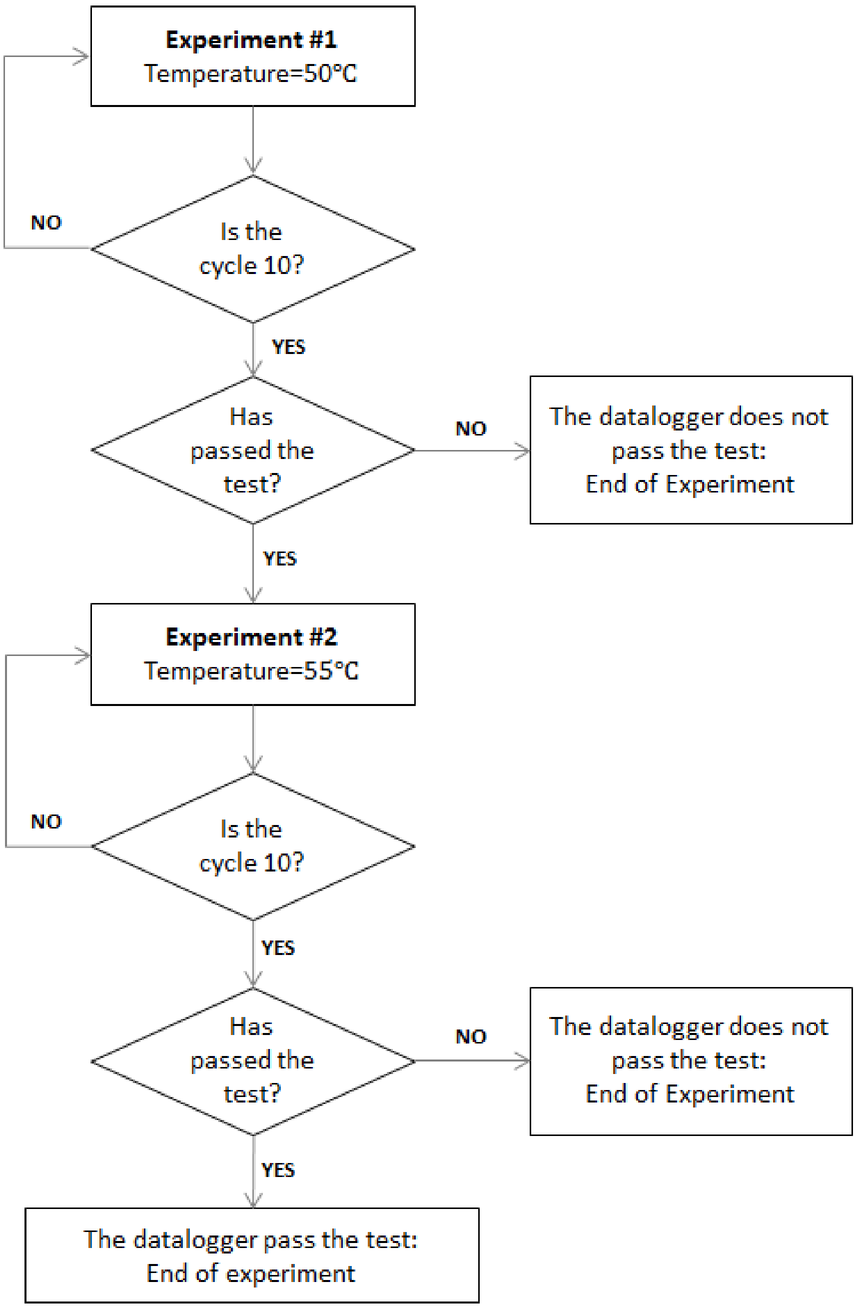


FIGURE 42: Block diagram of the entire experiment

TABLE XXIII: FINAL VALUES SELECTED FOR THE TESTS

Parameter	Experiment 1	Experiment 2
Maximum temperature	50 º C	55 º C
Speed of variation of the temperature	0.1 º C /min	0.1 º C /min
Exposure	11 hours	11 hours
Number of cycles	10	10

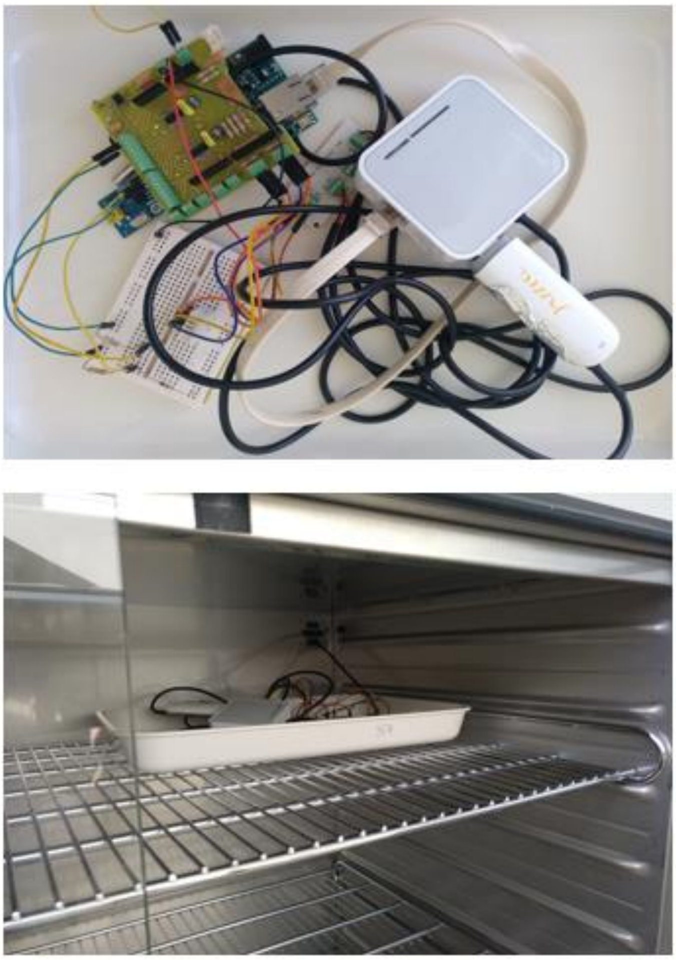
a
b


FIGURE 43: Prototype assembly used in all tests (a) and prototype under test in the climatic chamber (b).

The temperatures of both the modem and router were measured. The temperature of the microprocessor was also monitored. DS18B20 digital temperature sensors from Maxim Integrated™ were used for this purpose. Figure 43 shows the used configuration.

TABLE XXIV: TEMPERATURE MEASURED IN THE TESTS

Cycle	Date	Maximum modem temperature [°C]	Maximum processor temperature [°C]	Maximum router temperature [°C]	Maximum ambient temperature [°C]
1	29/05/2018	54.94	52.06	55.25	47.2
2	30/05/2018	56.56	55.38	55.75	47.2
3	31/05/2018	59.19	57.44	59.13	50.2
4	01/06/2018	59.13	57.5	59.13	50.2
5	04/06/2018	59.19	57.5	59.13	50.2
6	29/06/2018	59	54.81	58.69	50.2
7	02/07/2018	59.69	54.81	58.56	50.2
8	03/07/2018	59.63	54.81	58.5	50.5
9	04/07/2018	60.56	54.88	59	51
10	17/07/2018	62.13	55.56	59.13	50.8
11	18/07/2018	67.12	60.19	63.75	55.5
12	19/07/2018	67.56	60.19	63.81	55.4
13	23/07/2018	66.81	60.19	63.63	55.4
14	24/07/2018	67.25	60.25	63.69	55.5
15	25/07/2018	67.19	60.19	63.63	55.5
16	26/07/2018	67.31	60.25	63.69	55.5
17	27/07/2018	66.56	60.25	63.63	55.5
18	30/07/2018	67.19	60.19	63.63	55.5
19	31/07/2018	67.5	60.25	63.69	55.5
20	01/08/2018	68.25	60.25	63.69	55.5

6.2.3. Results of studying the system under harsh environmental conditions

The exposure time of each cycle was 11 h (See Section 6.2.1.2.C) and the speed of temperature variation was 0.1º C/min. The start temperature was the ambient temperature. The set-point temperature was 50 º C (Experiment 1, cycles from #1 to #5) and 55ºC (Experiment 1, cycles from #6 to #10). Table XXIV shows the results of the measured temperatures.

Due to variations in the flux of air inside the climate chamber, the measured ambient temperature fell within the ranges of 47.2 – 51 º C (cycles from #1 to #5, set-point temperature of 50 º C) and 55.4 – 55.5 º C (cycles from #6 to #10, set-point temperature of 55 º C). The maximum router temperature measured was 63.81 º C and the maximum modem temperature measured was 68.25 º C. The datalogger reached 60.25 º C. Figure 44 shows an example of the temperature profile used in the test jointly with the %RH measurement. Gradient, temperature and time values were defined using the experimental data (See Section 6.2.1.1.).

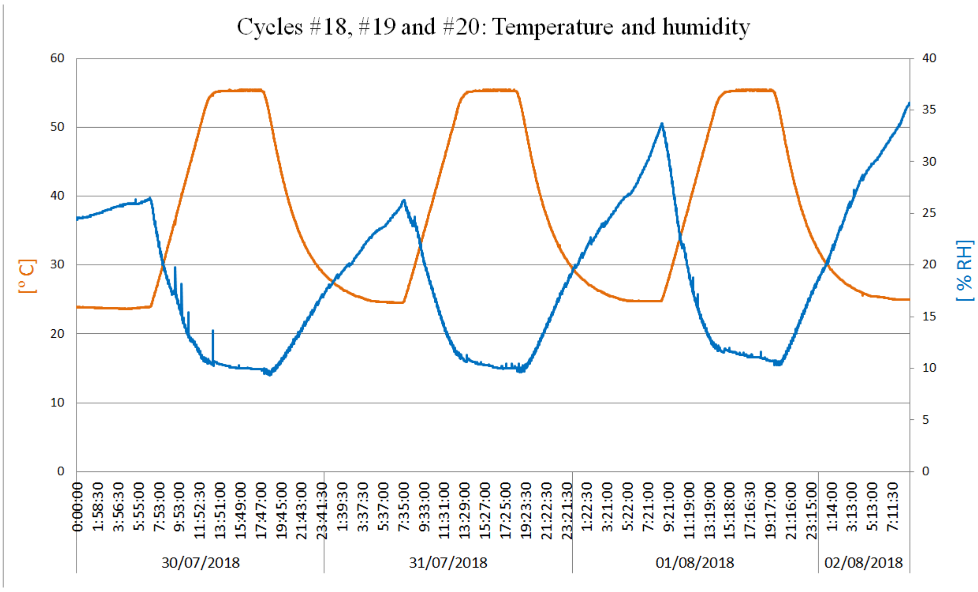


FIGURE 44: Temperature and humidity profiles: cycles #18, #19 and #20.

The rise period was programmed according to the worst case of the recorded gradients, and the maximum temperature was reach in approximately 5 h. Afterward, the cycle was extended to complete 11 h. When the maximum temperature was reached, the chamber was disconnected, the cycle's relaxing time started and the system was driven to ambient temperature.

The main result of this experimental campaign was that, the datalogger passed the temperature tests. During the 20 cycles, it measured correctly and did not stopp sending data. Even with the most critical functions, such as connectivity and data transmission functions that were the most temperature-sensitive functions (see Section 6.3), it correctly operated.

The results of the three dataloggers' 3-year uninterrupted operation under real conditions were excellent. Only one equipment failure occurred (the datalogger installed in Linares on 2/8/2018) which demonstrates system's reliability. On that day, the ambient was temperature 41 º C. The temperature inside the electrical cabinet (where the datalogger was installed) went above 48 º C.

6.3. Long-term performance in harsh environment

In order to check the system's performance under real experimental conditions, monitoring systems in uninterrupted operation measured electrical and climatic conditions every 30 s. This test provided information on the system's performance in presence of different humidity levels, temperatures or dust (among other variables).

6.3.1. Dataloggers under real climate conditions

Apart from the temperature tests, different versions of the monitoring systems were installed to test their performance under real climate conditions. The systems sent data every 30s. Table XXV describes the tested systems, their locations and time periods they operated in.

TABLE XXV: DATALOGGERS INSTALLED AND TESTED UNDER REAL CLIMATIC CONDITIONS; VERSIONS AND LOCATIONS.

Version	Location	Time of operation
Datalogger SD [19]	Linares, Jaén, Spain. Latitude 38.085° N, longitude 3.646° W	3 years
Datalogger with 3G connectivity [20]	Alcalá de Henares, Madrid, Spain. Latitude 40.513° N, longitude 3.339° E	3 years
Datalogger with 3G connectivity [20]	Linares, Jaén, Spain. Latitude 38.085° N, longitude 3.646° W	3 years
Datalogger with 3G connectivity and SD backup system	Linares, Jaén, Spain. Latitude 38.085° N, longitude 3.646° W	8 months

Dataloggers monitor a real SHS. In the three cases, the PV system included an 80 W mono-crystalline module, a 12 V lead-acid battery (90 Ah-

C100) and a PWM serial charge controller. Fig. 45 shows two of the dataloggers installed in Linares.

FIGURE 45: Two of the dataloggers installed in Linares: Datalogger SD version and Datalogger with a 3G connectivity version.

6.3.2. Long-term performance: Results

The installation of measurement systems allowed to evaluate the real behavior of the dataloggers and to record the possible errors that could did not appear working under real conditions. As stated before, different types of failures were identified: access failures, power failures, network failures and equipment failures. After extending the experimental campaign period to 3 years under adverse weather conditions, a few external failures were recorded, such as power shortage or server drops that hindered the data storage).

The experimental campaign also allowed the effect of expositing of the system to adverse conditions to be studied. Deterioration was mainly detected in sensors. The temperature and humidity sensor installed in Madrid broke. The sensor correctly measured temperature but, the humidity measurement was wrong: the relative humidity was 100% even on sunny days.

For the datalogger with 3G connectivity installed in Linares, the current sensor did not correctly measure. The sensor’s measurement was correct, but, some peaks often appeared as shown in Figure 46. Both sensors (humidity and current sensors) were replaced. As the system was designed using low-cost sensors, replacing damaged sensors had no economic impact.

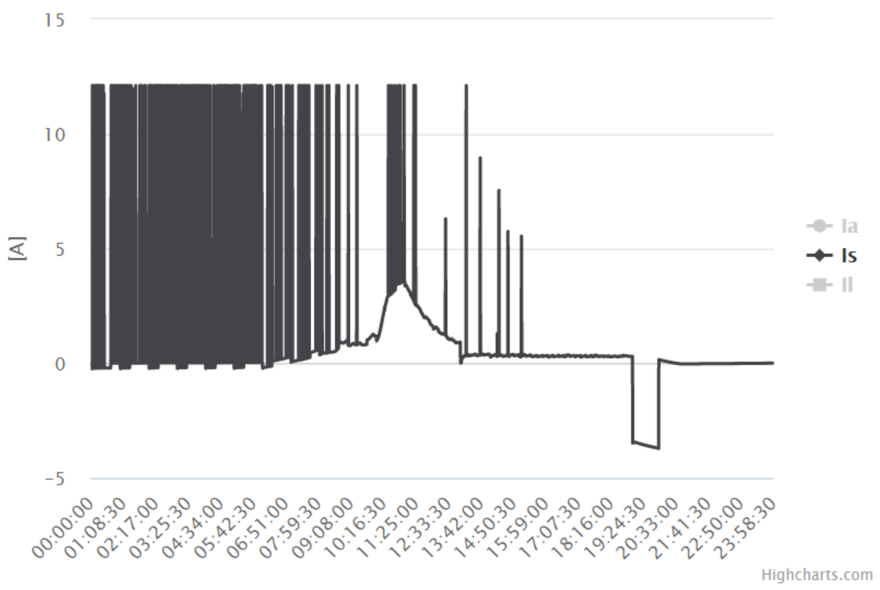


FIGURE 46: Battery current measured in Linares (24/6/2018).

Very few failures were recorded in all the dataloggers and the origin of most of them was external (power shortage, server falls,etc.) or, for the damaged sensors, failures were due of usual system deterioration when installed outdoors. The experimental campaign showed that the datalogger was most reliable and robust: it has been demonstrated that the datalogger is designed especially to work correctly under harsh conditions.

6.4. Addressing communication failures – adding redundancy to the system (SD)

López-Vargas et al. [20] installed a low-cost datalogger in Oaxaca; these authors recorded network failures with a certain frequency and these failures led to loss of data during the fault period. As a future improvement to avoid loss of data, they proposed implementing a backup system for data storage.

To help monitor PV system in remote areas of developing countries that lack electricity and wired telecommunication networks, a datalogger being independent of an external source (e.g. laptop) is crucial [23]. Hence, the use of an SD as a backup unit for data storage proved to be the best suited solution. However, due to the limited memory [24] of the Arduino™ UNO, integrating additional software to implement the storage process in an SD card as a backup system was no feasible.

An advanced board was selected as a solution. Arduino™ MEGA was presented as the best option given its extended memory and its compatibility with hardware improvements [19]. All the hardware designs were adaptable to the new platform. Table XXVI shows the comparison made between the Arduino™ UNO and Arduino™ MEGA boards. Every minute, in second 0 and second 30, parameters are measured. Every 30 s, after measuring and transmitting data, data were stored: in the cloud and the SD card (backup).

TABLE XXVI: ARDUINO™ UNO AND ARDUINO™ MEGA 250 COMPARISON

Name	UNO	MEGA250
Processor	ATmega328P	ATmega2560
Operating/Input Voltage	5 V / 7-12 V	5 V / 7-12 V
CPU Speed	16 MHz	16 MHz
Analog In/Out	6/0	16/0
Digital IO/PWM	14/6	54/15
EEPROM [kB]	1	4
SRAM [kB]	2	8
Flash [kB]	32	256
USB	Regular	Regular
UART	1	4
Price [€]	19	35

6.4.1. Integrating a backup data storage system

To avoid loss of data if failures occur(network, access,etc.), a backup system based on a micro SD card was integrated into the datalogger to prevent loss of data bystoring the measured parameters if a network failure occurs during disconnection periods.

Due to the change in platform (that implies a change of processor as shown in Table XXVI) the datalogger optimized was installed in Linares, Jaén, Spain. (latitude 38.085° N, longitude 3.646° W), for studying the behavior of the system under harsh environmental conditions. The dataloger measured ambient temperature, modem temperature and router temperature (digital Dallas sensors). Every 30 s, these parameters were sent to a server located in Jaén and in the cloud.

6.4.2. Results of the datalogger with a backup storage system

The datalogger with the backup storage system based on an SD card was installed on the rooftop of the EPS Linares, Jaén, Spain (latitude 38.085° N, longitude 3.646° W). In the summer of 2018 this datalogger ran continuously. Fig. 47 shows the temperature evolution recorded in the hottest month of the year in Jaén.

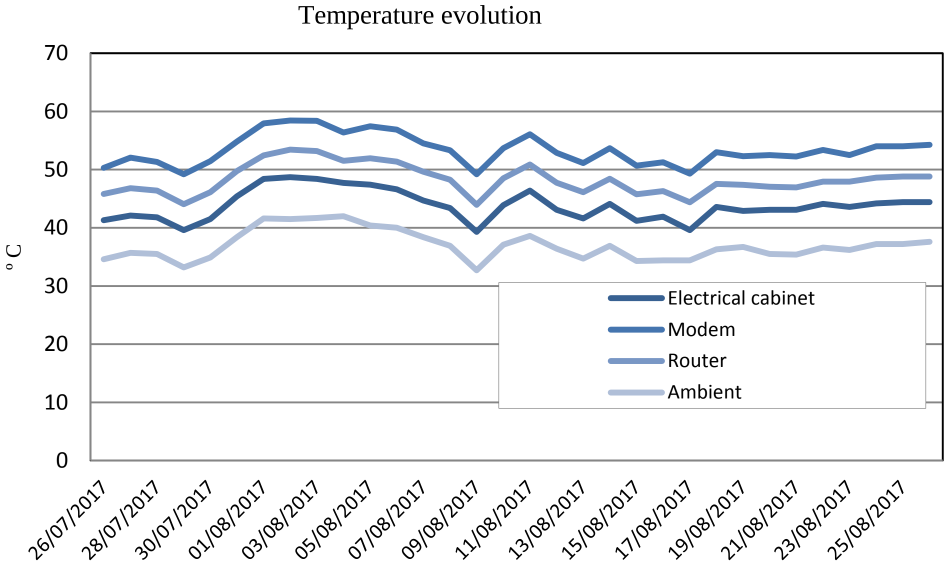


FIGURE 47: Temperature evolution measured by the datalogger designed around the platform Arduino^{TM} MEGA with a backup system of storage in Linares (Jaén, Spain) in August 2018.

During this period, ambient temperatures up to 40 º C were reached. The datalogger was installed inside an electrical cabinet, where the measured temperatures were higher: the datalogger worked at operating temperatures over 48 º C. The datalogger measured correctly. No failures were recorded for either sensing or connectivity functions.

6.5. Summary and Conclusions

It was demonstrated that the low-cost datalogger intended for stand-alone PV systems in developing countries met the accuracy requirements established by the IEC61724 standard about photovoltaic monitoring systems [15] and the integration of 3G connectivity with storage in a dedicate server and the cloud [16] was satisfactory. For studying the reliability of the measurements, a high-accuracy commercial datalogger was used as a pattern [15]. However, given the extreme climate conditions in many developing countries, the datalogger had undergone different performance tests

Three different versions of the datalogger were installed at different sites: datalogger with SD storage, datalogger with 3G connectivity and datalogger with a backup system for storing data if communications failures occurred. These monitoring systems were installed to take continuous measurements and they have worked from the date they were installed to the present-day uninterruptedly. Very few errors were recorded. The origin of all failures but one was external and not linked to the datalogger: network, power and access failures. One equipment error was recorded that was attributable to high temperatures.

The experimental campaign allowed to study the effect of exposing hardware to adverse conditions with deteriorating sensors: wrong humidity measurements due to DHT sensor breaking and peaks in current measurements due to the Hall-Effect current sensor breaking. Low-cost sensors were selected for the integration in the monitoring systems. After operating 3 years, the replacement of two sensors (8,98€) can be considered a minimum maintenance cost.

As stated above, equipment failures comprise the most hazardous failures. An equipment failure was registered in Linares that left the datalogger inoperative; and as it was attributed to the effect of high temperatures, this work focuses on the study of the reliability of the system by subjecting the datalogger to harsh temperature conditions.

The robustness of the system was proven by two different tests: first, the datalogger was subjected to extreme temperatures under controlled conditions while working under real conditions; the second test (long-term performance) comprised 3 years of continuous operation at the different sites. For the first test, the datalogger passed the temperature tests designed (applying the worst conditions measured) in a confined space. During 20 cycles the datalogger measured well and it did not stop sending the data. The most critical functions, the connectivity and data transmission functions passed the test. It was demonstrated that the datalogger is highly reliable measuring correctly even at 55º C.

After uninterruptedly operating under real conditions for 3 years, only one equipment failure occurred (three installed dataloggers); the datalogger recorded all the parameters in an uninterrupted way demonstrating the robustness of the system under real and uncontrolled climatic conditions. The results demonstrated that the datalogger is robust and endures extreme conditions.

The errors in the meteorological measurements were below 5% and the errors measured by electrical sensors were $< 1\%$ as set out in the IEC standard. To avoid loss of data, a redundant system based on an SD card was implemented, requiring the change of processor due to the limitation of memory. This improvement accounted for an increase in the final cost of only 16€. This latter datalogger version with a backup storage system based on an SD card was installed in the rooftop of the EPS Linares, Jaén, Spain (Latitude 38.085° N, longitude 3.646° W). In the summer of 2018 this datalogger was continuously running. The datalogger worked at operating temperatures over 48 º C. As no failure has been detected to date we can conclude that this datalogger version is robust and very reliable.

6.6. References

[1] M. Fuentes, M. Vivar, H. Hosein, J. Aguilera, E. Muñoz-Cerón, 'Lessons learned from the field analysis of PV installations in the Saharawi refugee camps after 10 years of operation', Renewable and Sustainable Energy Reviews, Vol 93, pp.100-109, 2018.

[2] T. Urmee, D. Harries, and A. Schlapfer, "Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific," Renew. Energy, vol. 34, no. 2, pp. 354–357, 2009.

[3] F. D. J. Nieuwenhout, A. Van Dijk, V. A. P. Van Dijk, D. Hirsch, P. E. Lasschuit, and G. Van Roekel, “Monitoring and evaluation of experiences with applications of solar PV for households in developing countries” September, 2000.

[4] H.E. Gad, H.E. Gad, “Development of a new temperature data acquisition system for solar energy applications”, Renew. Energy 74 (2015) 337–343.

[5] L. J. Claros-Marfil, J. F. Padial, and B. Lauret, “A new and inexpensive open source data acquisition and controller for solar research: Application to a water- flow glazing”, Renewable Energy, vol. 92, pp. 450–461, 2016.

[6]P. Papageorgas, D. Piromalis, K. Antonakoglou, G. Vokas, D. Tseles, and K. G. Arvanitis, “Smart solar panels: In-situ monitoring of photovoltaic panels based on wired and wireless sensor networks”, Energy Procedia, vol. 36, pp. 535–545, 2013.[7] Amely Jumaat, Siti & Hilmi Othman, Mohamad. (2018). Solar Energy Measurement Using Arduino. MATEC Web of Conferences. 150. 01007. 10.1051/matecconf/201815001007.

[8] Sadowski, Sebasttian & Spachos, P. (2018). Solar-Powered Smart Agricultural Monitoring System Using Internet of Things Devices. 18-23. 10.1109/IEMCON.2018.8614981.

[9] R. I. S. Pereira, I. M. Dupont, P. C. M. Carvalho, and S. C. S. Jucá, “IoT embedded linux system based on Raspberry Pi applied to real-time cloud monitoring of a decentralized photovoltaic plant”, Measurement, vol. 114, no. August 2017, pp. 286–297, 2018.

[10] F. Touati, M. A. Al-Hitmi, N. A. Chowdhury, J. A. Hamad, and A. J. R. San Pedro Gonzales, “Investigation of solar PV performance under Doha weather using a customized measurement and monitoring system”, Renew. Energy, vol. 89, pp. 564–577, 2016.

[11] A. J. Lewis, M. Campbell, and P. Stavroulakis, “Performance evaluation of a cheap, open source , digital environmental monitor based on the Raspberry Pi”, Measurement, vol. 87, pp. 228–235, 2016.

[12] José Miguel Paredes-Parra, Antonio Mateo-Aroca, Guillermo Silvente-Niñirola, María C. Bueso and Ángel Molina-García PV Module Monitoring System Based on Low-Cost Solutions: Wireless Raspberry Application and Assessment. Energies 2018, 11(11), 3051; https://doi.org/10.3390/en11113051

[13] M.E.A. López, F.J.G. Mantiñan, M.G. Molina, “Implementation of wireless remote monitoring and control of solar photovoltaic (PV) system”, in: Transm. Distrib. Lat. Am. Conf. Expo., 2012, pp. 1–6.

[14] F. Shariff, N.A. Rahim, W.P. Hew, “Zigbee-based data acquisition system for online monitoring of grid-connected photovoltaic system”, Expert Syst. Appl. 42 (2015) 1730–1742.

[15] K.H. Chao, C.T. Chen, “A remote supervision fault diagnosis meter for photovoltaic power generation systems”, Measurement 104 (2017) 93–104.

[16] P. Papageorgas, D. Piromalis, K. Antonakoglou, G. Vokas, D. Tseles, and K. G. Arvanitis, “Smart solar panels: In-situ monitoring of photovoltaic panels based on wired and wireless sensor networks”, Energy Procedia, vol. 36, pp. 535–545, 2013.

[17] SIMbaLink: Towards a Sustainable and Feasible Solar Rural Electrification System

[18] M. Fuentes, M. Vivar, J. M. Burgos, J. Aguilera, and J. A. Vacas, Design of an accurate, low-cost autonomous datalogger for PV system monitoring using Arduino^{TM} that complies with IEC standards, Sol. Energy Mater. Sol. Cells, vol. 130, pp. 529–543, Nov. 2014.

[19] A. López-Vargas, M. Fuentes, M. Vivar, and F. J. Muñoz-Rodríguez. “Low-cost datalogger intended for remote monitoring of solar photovoltaic stand-alone systems based on Arduino^{TM},” IEEE Sensors Journal, Accepted.

[20] A. López-Vargas, M. Fuentes and M. Vivar, "IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino™ With 3G Connectivity," in IEEE Sensors Journal, vol. 19, no. 2, pp. 679-691, 15 Jan.15, 2019.

[21] IEC 60068-2-14 Basic environmental testing procedures Part 2: Tests – Test N: Change of temperature

[22] <https://www.sparkfun.com> (accessed 19.06.2019)

[23] A. López-Vargas, M. Fuentes, M. Vivar. "Current challenges for the advanced mass scale monitoring of Solar Home Systems and the potential of open-source tools and Internet of Things for solar monitoring applications: A review". IEEE Internet of Things Journal, to be published.

[24] < https://www.arduino.cc/ > (accessed 26.04.2019).

[25] Real- time reliability test for a CPV module based on a power degradation model

[26] < http://www.bb-elec.com/Learning-Center/All-White-Papers/Fiber/MTBF,-MTTR,-MTTF,-FIT-Explanation-of-Terms/MTBF-MTTR-MTTF-FIT-10262012-pdf.pdf> (accessed 29.07.2019).

Chapter 7

Challenges and Opportunities of the Internet of Things for Development (IoT4D) to Achieve the Sustainable Development Goals

A. López-Vargas, M. Fuentes and M. Vivar," Challenges and opportunities of the Internet of Things for Development (IoT4D) to achieve Sustainable Development Goals".

7.1. Introduction

Internet of Things (IoT) is one of the defining and transformative technologies of our time. IoT is already making great efficiency and productivity gains in industrialized countries, but it would be a mistake to overlook the potential for an even bigger and more significant impact in the developing world [1]. IoT should not be restricted only to the challenges of industrialized countries; in the developing world IoT can act as a key piece to achieve stronger and sustainable development. IoT and connected sensors are driving improvements to human well-being in health care, water, agriculture, natural resource management, resilience to climate change and energy [2], among other areas. Apart from supporting economic growth, IoT also makes a significant contribution to development in both social and ecological terms [3]. Developing countries are ideal for IoT innovation: the problems faced by these countries can open up diverse and unexplored fields to which IoT can be applied [3]. In recent years, IoT projects have started to develop for their application in the developing world, mainly in sub-Saharan Africa and southern. For example, along with the installation of renewable energy system, IoT applications have been installed for the monitoring and management of energy, improving the access to electricity [2,4]. In the health sector, IoT proposals such as the monitoring of cold chain for vaccines have been implemented [5]. Water is another sector with a great potential for IoT: projects focus on the provision of water for both sanitary and agriculture (irrigation) have been also developed in rural areas of developing countries [6,7,8,5]. Emergency situations are one of the potential applications of IoT in developing countries to prevent and face natural disasters [9] detecting earthquakes, tsunamis or typhoons [2].

In 2017, at the 7th IoT Week held in Geneva, the IoT research and industry community, jointly with ITU and other stakeholders, expressed their support for researching, developing and leveraging IoT technologies for sustainable development and for building a brighter future for our planet and its inhabitants [10].The ultimate goal of this work is to study the current context and challenges to successfully apply IoT in developing countries by highlighting the weakness and strengths of its application in the developing world, to achieve the Sustainable Development Goals (SDGs). This work also studies the potential of combining IoT based on open-source tools and new financial models, and reviewing previous works conducted in developing countries using open-source hardware platforms and open cloud platforms.

7.2. IoT opportunities in developing countries

7.2.1. Potential and opportunities of the IoT in the developing world

SDGs were born during the 2012 United Nations Conference on Sustainable Development in Rio de Janeiro by replacing Millennium Development Goals (MDGs) to continue to face poverty beyond 2015 [11]. SDGs (listed in Table XXVIII) are a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity [12], all to be accomplished by 2030.

TABLE XXVIII: LIST OF SUSTAINABLE DEVELOPMENT GOALS [11]

Goal	Description
Goal 1: No poverty	End poverty in all its forms everywhere.
Goal 2. Zero hunger	End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
Goal 3. Good health and well being	Ensure healthy lives and promote well-being for all at all ages.
Goal 4. Quality education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
Goal 5. Gender equality	Achieve gender equality and empower all women and girls.
Goal 6. Clean water & sanitation	Ensure availability and sustainable management of water and sanitation for all.
Goal 7. Affordable & Clean Energy	Ensure access to affordable, reliable, sustainable and modern energy for all.
Goal 8. Decent work & economic growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
Goal 9. Industry, innovation & infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
Goal 10. Reduced inequalities	Reduce inequality within and among countries.
Goal 11. Sustainable cities & communities	Make cities and human settlements inclusive, safe, resilient and sustainable.
Goal 12. Responsible product & consumption	Ensure sustainable consumption and production patterns.
Goal 13. Climate action	Take urgent action to combat climate change and its impacts.
Goal 14. Life below water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
Goal 15. Life on land	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
Goal 16. Peace, justice, and strong institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
Goal 17. Partnerships for the goals	Strengthen the means of implementation and revitalize the global partnership for sustainable development.

By 2025, experts predict that the 40% of economic added value from IoT will be generated in the developing world (upwards trend), according to a KfW Group's report (2016) [13]. The IoT generate economic growth and can also make an important contribution to socially and ecologically sustainable development.

The World Economic Forum's IoT for Sustainable Development project aims to encourage the use of the Internet of Things (IoT) to accelerate progress on the 17 SDGs [14]. In 2018, the analysis of the World Economic Forum [15] reported that 84% of IoT deployments currently address (or have the potential to address) SDGs. This project presented an IoT analytics database of 640+ IoT projects [16] for studying the potential ot IoT to support the SDGs, stated that the 75% of these IoT projects focus on five SDGs; (25%) SDG9, (19%) SDG11, (19%) SDG7, (7%) SDG3 and (5%) SDG12. In addition, results showed that the 95% of projects studied are small/medium sized and the 70% of these IoT4D projects are led by private sector (80% originate in the Americas and Europe).

These IoT solutions could be replicated in the developing world generating new business opportunities. SDGs are interconnected, and often the key to success of one goal involves tackling issues more commonly associated with another. The report ”Harnessing the Internet of Things for Global Development” [2] written as a contribution to the ITU/UNESCO Braoadband Comission for suistanable Development mapped the SDGs in sectors (Table XXIX).

TABLE XXIX
SUSTAINABLE DEVELOPMENT GOALS GROUPED BY IOT SECTOR [19]

No of sector	IoT Sector	Goal
1	Health, Water and Sanitation	SDG3, SDG6
2	Agriculture and livelihoods	SDG1, SDG8, SDG2
3	Education	SDG4
4	Environment and conservation	SDG12, SDG13, SDG14, SDG15
5	Resiliency, Infrastructure and Energy	SDG7, SDG9,SDG11
6	Governance and Human Rights	SDG10, SDG16
7	Cross-cutting	SDG5, SDG17

The review focuses on Sectors 1-5. These areas include the five SDGs with most potential to be addressed using IoT applications. The objectives Zero Hunger (SDG2), Clean Water & Sanitation (SDG6) and Affordable & Clean Energy (SDG7), very important goals that together form the water-energy-food nexus (an index commonly used to measure development) [17, 18] are also included. The IoT context in the developing world as well as profitable IoT projects carried out in developing countries using Sectors 1-5 as a reference are presented below.

a) Health, water and sanitation: More than 2 billion people live without access to safe drinking water and more than twice that number lack access to safe sanitation [20]. Additionally, 850 million people from rural regions in developing countries also have no access to water for agricultural production, which is often their primary source of income [21]. Millions of women and children spend endless hours fetching water from long distances, and water sources are often unclean or unaffordable. So the Clean Water & Sanitation Goal (SDG6) is a precursor to other SDGs, such as health care (SDG3), education (SDG4), gender equality (SDG5) and jobs (SDG8) [22]. The application of IoT provides reliable objective information about the state of water resources, their use and management, and also about wastewater generation and treatment [22]. For example, in rural regions of Africa, an evaluation showed that 30-40% of pumps were nonfunctional and communities have no access to clean water up to 1 month after fixing pumps [23]. GSM enabled water meters to enhance water pump monitoring, especially in cases like India where 85% of drinking water is groundwater-dependent [23]. Several projects based on the application of IoT to Water have been successfully implemented. In Bangladesh, 48 arsenic sensors were installed to monitor the quality of clean water and water pollution prevention. In the JiangSu province in China, water supply quality is also monitored with a wide range of IoT sensors located at key points of the distribution network [6]. A clever low-cost reverse osmosis system, coupled to smart controllers, allows clean water to be efficiently distributed to rural areas of India, and to monitor and guarantee the quality and quantity of water supplied in real time [7].

In developing countries the mortality rate of children before 5 years old is 15 times higher than in high income countries. In 2017, 5.4 million children under-five died; the access to simple and affordable interventions could be prevented more than half of these early child deaths [24]. In 2015, an estimated 303,000 women around died due to complications of pregnancy and childbirth [25]. A major part of these deaths were in developing countries; 2/3 of those occurred in sub-Saharan Africa [26]. With an improvement of management and care in developing countries this number of deaths could be reduced [25]: lifetime risk of dying from maternal causes in Africa was 1 in 37, in Europe was 1 in 3300 [26]. The application of the IoT in healthcare allows remote monitoring and personal healthcare, medical device integration and even treatments of diseases [8]. One of the main IoT applications in developing countries is the monitoring of the vaccine cold chain. In Haiti, healthcare professionals are using smart thermometers to better track vaccine delivery and storage [5]. IoT technologies are also being used to address immediate challenges in humanitarian response, such as the Ebola outbreak in West Africa [2].

b) Agriculture and livelihoods: In 2017, the number of hungry people in the world reached 821 million [27]. Children are the most vulnerable victims of malnutrition. About 3 million young lives a year, nearly half of all deaths in children aged less than 5 years old are attributable to malnutrition [28]. The Zero Hunger Goal (SDG2) pledges to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture [27]. In 2050, the world population is estimated at about 9.7 billion, thus the demand for food will be very high [29]. To nourish the 821 million people who are hungry today and the additional 2 billion expected people, a profound change is needed in both agriculture and the current system to obtain food [12]. As estimated, agriculture will need to produce 60% more food globally and 100% more in developing countries [22]. The application of IoT to agriculture allows resources to be optimized, production costs to lower and crop losses to be avoided [31]. The promotion of sustainable agriculture reduces poverty (SDG1) and enables sustained, inclusive and sustainable economic growth (SDG8). In developing countries, the challenges of loT in agriculture are the cost of equipment and the need for wider internet coverage. These two prerequisites prevent many farmers in developing countries to enjoy this technology [31]. Specifically in the monitoring area, its adoption in small- and medium-scale farms is very much limited due to lack of awareness and deployment costs. So the potential to develop cost-effective agricultural-based IoT solutions remains a very open area [29]. Harnessing IoT to combat food insecurity, waste and spoilage is another IoT potential application in this sector [32]. Every year, 1/3 of the food produced in the world for human consumption— an estimated 1.3 billion tonnes — is wasted. Food losses and waste amounts to roughly US$ 680 billion in industrialized countries and US$ 310 billion in developing countries [33]. Projects based on applying IoT to SDG1, SDG8 and SDG2 have been successfully implemented in developing countries. In 2014, I. Hong et al. [34] presented a project for reducing food waste: an adaptive user-oriented charge policy was used to motivate residents to reduce their food waste, and Web-based services were provided to achieve more efficiency in the disposal and collection processes. In India farmers remotely control micro-irrigation pumps using Nano Ganesh. With this mobile phone-based remote control system, farmers switch water pumps on/off and check the availability of the water supply near the pump end [35]. Another IoT project in Sri Lanka and Rwanda, based on sensor networks installed in tea plantations, constantly analyzes the moisture and nutrient content of soils to ensure that water and fertilizer are optimally used [13]. Kilimo Salama allows Kenyan smallholders to insure their crops against drought and floods by IoT technology [36].

c) Education: Globally, 264 million children and adolescents do not have the opportunity to enter or complete school. [37]. In 2017, the highest levels of illiteracy between young people (youth aged 15 to 24) were found in Sub-Saharan Africa (more than 50% of the youth population in countries such as Mali, Niger or Chad) and Southeast Asia [38]. The Higher Education Support Project, launched in Burkina Faso, established a new Virtual University with the aim to diversify higher education delivery models [39]. In China, the Guangdong Compulsory Education Project supports the installation and use of ICT equipment and the development of digital educational content for students [39].

d) Environment and conservation: The World Bank estimates that, climate change could result in more than 100 million additional people living in extreme poverty by 2030 (without measures to protect poor families from its impacts) [40].A changing climate will impact everyone, but it is already having the highest impact on poor communities with the fewest resources to adapt [41]. The poor are disproportionately affected by disasters [42]: of the 30 countries most vulnerable to natural disasters and a changing climate, 26 are least developed countries. The vast majority of deaths and people affected by natural disasters take place in the developing world: between 1991 and 2005, around 90% of deaths as a result of disasters and 98% of the population affected by disasters lived in developing countries [9]. Another key element is the conservation and sustainably use of marine resources as well as terrestrial ecosystems. Fisheries and aquaculture offer ample opportunities to reduce hunger and alleviate poverty, generating economic growth [43]. Overfishing threatens a valuable source of food; unmanaged aquaculture can be the driver of pollution contributing to the ocean acidification [43]. An example of IoT application in this area is the initiative developed by IBM’s China Research Lab and the Beijing Environmental Protection Bureau (BEPB) [44] to scale-up its air quality forecasting system. A network of sensors spread throughout Beijing returns increasingly precise forecasts of air pollution levels in different neighborhoods. Very interesting IoT applications are the Tsunami Early Warning Systems installed in India, Islamic Republic of Iran, Pakistan, and Oman [45]. The tsunami detection using IoT is extremely helpful to spread early warning messages as compared to normal detection systems and hence it avoids more destruction. Adoption of IoT could reduce the chances of losing human lives as well as damage to large-scale infrastructures due to disasters [30].

e) Resiliency, infrastructure and energy: Today 1.06 billion people still have no access to electricity and 3.04 billion people still rely on solid fuels and kerosene for cooking and heating [46]. Income levels and no having access to modern energy and good infrastructures are well correlated: countries with the highest ratio of the population living on an income of less than $1.90 per day tend to have low electrification rates and a high proportion of the population relies on traditional biomass use for cooking [46]. A majority of the people with no access to electricity live in sub-Saharan Africa and Southeast Asia, and, to a lesser extent, in the Middle East, Central Asia and Latin America. Likewise, most people with no clean cooking means live in Southeast Asia (1.9 billion), followed by sub-Saharan Africa (850 million) [46].

The application of IoT to energy projects has provided excellent results. In Kenya, M-Kopa [2] (IoT Microsoft award) was designed to provide everyone with high-quality energy at an affordable rate, especially off-grid people. After installing Solar Home Systems, customers are able to utilize the electricity generated by solar cells to power home appliances, and M-Kopa remotely monitors system uses and failures. In example, the monitoring of Solar Home Systems allows the early detection of failures extending the long-life of the photovoltaic system. In 2014, Project Surya launched a solution to enable extremely low-income women in Odisha, India, to afford clean cooking stoves. Sensors installed on forced draft stoves detected and uploaded data about cooking events on clean cook stoves [4].

These projects have improved the lives of many people in developing countries. IoT applications in agriculture are focused on water management, providing mechanisms for avoiding water stress (under-irrigation and over-irrigation). The outcome of this IoT projects is to reduce the waste of water and energy. On the other hand, effectiveness and productivity increase, and consequently, the economy of the families improve. Additionally, in most developing countries women are disproportionately affected because their access to resources and energy benefits is further limited by gender disparities as the role of the woman in developing countries is to collect wood and water. This situation has negative consequences such as the physical effects of drudgery in traveling long distances to obtain fuel wood and water, the health effects of indoor air pollution and reduced school attendance. IoT projects focused on energy and water also improve other aspects such as gender equality, health or education. However, some of these initiatives required large initial investments or the use of previously installed infrastructures. As indicated in Section 7.2.2., in developing countries, infrastructures are often very poor or nonexistent. To achieve high IoT dissemination in developing countries, one of the main requirements is to use simple inexpensive technology.

7.2.2. Challenges of IoT in developing countries

With the emergence of IoT, several works [2, 34, 47] have analyzed the expansion of this technology in the developing world by highlighting the challenges for IoT to reach billions of people living in developing countries to accelerate income growth and social development as a result. This section summarizes the key features to contextualize IoT in developing countries.

7.2.2.1. Technical challenges

a) Design requirements [47]: In 2013, Lutful Karim et al. [48] reported that information requirements in developing countries differ from those in industrialized countries. So IoT systems for developing countries generally have different design requirements and technological frameworks. As reported by the World economic Forum’s report [49] “Internet of Things Guidelines for Sustainability” (2018), the full potential of IoT acting as a catalyst to sustainable development is achieved when sustainability is integrated at the design phase of the IoT initiatives.

b) Simple and cost-effective technology: As resources are lacking, simpler and cost-effective [50] solutions may prove more suitable in a developing country context [2].

c) Lack of modern Infrastructure [13, 50]: Stable and reliable power supply systems are more limited in developing countries. The same happens with the availability of data centers. [13]

d) Connectivity: The International Telecommunication Union (ITU) [51] estimated in 2016 that approximately seven billion persons, the 95% of the global population, live in an area that is covered by a mobile network. According to a Groupe Speciale Mobile Association (GSMA) report [52], 63% of Africans had access to improved water supply and 32% to electricity in 2014, compared to 82 % who had access to GSM coverage. In 2008, United Nations research in India [53] showed that nearly 366 million people (31% of the population) had access to improved sanitation, while, 545 million mobile phones were connected to service.

e) Internet connectivity: Internet connectivity is a prime issue for enabling IoT. Internet penetration in developing countries is increasing [34]. In most developing countries, mobile broadband is more affordable than fixed broadband services [51]. Figure 48 shows the growth of mobile broadband subscriptions during the period from 2012 to 2017. In industrialized countries, 94% of young people aged 15-24 use the Internet compared with 67% in developing countries and only 30% in Least Developed Countries (LDCs) [51]. However, overall figures reveal that of the 830 million young people who are online worldwide, 320 million (39%) live in China and India [51].

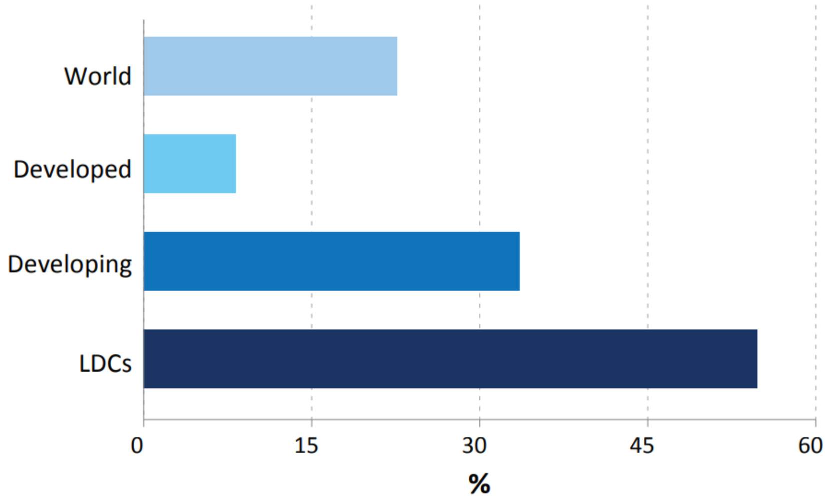


FIGURE 48: Mobile broadband subscriptions (2012-2017). Despite the high growth rates in developing countries and LDCs, there are twice as many mobile broadband subscriptions per 100 inhabitants in developed countries as in developing countries, and 4 times as many in developed countries as in LDCs. 2017 data. ITU [51].

f) Power supply: As things move around and they are not connected to a power supply, their smartness needs to be powered from a self-sufficient energy source [54]. On the other hand, N.S.Miazi et al (2016) [47] reported that reliable power supply is a big challenge for enabling IoT in most of the developing countries, being solar and wind the effective solutions.

g) Lacking local IoT expertise [13]: In developing countries, one main challenge is lack of technically knowledgeable personnel [55] due to IoT systems requiring regular maintenance, updates and function testing.

7.2.2.2. Environmental conditions

a) Harsh environmental conditions: The "Global Climate Risk Index 2018" [56] report studies to what extent countries have been affected by the impacts of weather-related loss events (storms, floods, heat waves etc.)[57]. During the 1997-2016 period, nine of the ten most affected countries were developing countries [56]. This means that the IoT systems installed in developing countries must be prepared to operate under extreme climatic conditions (heat, humidity, etc.).

7.2.2.3. Social differences

a) Rural-Urban differences: In developing countries, the differences between rural and urban areas are vast: 85% of poor people live in rural areas [61]. These differences affect to infrastructure used by IoT deployment such as telecommunications networks or electricity grid.

7.2.2.4. Policy

a) Security and privacy [62]: In 2016, Ivaşcu, T et al. stated that the two main obstacles to IoT are security and privacy. IoT devices are largely being designed without security in mind; in 2019, the African Academic Network on Internet Policy stated that urgent privacy/security regulation is required in Africa [63].

b) Absence of standards [64]: Developments with no standardization sometimes results as designed products that operate in disruptive ways on the Internet [64]. In 2016, F.J. Ferrández-Pastor [65] argued that there are still several IT related issues that hinder further dissemination of IoT in agriculture. These include expensive the lack of established sensor network standards.

c) Government regulations [66]: In 2019, A.S. Abunohaiah et al. [67] reported that the IoT has broadly been unregulated so far. A clear regulatory framework could accelerate the expansion of IoT and make it more potential [67]. Large majority of IoT consumers lack trust in the IoT devices and favor more government regulations to protect data access and use, amongst other aspects [66]. Countries such as India [68] and Senegal [69] have just included IoT regulation as a priority. Concretely the Government of India has introduced policies and initiatives simplifying the licensing and regulatory frameworks whilst ensuring appropriate security frameworks, to leverage benefits of IoT in several sectors [70].

7.2.2.5. Financial conditions

a) Lack of financial systems [58] Access to basic banking services in developing countries is extremely limited [59]. This is the main reason why different business models, such as pay-as-you-go (PAYG), are emerging especially in developing countries and are combined with IoT initiatives [60].

7.3. The future of IoT4D

After studying the current context and the challenges for applying IoT in the developing world and reviewing successful projects in which IoT has been applied, the future of IoT4D is presented as a combination of two key aspects: low-cost IoT and PAYG. Today 1.7 billion people remain unbanked, but two thirds of them own a mobile phone [71]. It has been necessary to adopt different ways of doing business to reach these people with product and services to improve their livelihoods. In recent years in developing countries, the tendency is to combine IoT technologies with seamless digital payments and new business models like PAYG. The integration of open-source tools into the design of IoT projects considerably reduces technology costs. The use of this low-cost IoT allows consumers to be provided with previously inaccessible products that enhance their livelihood and also allow them to start on a path to financial inclusion [60].

7.3.1. Low-cost IoT

In recent years, open-source tools have exponentially increased and have become a trend in the last decade. With the proliferation of open-source hardware-based (OSHW) projects, novel OSHW platforms have been progressively incorporated into the design of precise low-cost IoT systems. Table XXX shows initiatives that have been developed in the last 10 years in the IoT4D area. Most of the found projects have been designed around open-source tools. Of all the OSHW platforms available on the market, Arduino™ [71,72,74,78,80,84,86,87,88,90,91,93,94,95,96,99] and Raspberry PI[73,75,76,77,81,85,90] have been the most widely used platforms to be integrated into IoT4D projects. The most widespread open cloud platform was Thingspeak [82, 90, 92, 94, 99]. Table XXX shows the IoT4D projects linked to SDGs. Several projects focus on improving the water-energy-food index. In 2019, J. Fell et al. [98] presented a smart low-cost remote-monitoring flow sensor designed for the developing country context. The sensor used low-cost off-the-shelf sonar devices to gauge river height as a proxy for flow rates and operates via an IoT node based on mobile communications (GSM) to provide real-time data. The sensor was applied in Franschhoek, South Africa. In relation to the smart energy for developing, in 2019 A. López-Vargas et al. [99] presented a new low-cost datalogger designed specially to monitor Solar Home Systems installed in rural areas of developing countries. The datalogger used mobile communications to transmit data, and provided real-time remote monitoring to collaborate in the success of rural electrification programs [100, 101]. Along the same line, in 2018 Sanni et al [96] applied the IoT concept to smart metering to measure key energy use data and to send instantaneous data to a web server to be accessed by permitted users. It was developed to be applied in Africa. Several projects work in line with the Zero Hunger objective throughout smart irrigation and smart farmer projects. In 2018, A. T. Abagissa et al. [94] presented a system composed of: a sensor network to assess temperature, humidity and water level adjustments: a sensor node needed for an optimal farming environment; monitoring management devices to collect and analyze the data from collected the sensor node, to store them in the management server and to alert an emergency. In 2017, Salvi et al. [84] presented a new framework for multilevel farming in urban areas with limited cultivation space; it was designed to be applied in India. Cloud-based data analysis and monitoring allowed the user to analyze and monitor the irrigation system over the Internet by providing ubiquitous access via Bluetooth modules. Their experimental results showed reduced water use and better power use.

One of the main challenges for expanding IoT in developing countries is connectivity. Among all the different standards deployed on the market [102], usually distributed in different frequency bands and using multiple communication protocols, selecting the most suitable connectivity technology for an IoT application can be challenging. Wireless technologies have been widely used for decentralized systems, although Ethernet cable is an alternative for centralized systems [103]. The connectivity requirements of different types of IoT networks vastly vary depending on their purpose and resource constraints. Most of the reviewed projects use WLAN [81, 79, 87, 97, 94, 77, 86, 91, 93, 96] technologies for connectivity systems, mainly Wi-Fi. Another interesting solution implemented into some studied projects is the creation of low-power wide-area networks (LPWAN) [104, 84, 95]. The network sends data to a central node that usually acts as a gateway by sending information to the cloud via WWAN technologies (mobile communications in many cases).

TABLE XXX: LIST OF IoT4D INITIATIVES

Year	Authors	Details	Low-cost IoT	Connectivity	Goal	Country /Region
2012	N.Gupta et al. [71]	Learning by creating: Interactive programming for Indian high schools	Arduino	NF	SDG4	India
2013	Mukundhan Srinivasan, Anand. B et al. [72]	GreenEduComp: Low cost green computing system for education in Rural India: A scheme for sustainable development through education	Arduino	wired	SDG4	India
2013	M. Ali [73]	Technical development and socioeconomic implications of the Raspberry Pi as a learning tool in developing countries	Raspberry Pi	NF	SDG4	Uganda
2014	Prajakta A. Pawar[74]	Heart Rate Monitoring System using IR base Sensor & Arduino Uno	Arduino UNO	IR	SDG3	India
2014	S.S.Lagu et al. [75]	Raspberry Pi for automation of water treatment plant	RPi	Wired	SDG6	India
2014	S. Mashrura [76]	Towards ubiquitous learning tools for computer aided classroom in developing regions	RPi	NF	SDG4	Bangladesh
2015	P. Pruet et al. [77]	Exploring the Internet of "Educational Things"(IoET) in rural underprivileged areas	RPi	WIFI	SDG4	Thailand
2015	B.S.Butola et al.[78]	Arduino based supervision of banana ripening stages	Arduino	GSM	SDG2	India
2016	Bharath. S [79]	Smart Portable IOT Vaccine Monitor	Intel Galileo Gen 2	Wi-Fi	SDG3	NF
2016	N. S. Kumar et al. [80]	IOT Based Smart Garbage alert system using Arduino UNO	Arduino uno	gprs module	SDG11	India
2016	Rohini Shete and Sushma Agrawal [81]	IoT Based Urban Climate Monitoring using Raspberry Pi	RPI	Wi-Fi module	SDG13	India
2017	M. S. Mekala and P. Viswanathan [82]	A Novel Technology for Smart Agriculture Based on IoT with Cloud Computing	Thingspeak	lIfi	SDG2	India
2017	Amandeep et al.[83]	Smart Farming Using IOT	NF	wireless Zigbee modules	SDG2	India
2017	S. Salvi et al[84]	Cloud Based Data Analysis and Monitoring of Smart Multi-level Irrigation System Using IoT	Arduino	Bluetooth modules	SDG2	India
2017	Md. Sultanul Arefin et al. [85]	Smart Health Care System for Underdeveloped Countries	Raspberry Pi	wireless technologies	SDG3	Bangladesh
2017	Ashish.B [86]	Temperature monitored IoT based smart incubator	Arduino, RPI	ESP2866 (WIFI)	SDG3	NF

Year	Authors	Details	Low-cost IoT	Connectivity	Goal	Country /Region
2017	Arrizon [87]	Vital sensor kit for use with telemedicine in developing countries	Arduino Uno	via Wi-Fi or SMS	SDG3	NF
2017	C. Raj et al. [88]	HEMAN: Health Monitoring and Nous An IoT based e-Health Care System for Remote Telemedicine	Atmega 328P, Arduino, Amazon AWS	NF	SDG3	India
2017	S. Rimern [89]	An IoT architecture for financial services in developing countries	ATmega328P	Near Field Communication (NFC)	SDG8	Sub-Saharan Africa
2017	A. Mohan et al. [90]	A Waste Collection Mechanism based on IoT	RPi, Arduino, ThinkSpeak	GSM	SDG11	India
2017	T. Tsokov1 et al [91]	IoT Platform for Control of Carbon Emissions	Arduino Uno and R Pi B+	802.11n wireless network	SDG12	NF
2017	A. Carrasquilla-Batista et al.[92]	IoT applications: On the path of Costa Rica's commitment to becoming carbon-neutral	ThinkSpeak	GSM/GPRS	SDG13	Costa Rica
2017	Abhinav Kumar Sharma [93]	IOT enabled forest fire detection and online monitoring system	Arduino	Wi-Fi	SDG15	NF
2018	A. T. Abagissa et al. [94]	IoT Based Smart Agricultural Device Controlling System	Arduino, ThingSpeak	Wi-Fi	SDG2	India
2018	Sai Sreekar Siddula et al.[95]	Water Level Monitoring and Management of Dams using IoT	Arduino	Bluetooth modules	SDG6	India
2018	Sanni [96] et al.	Smart Metering System: A Solution for Adoption in Developing Countries	Arduino	Wi-Fi module	SDG7	Nigeria
2018	R. S. Cabrera and A. P. de la Cruz [97]	Public Transport Vehicle Tracking Service for Intermediate Cities of Developing Countries, based on ITS Architecture using Internet of Things (IoT)	ESP8266 12E	Wi-Fi	SDG9	Colombia
2019	J. Fell et al. [98]	Low-Cost Flow Sensors: Making Smart Water Monitoring Technology Affordable	Particle Electron	GSM	SDG6	South Africa
2019	A López – Vargas et al. [99]	IoT application for real-time monitoring of Solar Home Systems based on Arduino™ with 3G connectivity	Arduino, Thingspeak	3G	SDG7	Mexico

7.3.2. Pay-as-you-go and developing countries

Pay-as-you-go refers to a business model that allows users to pay for their product by visa-embedded consumer financing [105]. Companies typically offer a product for which a customer makes a down payment, followed by regular payments for a term ranging from 6 months to 8 years. Payments are usually made using mobile money, although alternative methods include scratch cards, mobile airtime and cash [105].

Of all the industries leveraging PAYG models in developing countries, the market for PAYG Solar Home Systems (PAYG solar) is the most mature, especially in Sub-Saharan Africa [60]. The global PAYG solar market is projected to grow to $6-7 billion in revenue and 20 million in unit sales annually by 2022 [60].

Solar PAYG is taken as an example of PAYG application in the developing world that can be used as a test, and can help predict how the PAYG model can be applied to other development aspects in line with SDGs. Other industries beyond PAYG solar in which PAYG models are creating livelihood improvements are clean water, telecommunications, agriculture, cooking stoves and gas, sanitation or education [60]. All this makes the PAYG model most appropriate for IoT to expand in the developing world.

Some projects focused on different SDGs have included the PAYG model. eWaterPay [106] is a pre-payment water dispenser harnessing IoT. Awarded in 2018 with a GSMA's Global Mobile Award in the category "Outstanding Mobile Contribution to the UN SDGs" this project works across sub-Saharan Africa ensuring 24/7 accessibility to clean water in communities that need it most. This project uses the PAYG model of payment applied to water ("Pay as you drink"). This project has impacted in sub-Saharan communities -who previously had little or no access to a clean, reliable water source- and now have access through a low-cost, PAYG water model. eWATERtap is an example of how the combination of IoT and PAYG is providing livelihood essentials and helping drive inclusion[60]. The Hello Tractor initiative [107] allows farmers to request affordable tractor services using a mobile application. Hello tractor works in Nigeria and it uses the PAYG model. By accessing tractors through Hello Tractor, farmers can drastically increase their yields and enhance their incomes [60]. The Acacia irrigation project [108] is an initiative by the Sustainable Engineering Lab, to provide solar powered irrigation for farmers in Senegal [108]. The acacia irrigation project also uses the PAYG model. In 2017, the United Nations Capital Development Fund [109] and the Promoting Equality in African Schools [110] in Uganda investigate how digital finance can help to alleviate the school fees payment issues for parents, schools and students, using the "Pay-as-you-learn" (PAYL) as a payment model for schools in Uganda [111].

Summarizing, in developing countries, to combine low-cost IoT technologies with seamless digital payments and new business models like PAYG provides consumers with previously inaccessible, capital-intensive products that enhance their everyday lives while simultaneously placing them on a path to financial inclusion [60]. In Table XXXI, key characteristic studied in this work are listed; they are presented as the optimal solution for the expansion of IoT4D.

TABLE XXXI
IOT4D CHARACTERISTICS FOR APPLICATIONS

Key feature	Description
Software	Open software
Hardware	Open Source Hardware
Data storage	Open cloud platform [112]
Communications	Low-power wide-area networks (LPWAN)
Payment	PAYG

7.4. Conclusions

The potential of IoT in the developing world is to make an even greater and more significant impact than in industrialized countries. Problems faced by developing countries can open up new unexplored fields to apply IoT to. Around 85% of IoT deployments have the potential to address SDGs. The application of IoT between developed and developing countries differs. Infrastructures, connectivity, lack of personnel with technical knowledge, environmental conditions or financial systems are key aspects for implementing IoT into the developing world. One of the main challenges for expanding IoT in developing countries is connectivity. Most projects use wireless communications. In many cases the combination of low-range networks combined with mobile communications offers an excellent cost-effective solution.

With open-source hardware-based (OSHW) projects proliferating, novel OSHW platforms have been progressively incorporated into the design of precise low-cost IoT systems. Such projects do not generally require high initial costs, which allows greater dissemination and makes this area more appealing and affordable for the scientific community to achieve SDGs. To combine IoT technologies, seamless digital payments and pay-as-you-go are a tendency in the developing world that is obtaining excellent results. So the combination of Low-cost IoT and PAYG is presented as the perfect scenario to better disseminate IOT4D to achieve SDGs.

7.5. References

[1] < https://blogs.cisco.com/gov/iot-using-technology-for-the-developing-world > (accessed 25.06.2019)

[2] ITU report “Harnessing the Internet of Things for Global Development”.

[3] < https://www.allerin.com/blog/developing-countries-and-their-tryst-with-iot > (accessed 25.06.2019)

[4] < http://www.ccacoalition.org/en/blog/internet-things-development-clean-cooking > (accessed 25.06.2019)

[5] < https://path.azureedge.net/media/documents/VAC_investing_fs_2015.pdf > (accessed 04.09.2019)

[6] < http://projects.worldbank.org/P096926/jiangsu-water-wastewater?lang=en&tab=overview > (accessed 25.06.2019)

[7] < https://barbaraiot.com/articles/iot-developing-countries/ >(accessed 25.06.2019)

[8] < https://medium.com/sciforce/iot-in-healthcare-are-we-witnessing-a-new-revolution-6bb0ecf55991> (accessed 04.09.2019)

[9] Zorn, Matija. “Natural Disasters and Less Developed Countries”. 2018

[10] < http://www.eglobalmark.com/wp-content/uploads/2018/06/2018-05-IoT-Standards-for-Africa-and-Sustainable-Development-Goals-SDGs.pdf > (accessed 04.09.2019)

[11] < http://enb.iisd.org/vol27/enb2751e.html > (accessed 25.06.2019)

[12]< http://www.undp.org/content/undp/en/home/sustainable-development-goals.html > (accessed 25.06.2019)

[13] KfW Development Research’s report. “Internet of Things – hype or hope for developing countries? “. 2016.

[14] < http://widgets.weforum.org/iot4d/ > (accessed 04.09.2019)

[15] < http://www3.weforum.org/docs/IoTGuidelinesforSustainability.pdf > (accessed 25.06.2019)

[16] IoT Analytics database of 640+ IoT projects (World Economic Forum)

[17] E.M.Biggs, E.Bruce, B.Boruff, J.M.A.Duncan, J.Horsley, N.Pauli, K.McNeill, A.Neef, F.Ogtrop, J.Curnow, B.Haworth, S.Duce, Y. Imanari “Sustainable development and the water–energy–food nexus: A perspective on livelihoods”. Environmental Science & Policy Volume 54, December 2015, Pages 389-397.

[18] Chi Zhang, Xiaoxian Chen, Yu Li, Wei Ding, Guangtao Fu, “Water-energy-food nexus: Concepts, questions and methodologies”, Journal of Cleaner Production, Volume 195, 2018, Pages 625-639.

[19] < http://wireless.ictp.it/school_2016/Slides/Garrity-IoT4D-ICTP.pdf > (accessed 04.09.2019)

[20] NATURE-BASED SOLUTIONS FOR WATER. The United Nations World Water Development Report 2018.

[21] Namara, Regassa E.; Hanjra, M. A.; Castillo, G. E.; Ravnborg, H. M.; Smith, L.; van Koppen, Barbara. 2010. Agricultural water management and poverty linkages. Agricultural Water Management, 97(4):520?527. Special issue with contributions by IWMI authors.

[22] Report of United Nations “Water for a sustainable world Report 2015”

[23] Sustainable Energy & Water Access through M2M Connectivity. GSMA Report. 2013.

[24] < www.who.int > (accessed 04.09.2019)

[25] < https://sustainabledevelopment.un.org/sdg3 > (accessed 04.09.2019)

[26] < https://apps.who.int/iris/bitstream/handle/10665/311696/WHO-DAD-2019.1-eng.pdf?ua=1 > (accessed 04.09.2019)

[27] United Nations Report “Zero Hunger: Why it matters “< https://www.un.org/sustainabledevelopment/wp-content/uploads/2018/09/Goal-2.pdf > (accessed 25.06.2019)

[28] < https://data.unicef.org/topic/nutrition/malnutrition/ > (accessed 25.06.2019)

[29] O. Elijah, T. A. Rahman, I. Orikumhi, C. Y. Leow and M. N. Hindia, "An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges," in IEEE Internet of Things Journal, vol. 5, no. 5, pp. 3758-3773, Oct. 2018.

[30] P. P. Ray, M. Mukherjee and L. Shu, "Internet of Things for Disaster Management: State-of-the-Art and Prospects," in IEEE Access, vol. 5, pp. 18818-18835, 2017.

[31] < http://www.fao.org/e-agriculture/news/possibilities-internet-things-iot-agriculture > (accessed 25.06.2019)

[32] < https://www.delltechnologies.com/en-us/microsites/legacyofgood/2018/net-positive/harnessing-iot-to-combat-food-insecurity-waste-and-spoilage.htm > (accessed 04.09.2019)

[33] FAO < http://www.fao.org/save-food/resources/keyfindings/en/ > (accessed 04.09.2019)

[34] IoT-Based Smart Garbage System for Efficient Food Waste Management

< http://downloads.hindawi.com/journals/tswj/2014/646953.pdf> (accessed 04.09.2019)

[35] FAO Report. Success stories on information and communication technologies for agriculture and rural development < http://www.fao.org/3/a-i4622e.pdf > (accessed 04.09.2019)

[36] < https://www.ifc.org/wps/wcm/connect/e0ed35804c33fc309479def12db12449/KS+story.pdf?MOD=AJPERES > (accessed 25.06.2019)

[37] < https://www.unicef.org/media/55331/file > (accessed 04.09.2019)

[38] UNESCO < https://www.tellmaps.com/uis/literacy/#!/tellmap/-1082895961 > (accessed 29.07.19).

[39] < https://www.worldbank.org/en/topic/edutech#3 > (accessed 04.09.2019)

[40] < http://www.worldbank.org > (accessed 08.01.2018).

[41] < https://www.odi.org/faq-coal-poverty-and-environment > (accessed 29.07.19).

[42] World Risk Report Analysis and prospects 2017 < https://reliefweb.int/sites/reliefweb.int/files/resources/WRR_2017_E2.pdf

> (accessed 29.07.19).

[43] < https://unctad.org/meetings/en/SessionalDocuments/Background-Note-Second-Oceans-Forum-July2018-v4.pdf > (accessed 04.09.2019)

[44] < https://www.weforum.org/agenda/2016/04/3-ways-the-iot-could-help-fight-climate-change/ > (accessed 04.09.2019)

[45] < https://www.unescap.org/sites/default/files/ESCAP-Synthesis-Report.pdf > (accessed 04.09.2019)

[46] Energy Access Outlook 2017. From Poverty to Prosperity" report. International Energy Agency, 2017.

[47] M. N. S. Miazi, Z. Erasmus, M. A. Razzaque, M. Zennaro and A. Bagula, "Enabling the Internet of Things in developing countries: Opportunities and challenges," 2016 5th International Conference on Informatics, Electronics and Vision (ICIEV), Dhaka, 2016, pp. 564-569.

[48] Lutful Karim, Alagan Anpalagan, Nidal Nasser, Jalal Almhana. "Sensor-based M2M Agriculture Monitoring Systems for Developing Countries: State and Challenges".

[49] IoT Sustainability Guidelines Published by World Economic Forum < http://www3.we+forum.org/docs/IoTGuidelinesforSustainability.pdf > (accessed 04.09.2019)

[50] < https://lirima.inria.fr/fr/focus-on-a-joint-project-team-iot4d/ > (accessed 04.09.2019)

[51] < https://www.itu.int/en/itu-D/Statistics/Documents/facts/ICTFactsFigures2017.pdf >(accessed 25.06.2019)

[52] Groupe Speciale Mobile Association (GSMA). The Synergies between Mobile, Energy and Water Access: Africa.

[53] < https://unu.edu > (accessed 16.06.2019).

[54] M. Masinde, "IoT applications that work for the African continent: Innovation or adoption?," 2014 12th IEEE International Conference on Industrial Informatics (INDIN), Porto Alegre, 2014, pp. 633-638.

[55] M. Fuentes, M. Vivar, H. Hosein, J. Aguilera, E. Muñoz-Cerón, Lessons learned from the field analysis of PV installations in the Saharawi refugee camps after 10 years of operation, Renewable and Sustainable Energy Reviews,Volume 93,2018,Pages 100-109, ISSN 1364-0321

[56]GLOBAL CLIMATE RISK INDEX 2018 Who Suffers Most From Extreme Weather Events? Weather-related Loss Events in 2016 and 1997 to 2016 < https://germanwatch.org/sites/germanwatch.org/files/publication/20432.pdf > (accessed 25.06.2019)

[57] IoT - Challenges and Opportunities in Indian Market", COMSNET, Bangalore India.

[58] < http://www.iynf.org/2018/08/a-guide-to-sustainable-development-and-its-challenges-in-developing-countries/ > (accessed 04.09.2019)

[59] Rimer, Suvendi (2017). An IoT architecture for financial services in developing countries.

[60] “Pay-As-You-Go and the Internet of Things: Driving a New Wave of Financial Inclusion in the Developing World”. Mastercard Report.2018.

[61] < https://www.ophi.org.uk/wp-content/uploads/Poverty-in-Rural-and-Urban-Areas-Direct-Comparisons-using-the-Global-MPI-2014.pdf > (accessed 25.06.2019)

[62] < https://pdfs.semanticscholar.org/c1fa/4a3f4e66d8ebb25d5d895ce805c2f83295bc.pdf > (accessed 04.09.2019)

[63] < https://aanoip.org/iot-in-africa-urgent-regulation-required/ > (accessed 04.09.2019)

[64] Yadav, Er Pooja & Yadav, Hemant. (2018). IoT: Challenges and Issues in Indian Perspective.

[65] Ferrández-Pastor, F. J., García-Chamizo, J. M., Nieto-Hidalgo, M., Mora-Pascual, J., and MoraMartínez, J. 2016. "Developing Ubiquitous Sensor Network Platform Using Internet of Things: Application in Precision Agriculture," Sensors (14248220) (16:7), pp. 1-20.

[66] G. S. Tzafestas, “Ethics and Law in the Internet of Things World,” Smart Cities , vol. 1, no. 1. 2018.

[67] A.S. Abunohaiah, Q.A. Al-Haija “IOT Politics, Regulations and Civic Engagement. International Journal of Engineering and Information Systems (IJEAIS)”. Vol. 3 Issue 1, January – 2019, Pages: 25-32

[68] < https://meity.gov.in/sites/upload_files/dit/files/Draft-IoT-Policy%20%281%29.pdf > (accessed 04.09.2019)

[69] < https://www.iotsecurity.sn/news/ > (accessed 04.09.2019)

[70] < https://www.ey.com/Publication/vwLUAssets/EY_-_Future_of_IoT/$FILE/EY-future-of-lot.pdf > (accessed 04.09.2019)

[71] < https://www.worldbank.org/en/news/press-release/2018/04/19/financial-inclusion-on-the-rise-but-gaps-remain-global-findex-database-shows > (accessed 25.06.2019)

[71] N. Gupta, N. Tejovanth and P. Murthy, "Learning by creating: Interactive programming for Indian high schools," 2012 IEEE International Conference on Technology Enhanced Education (ICTEE), Kerala, 2012, pp. 1-3.

[72] M. Srinivasan et al., "GreenEduComp: Low cost green computing system for education in Rural India: A scheme for sustainable development through education," 2013 IEEE Global Humanitarian Technology Conference (GHTC), San Jose, CA, 2013, pp. 102-107.

[73] Ali, Murat & Hubertus Alfonsus Vlaskamp, Jozef & Nasser Eddin, Nof & Falconer, Ben & Oram, Colin. (2013). Technical development and socioeconomic implications of the Raspberry Pi as a learning tool in developing countries. 2013 5th Computer Science and Electronic Engineering Conference, CEEC 2013 - Conference Proceedings.

[74] P. A. Pawar, "Heart rate monitoring system using IR base sensor & Arduino Uno," 2014 Conference on IT in Business, Industry and Government (CSIBIG), Indore, 2014, pp. 1-3.

[75] S. Lagu, Sonali & B. Deshmukh, Sanjay. (2015). Raspberry Pi for Automation of Water Treatment Plant. 532-536.

[76] Tasnim, Mashrura & Zaman, Farhana & Shahid Ferdous, Hasan & Md. Saad, Sharif. (2013). Towards Ubiquitous Learning Tools For Computer Aided Classroom In Developing Regions. 16th Int'l Conf. Computer and Information Technology, ICCIT 2013.

[77] < https://core.ac.uk/download/pdf/30710091.pdf > (accessed 04.09.2019)

[78] B. S. Butola, P. K. Sharma, Y. Singh and Y. Amin, "Arduino based supervision of banana ripening stages," 2015 1st International Conference on Next Generation Computing Technologies (NGCT), Dehradun, 2015, pp. 921-924.

[79] Bharath. S. Smart Portable IOT Vaccine Monitor. International Journal of Engineering and Technical Research (IJETR) ISSN: 2321-0869 (O) 2454-4698 (P), Volume-5, Issue-3, July 2016

[80] N. S. Kumar, B. Vuayalakshmi, R. J. Prarthana and A. Shankar, "IOT based smart garbage alert system using Arduino UNO," 2016 IEEE Region 10 Conference (TENCON), Singapore, 2016, pp. 1028-1034.

[81] R. Shete and S. Agrawal, "IoT based urban climate monitoring using Raspberry Pi," 2016 International Conference on Communication and Signal Processing (ICCSP), Melmaruvathur, 2016, pp. 2008-2012.

[82] M. S. Mekala and P. Viswanathan, "A novel technology for smart agriculture based on IoT with cloud computing," 2017 International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC), Palladam, 2017, pp. 75-82

[83] Amandeep et al., "Smart farming using IOT," 2017 8th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), Vancouver, BC, 2017, pp. 278-280.

[84] S. Salvi et al., "Cloud based data analysis and monitoring of smart multi-level irrigation system using IoT," 2017 International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC), Palladam, 2017, pp. 752-757.

[85] M. S. Arefin, T. H. Surovi, N. N. Snigdha, M. F. Mridha and M. A. Adnan, "Smart health care system for underdeveloped countries," 2017 IEEE International Conference on Telecommunications and Photonics (ICTP), Dhaka, 2017, pp. 28-32.

[86] Ashish, Babhulkar. "Temperature monitored IoT based smart incubator." 2017 International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC) (2017): 497-501.

[87] Natalie et al. "Vital sensor kit for use with telemedicine in developing countries." 2017 IEEE Global Humanitarian Technology Conference (GHTC) (2017): 1-5.

[88] C. Raj, C. Jain and W. Arif, "HEMAN: Health monitoring and nous: An IoT based e-health care system for remote telemedicine," 2017 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET), Chennai, 2017, pp. 2115-2119.

[89] S. Rimer, "An IoT architecture for financial services in developing countries," 2017 IST-Africa Week Conference (IST-Africa), Windhoek, 2017, pp. 1-10.

[90] A. Mohan, S. Johar and S. Mini, "A Waste Collection Mechanism based on IoT," 2017 14th IEEE India Council International Conference (INDICON), Roorkee, 2017, pp. 1-5.

[91] EcoLogic: IoT Platform for Control of Carbon Emissions Tsvetan Tsokov1 and Dessislava Petrova-Antonova2 1 Department of Information Technologies, Sofia University, Sofia, Bulgaria 2 Department of Software Engineering, Sofia University, Sofia, Bulgaria

[92]A. Carrasquilla-Batista, A. Chacón-Rodriguez, M. Solórzano-Quintana and M. Guerrero-Barrantes, "IoT applications: On the path of Costa Rica's commitment to becoming carbon-neutral," 2017 International Conference on Internet of Things for the Global Community (IoTGC), Funchal, 2017, pp. 1-6.

[93] IoT enabled forest fire detection and online monitoring system (by using ATmega 328-P microcontroller). Abhinav Kumar Sharma1 , Md Faiz Raza Ansari2 , Md Firoz Siddiqui3 , Mirza Ataullah Baig41,2,3,4 GLBITM, Gr. Noida, U.P

[94] A. T. Abagissa, A. Behura and S. K. Pani, "IoT Based Smart Agricultural Device Controlling System," 2018 Second International Conference on Inventive Communication and Computational Technologies (ICICCT), Coimbatore, 2018, pp. 26-30.

[95] S. S. Siddula, P. Babu and P. C. Jain, "Water Level Monitoring and Management of Dams using IoT," 2018 3rd International Conference On Internet of Things: Smart Innovation and Usages (IoT-SIU), Bhimtal, 2018, pp. 1-5. doi: 10.1109/IoT-SIU.2018.8519843

[96] Sanni, Timilehin & Adoghe, Anthony & Amaize, Peter & Ajaegbu, C.D.. (2018). Smart Metering System: A Solution for Adoption in Developing Countries. 623-627.

[97] R. S. Cabrera and A. P. de la Cruz, "Public Transport Vehicle Tracking Service for Intermediate Cities of Developing Countries, based on ITS Architecture using Internet of

Things (IoT)," 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 2018, pp. 2784-2789.

[98] J. Fell, J. Pead and K. Winter, "Low-Cost Flow Sensors: Making Smart Water Monitoring Technology Affordable," in IEEE Consumer Electronics Magazine, vol. 8, no. 1, pp. 72-77, Jan. 2019.

[99] López-Vargas, A., Fuentes, M., & Vivar, M. (2019). IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino™ With 3G Connectivity. IEEE Sensors Journal, 19, 679-691.

[100] T. Urmee, D. Harries, and A. Schlapfer, "Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific," Renew. Energy, vol. 34, no. 2, pp. 354–357, 2009.

[101] F. D. J. Nieuwenhout, A. Van Dijk, V. A. P. Van Dijk, D. Hirsch, P. E. Lasschuit, and G. Van Roekel, "Monitoring and evaluation of experiences with applications of solar PV for households in developing countries" September, 2000.

[102] N. Lethaby, "Wireless connectivity for the Internet of Things: One size does not fit all," Texas Instrum., Dallas, TX, USA, Tech. Rep., 2017.

[103] R. I. S. Pereira, I. M. Dupont, P. C. M. Carvalho, and S. C. S. Jucá, "IoT embedded linux system based on Raspberry Pi applied to real-time cloud monitoring of a decentralized photovoltaic plant," Measurement, vol. 114, pp. 286–297, Jan. 2018.

[104] W. Lawrence, Piers & M. Phippard, Trisha & Ramachandran, Gowri & Hughes, Danny. (2017). Developing IoT to support the health sector: A case study from Kikwit, DR Congo. 10.1007/978-3-319-67837-5_5.

[105] < https://www.lightingafrica.org/wp-content/uploads/2018/02/2018_Off_Grid_Solar_Market_Trends_Report_Full.pdf > (accessed 25.06.2019)

[106] < https://www.ewaterpay.com/ > (accessed 04.09.2019)

[107] < https://www.hellotractor.com/home > (accessed 04.09.2019)

[108] < https://qsel.columbia.edu/acacia-irrigation-project/ > (accessed 04.09.2019)

[109] < https://www.uncdf.org/mm4p/home > (accessed 04.09.2019)

[110] < https://www.peas.org.uk/ > (accessed 04.09.2019)

[111] < https://www.uncdf.org/article/3481/exploring-the-prospects-of-pay-as-you-learn-in-uganda > (accessed 04.09.2019)

[112] C. Dupont, T. Bures, M. Sheikhalishahi, C. Pham, and A. Rahim, "Low-cost IoT, Big Data, and Cloud Platform for Developing Countries BT - Economics of Grids, Clouds, Systems, and Services," 2017, pp. 285–299.

Chapter 8

Summary of Results and Conclusions

This Summary of Results and Conclusions sets out the findings of the studies undertaken in this thesis work that is presented as a compendium of scientific research articles, corresponding to Chapters 3-7.

The main objective of this thesis was to develop a robust and autonomous low-cost ad hoc system based on open source tools for the monitoring of Solar Home Systems located in isolated areas of developing countries.

Throughout the different chapters, the experiences conducted have been explained in detail, establishing the objectives of each of them as well as discussing the main results obtained. Chapter 3 comprises the results of the comprehensive review carried out on the mass-scale monitoring of Solar Home Systems. Chapters 4, 5 and 6 include the experimental results obtained. Chapter 7 presents a recent review on the use of IoT for sustainable development due to the new possibilities that IoT opens, and the associated rising interest during recent years (with an increasing number of scientific study concerning this area during recent PhD thesis years). Conclusions have been drawn in each chapter, but the most relevant ones are summarised below along with the main results.

First, the review carried out in Chapter 3 ('Current challenges for the advanced mass scale monitoring of Solar Home Systems, and the potential of open-source tools and Internet of Things for solar monitoring applications: A review') focused on the current challenges for the mass scale SHSs monitoring in developing countries and the data acquisition systems that could be applicable to the monitoring of SHSs by integrating open source tools and IoT, provided valuable information as a starting point for the design of the new datalogger. To obtain an accurate monitoring at low-cost was identified as the main challenge of the Solar Home Systems monitoring. Conventional and novel monitoring systems were reviewed. Regarding the former, the key disadvantages of conventional monitoring systems were identified: the high cost, the strong dependency on external hardware (PC or external power supply) and the non-compliance of measurement errors and accuracies with the international standards. Novel technologies were analysed, specifically the integration of open source systems in monitoring systems as well as the integration of IoT. The use of open source tools was presented as an optimal solution that would allow the development of low-cost ad-hoc monitoring systems. As the PV systems studied are commonly located in isolated regions, often without access to electrical grid and wired telecommunication networks, remote monitoring is a priority. For this purpose, the use of mobile communication was identified as the most appropriate technology for transmitting data. The study also concluded that the integration of open IoT cloud platforms could be an advantage as it would allow the remote monitorization of SHSs and the visulisation of data measured by the datalogger using laptops or smartphones at a low cost.

Based on the monitoring systems review, in Chapter 4 ('Low-Cost Datalogger Intended for Remote Monitoring of Solar Photovoltaic Stand-alone Systems Based on Arduino™') a novel datalogger intended for the monitoring of stand-alone PV systems was designed and tested. This version (Datalogger SD) included a wide range of climatic measures: irradiance, temperatures, humidity, horizontal wind speed and rainfall. Voltage and current parameters were monitored using improved amplifiers, voltage dividers, and Hall-effect sensors to adapt the measurement to the designed monitoring system. A SD data storage system was integrated allowing collected data to be kept and autonomous work in areas deprived of telecommunications networks, requiring minimal maintenance. Measurements were shown on an LCD screen and an interactive system based on a display, as well as this a pushbutton system allowed the user to control internal processes such as data extraction from an SD card and clock synchronization. Specific techniques to reduce both sensors and microprocessor board power consumptions were implemented. Open source tools were applied to achieve the low-cost objective. For the experimental campaign, and with the objective of reproducing real-life conditions as much as possible, a review on the typical daily energy consumption profiles of families living in a rural area and the most common characteristics of the photovoltaic systems used in developing countries was conducted. With this information, a real stand-alone PV system was designed and installed (Figure 49). This included the corresponding load for testing and validating the new low-cost datalogger under real conditions.

FIGURE 49: SAPV system installation in Jaén: (a) PV mono-crystalline module, (b) Charge controller and (c) lead-acid battery.

A low-cost meteorological station was also designed and installed (Figure 50). To test the new datalogger performance, a commercial datalogger with high accuracy was used as a pattern so both dataloggers were monitoring the same parameters simultaneously. An outdoor campaign lasting over a month at IMDEA Water Institute, in Alcalá de Henares (Madrid, Spain), was performed to test the new low-cost datalogger using the PV system and the low-cost weather station. The findings of the experimental campaign revealed a good fit between meteorological parameters measured by the new prototype and the pattern datalogger measurements. With regards to the results of the electrical measurements, the novel datalogger presented errors < 1% of measurements. The comparison of the results measured by the prototype with those of other high accuracy monitoring systems (used as a pattern) demonstrated compliance with the IEC61724 standard, monitoring all of the requested (electrical and environmental) parameters with high precision. The final cost of the new prototype, including high voltage and current sensing, was approximately 81€. This demonstrated that the datalogger based on open-source tools could be feasible for its use in SHS complying with accuracy and costs.

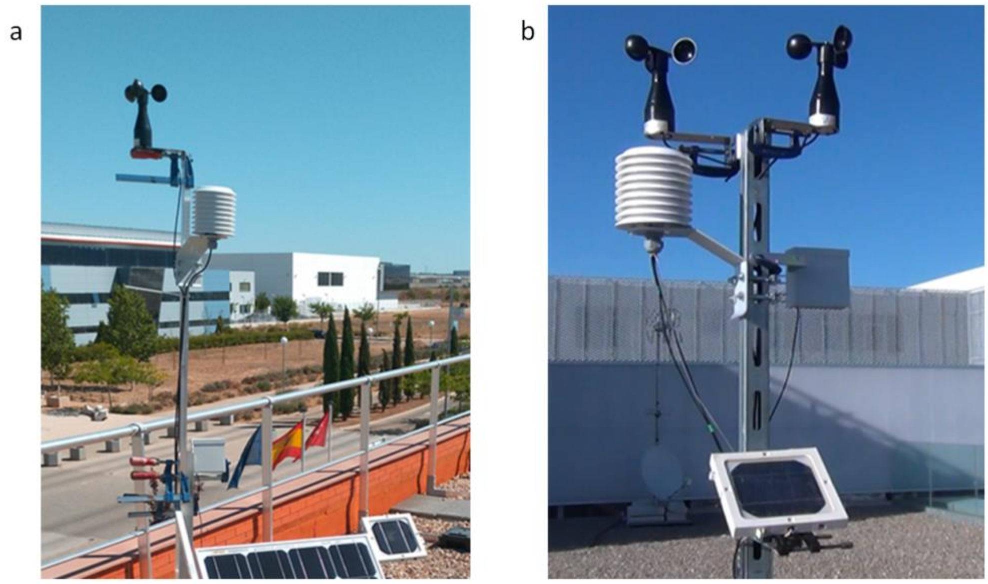


FIGURE 50: Weather stations installed in Alcalá de Henares (a) and Linares (b).

The version Datalogger SD had minimal maintenance but it was based on a manual procedure requiring human operator intervention for collecting data, which can be an inconvenient at locations that are difficult to access, also increasing the maintenance costs and operation. Thus, an advanced version of the datalogger (Datalogger 3G) for monitoring SHSs via website or mobile applications was presented in Chapter 5 (‘IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino^{TM} With 3G Connectivity’). The new prototype was also based on free software and hardware. In this study, the integration of wireless technology in it, specifically 3G, along with IoT was successfully carried out. Two types of data storage were tested: a dedicated server (conventional method) and a cloud service platform (novel application of IoT). Both storage alternatives allowed a remote system monitorization. The integration of an open cloud based IoT platform allowed remote monitorization of small stand-alone PV systems in real time via web or mobile app at low cost. The prototype was installed in three different sites: (Alcalá de Henares (Madrid, Spain), Linares (Jaén, Spain) and Oaxaca (Oaxaca, Mexico), to study the performance of the datalogger under different conditions, monitoring the systems for 12 months. With regards to electrical and meteorological parameters monitoring (again by comparing with a pattern commercial datalogger), the results showed that after the connectivity integration, as expected the new datalogger continued to measure correctly both the meteorological and electrical parameters. As resulted of the experimental campaign, the dataloggers only failed on 4 occasions throughout the year, due to different reasons: an access failure, a network outage, a power shortage and equipment failure. The remote visualization of the data in real time via web or smartphone was one of the main results due to the incorporation of connectivity to the system via 3G. The final cost of the new prototype, including sensing and connectivity, was approximately 141 €. The cost of the monitoring system was considerably lower than commercial devices and allowed high accurate remote monitoring. It was concluded that small PV systems can be monitored remotely using a smartphone, all at a low cost by integrating open source tools (open hardware and open cloud platforms). Figure 51 shows the prototypes installed in Alcalá de Henares (a), Oaxaca (b) and Linares (c).

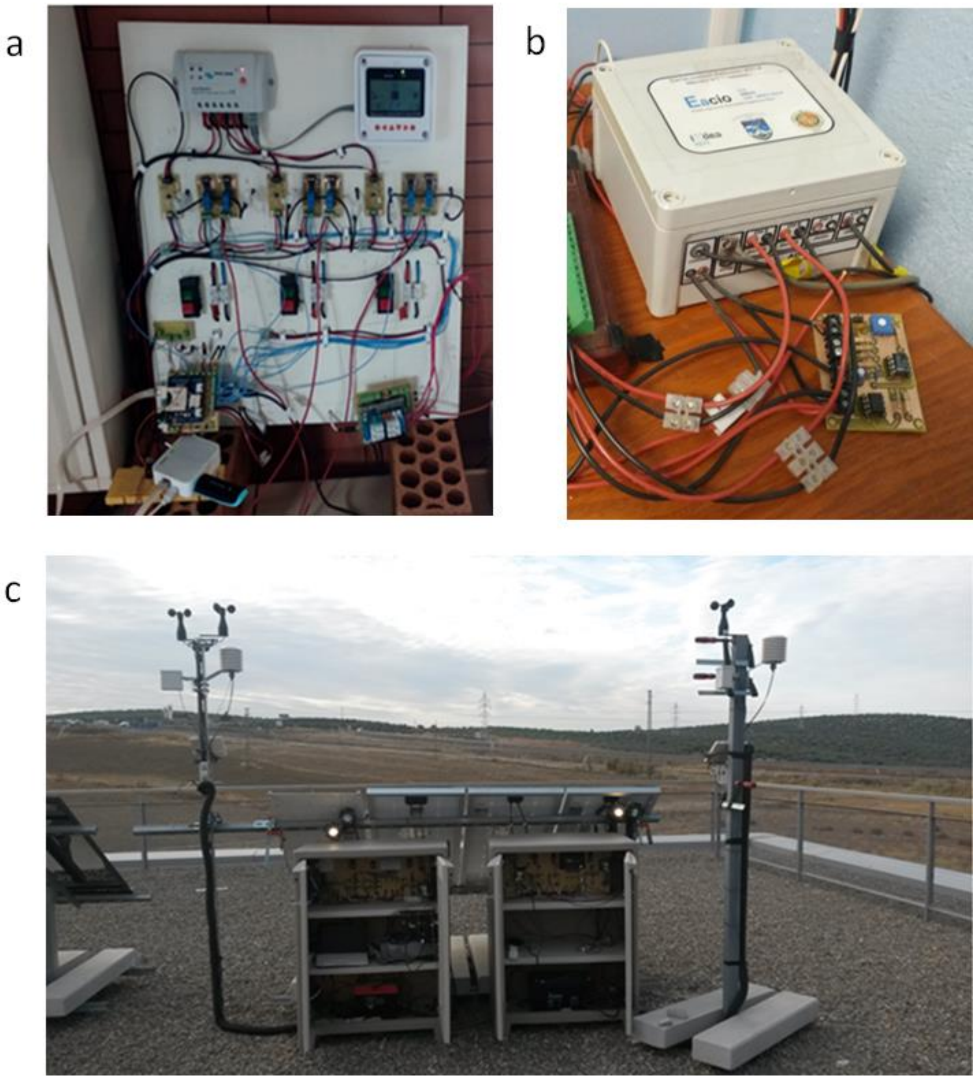


FIGURE 51: Final prototype assembly. (a) Version with 3G installed in Madrid (b) Version with 3G installed in Oaxaca (c) Versions SD and 3G installed in Linares.

Due to the failures detected during operation presented in Chapter 5, in Chapter 6 ('Evaluation of long-term performance and reliability of a SHS monitoring system on harsh environments') the datalogger was optimised, performing the system under stream temperatures and reinforcing the data storage system. The thermal evaluation of the system to guarantee the reliability of the long-term datalogger was carried out through an indoor campaign (temperature cycling tests) and an evaluation of the dataloggers under real-life conditions. In addition, the design and testing of a new prototype with a backup storage system (version Datalogger SD+3G) was carried out as another important optimization. Table XXXII shows all the versions of the datalogger developed in this thesis with a brief description. First, the effect of thermal stress was analysed. The datalogger was subjected to a temperature test in a confined area for evaluating its behavior under controlled conditions, to simulate the real-life outdoor conditions that produced the equipment failure and rendered the datalogger inoperative. The ambient temperature registered in the days before the error exceeded 40 degrees Celsius. A refrigeration system composed of two fans was installed but it was not enough: the temperature measured inside the electrical cabinet (where the datalogger was located) reached over the ambient temperature, exceeding 47 degrees Celsius, reaching well above the maximum operative conditions of the connectivity system (router and modem). After inspecting the system, it was confirmed that the data delivery system stopped working.

TABLE XXXII: VERSIONS DEVELOPED IN THIS WORK

Version	Description
Datalogger SD	Datalogger with a SD storage system
Datalogger 3G	Datalogger with 3G connectivity
Datalogger SD + 3G	Datalogger with 3G connectivity and SD backup system

During the entire test (20 cycles) the datalogger measured well and it did not stop sending the data. Even in the most critical functions, such as connectivity and data transmission capabilities that were the most temperature-sensitive functions, the datalogger functioned correctly. Additionally, the duration of the experimental campaign showed in Chapter V was extended over three years under adverse climatic conditions. This long-term testing exhibited excellent results. Only a few external failures such as power shortage or server falls (that hindered the storage of data) were registered. The total number of failures suffered in all dataloggers was very low. In addition, most of these failures were external errors (power shortage, server collapse…). From all of these results and information on the datalogger performance, a new prototype (version Datalogger SD+3G) was developed, integrating a backup storage system based on an SD card. The datalogger with the backup storage system based on an SD card was installed in Linares. During the summer of 2018 this datalogger was running continuously testing its performance. During this period, ambient temperatures of up to 40 º C were reached. The datalogger was installed inside an electrical cabinet, where the measured temperatures were even higher: the datalogger worked at operating temperatures above of 48 º C. The datalogger measured correctly. No failures were recorded, either of sensing or connectivity functions. After the evaluation of the long-term performance of the datalogger it was concluded that the datalogger is highly reliable and robust. It was demonstrated that the datalogger is especially designed to work correctly under harsh conditions.

Finally, during the PhD thesis study years the interest in the application on IoT has been increasing rapidly, along with the scientific articles published in the subject. To wrap up the thesis study it is essential to see how this new datalogger as an application of IoT lies within the scientific community, and how the research area has advanced. In this regard, Chapter 7 presents a review of the novel possibilities that IoT opens for meeting the Sustainable Development Goals. Problems faced by developing countries can open up new unexplored fields to apply IoT to, and around 85% of IoT deployments have the potential to address SDGs. It has identified key aspects for implementing IoT into the developing world: infrastructures, connectivity, lack of personnel with technical knowledge, environmental conditions or financial systems. The results showed that one of the main challenges for expanding IoT in developing countries is connectivity. Projects based on open-source hardware (OSHW) do not generally require high initial costs, which allows greater dissemination and makes this area more appealing and affordable for the scientific community to achieve SDGs. After an exhaustive revision, the combination of Low-cost IoT and PAYG was presented as the perfect scenario to better disseminate IOT4D to achieve SDGs.

To sum up, the study presented confirms the high reliability and robustness of a new monitoring system for SHSs, demonstrating its suitability for rural areas of developing countries with no wired telecommunication networks or electrical grid, braving extreme climate conditions.

Finally, handling the potential installation of the monitoring system in rural and isolated areas of developing countries, future work includes the creation of small networks that allow the monitoring of several SHSs using a single datalogger with a 3G connection as a gateway. Due to the stackable hardware design (by adding boards) several stand-alone PV systems installed close enough could be monitored using a single datalogger as a central node. Another fascinating future line is the creation of small networks using medium-low range communications that allow the measurement of several systems at the same time and sending data to the cloud through a central node that uses 3G. Both alternatives optimize the use of hardware minimizing the total cost.

Annex A

Índice

Annex B

Resumen

En la actualidad, hay más de mil millones de personas en el mundo sin acceso a electricidad. Se trata principalmente de un problema de electrificación rural, pues la mayoría de estas poblaciones vive en zonas rurales de países en desarrollo. Encontramos las tasas más bajas de electrificación en el África subsahariana, en el sudeste asiático y en menor medida, en Latinoamérica.

En los últimos años se han realizado grandes esfuerzos para dar acceso básico de electricidad en hogares de zonas rurales de países en desarrollo a través de iniciativas como los Objetivos del Milenio de las Naciones Unidas. Esta iniciativa tiene como uno de sus principales objetivos conseguir el acceso universal a electricidad en 2030. Una de las tecnologías más utilizadas en electrificación rural es la energía solar fotovoltaica. A través de diferentes programas de electrificación rural, se han instalado millones de sistemas fotovoltaicos (FV) autónomos que han mejorado la vida de muchas personas, proporcionándoles acceso a electricidad y dando servicio a los hogares para la conexión de luminarias, cargadores de móviles, televisores o pequeños frigoríficos. Además de combatir la pobreza energética, la instalación de estos sistemas fotovoltaicos ayuda a dar solución a otros aspectos de la pobreza como es la salud, la educación o la igualdad de género.

Estudios sobre electrificación rural han concluido que la monitorización de los sistemas fotovoltaicos es determinante en el éxito de estos programas. La importancia de la monitorización en los programas de electrificación rural reside en que permite realizar el seguimiento y mantenimiento de los sistemas; ayuda a la detección de fallos y su rápida solución, alargando así la vida útil de los sistemas y mejorando su rendimiento.

Aunque existen distintas soluciones comerciales aplicables a la monitorización de los sistemas FV, el caso de los sistemas fotovoltaicos autónomos es especial, pues estos sistemas son de tamaño reducido y la implementación de sistemas de monitorización está limitada por el coste. De esta forma, la monitorización de estos sistemas fotovoltaicos con sistemas de adquisición de datos comerciales no es una solución óptima, pues en muchos casos el precio del sistema de monitorización supera el precio total de la instalación. Otro de los problemas encontrados es que los sistemas comerciales de menor coste (susceptibles a ser instalados en este tipo de instalaciones) no cumplen los requisitos de precisión establecidos por los estándares internacionales, obteniendo incertidumbres en las medidas por encima de lo establecido por las normativas.

En los últimos años, con la aparición de tecnologías basadas en SW/HW libre, se han desarrollado nuevos diseños de muy altas prestaciones a muy bajo coste. El SW/ HW libre también se ha integrado en la monitorización de sistemas fotovoltaicos. Sin embargo, estos sistemas de monitorización presentan algunos problemas que impiden aplicarlo al caso de los sistemas fotovoltaicos autónomos ubicados en zonas rurales de países en desarrollo. Por un lado, algunos de estos sistemas dependen de hardware externo (como ordenadores portátiles) que aumentan el coste del sistema. Es otras ocasiones, los sistemas no han sido evaluados: no se han comparado las medidas de los sistemas con patrones, con medidas realizadas por sistemas de alta precisión. Además en muchas ocasiones, no se ha aplicado ningún tipo de normativa por lo que los sistemas de monitorización no cumplen los estándares internacionales.

Esta tesis nace con el objetivo de ofrecer una solución adecuada a la problemática presentada para la monitorización masiva de sistemas fotovoltaicos autónomos instalados en zonas rurales de países en desarrollo. El trabajo de esta tesis se centra en el desarrollo de tres versiones diferentes del sistema de monitorización. Todas las versiones integran herramientas de HW/SW libre para obtener sistemas de monitorización de bajo coste. Tras un estudio del estado del arte, se seleccionó una plataforma de desarrollo de hardware libre de la familia Arduino™ basada en microcontroladores de la familia ATMEL principalmente por su bajo coste, su robustez (mecánica y frente a las altas temperaturas) y la gran comunidad de desarrolladores de la que dispone. El primer prototipo utiliza una tarjeta SD para el almacenamiento de los datos. Para la campaña de experimentación se instaló un sistema fotovoltaico autónomo con las características de los sistemas fotovoltaicos instalados en los países en desarrollo a través de programas de electrificación rural. Se comprobó que el sistema de monitorización medía correctamente en condiciones reales y cumplía con los estándares internacionales gracias a una campaña de experimentación en intemperie de un mes de duración en el Instituto IMDEA Agua, en Alcalá de Henares (Madrid, España). El segundo prototipo constituye una versión más avanzada del registrador de datos que permite monitorizar los sistemas fotovoltaicos autónomos en tiempo real a través de un ordenador o de un Smartphone gracias a la integración de tecnología inalámbrica (concretamente 3G), de manera que se puede monitorizar remotamente sin necesidad de un operador que extraiga manualmente la tarjeta SD de manera periódica en todos los sistemas. Versiones del primer y del segundo prototipo se instalaron en localizaciones diferentes para estudiar el comportamiento del registrador de datos trabajando bajo diferentes condiciones climáticas. La instalación de prototipos se llevó a cabo en la azotea del Instituto IMDEA Agua en Alcalá de Henares (Madrid, España), en la azotea de la Escuela Politécnica de Linares (Jaén, España) y en la Escuela de Ciencias de la Universidad Benito Juárez (Oaxaca, México). El sistema de adquisición de datos ha estado funcionando de manera ininterrumpida durante tres años trabajando bajo condiciones climáticas reales y en muchas ocasiones, adversas. Durante este periodo, se registraron únicamente 4 fallos en la versión del prototipo con conectividad 3G. La mayoría de los errores fueron de origen externo: se detectó 1 fallo de alimentación por corte de luz, 1 fallo de acceso al servidor instalado en Linares y 1 fallo de red. Estos errores no tuvieron mayores consecuencias en el registrador, pues el sistema de monitorización está diseñado para reiniciarse en caso de fallo de alimentación o de problema en el envío de datos (fallos de acceso a servidor y de red). Estos dos últimos fallos supusieron la pérdida de los datos en los periodos que duró el fallo. El fallo de equipo fue detectado en el prototipo instalado en Linares; fue el error de mayor gravedad registrado pues dejó al prototipo inoperativo. La inspección del sistema de adquisición de datos determinó que lo más probable es que el fallo fuera consecuencia de un fallo en el sistema de conectividad debido a las altas temperaturas registradas (por encima de 50 ℃) en los días previos al fallo. Para tratar de solucionar los errores detectados y aumentar la fiabilidad del nuevo registrador, se diseñaron pruebas de fiabilidad en las que se sometía al datalogger a condiciones extremas de temperatura (ciclados térmicos en laboratorio) teniendo en cuenta las condiciones de fallo en el exterior. El sistema pasó las pruebas satisfactoriamente aumentando la confianza en su durabilidad. Esta batería de pruebas junto a la campaña en intemperie en condiciones reales e incontroladas (funcionando correctamente durante tres años con un mínimo número de fallos) demostró la robustez y fiabilidad del sistema. Finalmente, con los fallos detectados durante la larga campaña experimental bajo condiciones reales de operación y los resultados de las pruebas de fiabilidad en laboratorio, se diseñaron las mejoras del último prototipo del registrador de datos en la que se integraron tanto la comunicación remota como un sistema de almacenamiento redundante para evitar la pérdida de datos en caso de no poder establecerse la comunicación. Esta última versión se ha probado en exterior durante 8 meses con resultados positivos. En cuanto al coste del prototipo, la primera versión del prototipo está por debajo de los 100€. El prototipo que integra conectividad 3G tiene un coste por debajo de 150€. Se trata de prototipos experimentales en laboratorio, una mayor producción de dataloggers reduciría el coste final.

En resumen, en este trabajo se ha demostrado la alta precisión y robustez de un nuevo registrador de datos diseñado específicamente para la monitorización de sistemas fotovoltaicos autónomos que además tiene un coste contenido en sus primeros prototipos. Este sistema está especialmente diseñado para su instalación en áreas rurales de países en desarrollo sin acceso a red eléctrica ni redes de telecomunicación tradicionales (cable), demostrándose que el sistema cumple con los estándares internacionales y que es capaz de trabajar correctamente incluso bajo condiciones climáticas adversas, soportando temperaturas extremas.

Annex C

Capítulo 1: Introducción

C.1. Energía y desarrollo

Actualmente 1.060 millones de personas continúan sin acceso a electricidad y 3.040 billones hacen uso de combustibles sólidos y queroseno para cocinar y calentar sus hogares [1]. El acceso a sistemas de energía que sean asequibles y fiables es uno de los factores determinantes para la reducción de la pobreza en el mundo [1]. En 2015, el Banco Mundial fijó el umbral de pobreza en 1,70 € diarios; se estima que el 10,7% de la población mundial (unos 760 millones de personas) viven por debajo de este umbral [2]. El Banco Mundial considera que este conjunto de población que vive por debajo de este umbral, es una población que sufre "pobreza extrema".

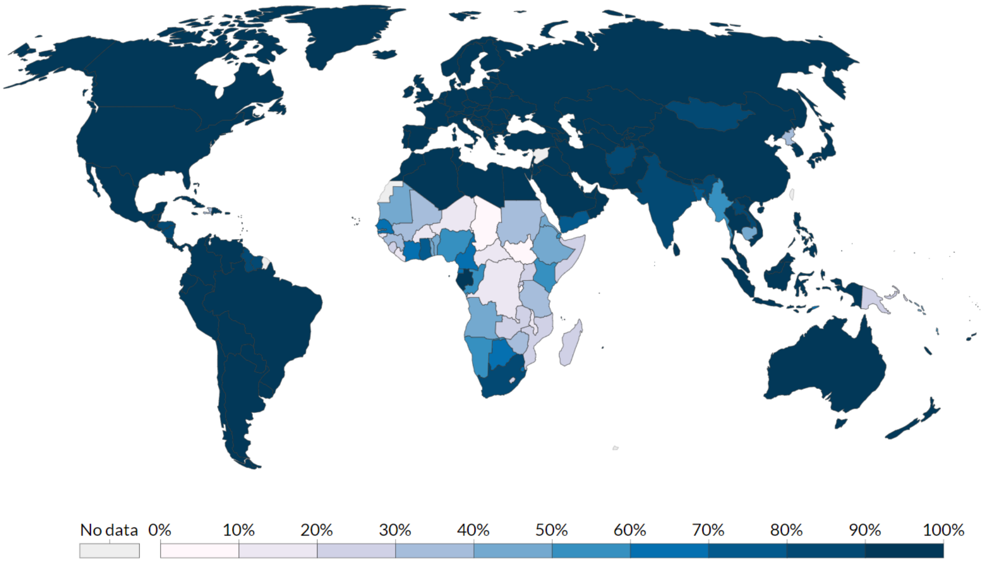


FIGURA 1: Distribución mundial del acceso a electricidad en 2015 (% de la población) [3]. Las principales áreas sin acceso a red eléctrica se encuentran en el sudeste de Asia (India) y en el África subsahariana.

Existe una estrecha correlación entre los niveles de ingresos y la falta de acceso a la energía moderna: los países con una mayor proporción de la población viviendo en extrema pobreza son los países que presentan una menor tasa de electrificación [1]. La Fig. 1 muestra la distribución mundial del acceso a electricidad. Como se muestra en la figura, la mayoría de las personas sin acceso a electricidad viven en el África subsahariana y en el sudeste de Asia y, en menor medida, en Oriente Medio, Asia Central y América Latina. De forma análoga, la mayoría de las personas que hacen uso de combustibles fósiles para cocinar y calentar sus viviendas se localizan en el sudeste de Asia (1.900 millones) y en el África subsahariana (850 millones) [1].

Existen también grandes diferencias entre las ciudades y las zonas rurales en cuanto al acceso de electricidad. En las áreas urbanas encontramos prácticamente acceso universal a electricidad: el 96,89% de la población mundial urbanita está conectada a red eléctrica, aunque seguimos encontrando algunos problemas en África y Asia-Pacífico debido al rápido crecimiento de las zonas urbanas. La Fig. 2 muestra la distribución de los 1,06 mil millones de personas que viven sin electricidad en la actualidad en el mundo, haciendo distinción entre zonas urbanas y zonas rurales. De la población total sin acceso a la energía en el mundo, 861 millones de personas viven en zonas rurales, en comparación con los 132 millones de personas que viven en zonas urbanas. Casi la mitad de la población mundial sin acceso a electricidad vive en zonas rurales de África subsahariana (482 millones de personas).

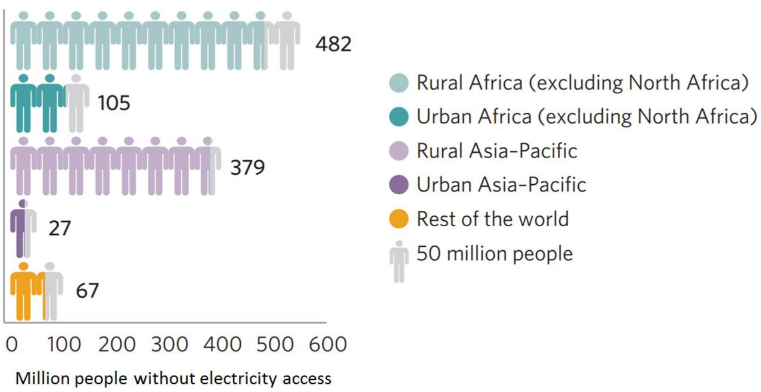


FIGURA 2: Distribución de la población sin acceso a la electricidad distinguiendo entre zonas rurales y zonas urbanas [4]. El 45,47% de la población sin electricidad vive en zonas rurales de África subsahariana.

El acceso a electricidad está íntimamente relacionado con otros aspectos de la pobreza, considerándose un factor determinante para el desarrollo y un aspecto esencial en la transformación de las sociedades agrarias a sociedades industriales [5]. La pobreza energética tiene también consecuencias negativas en la educación: en muchas regiones es habitual que sean los niños los encargados de recolectar biomasa y buscar agua potable [6] dedicándose a estas actividades en lugar de acudir a la escuela; además, sin electricidad, no tienen iluminación por la noche por lo que se reducen las horas de estudio, sobre todo en las estaciones en las que hay menos horas de luz. En ocasiones utilizan velas y queroseno para alumbrarse, pero es caro, con una gran repercusión en la economía familiar, y además afecta negativamente a la salud. Se ha demostrado que el aumento de las tasas de electrificación ayuda a reducir la tasa de analfabetismo y mejora la calidad de la educación [7]. La Figura 3 muestra la distribución mundial de la tasa de alfabetización entre la población joven (15-24 años). Los niveles más altos de analfabetismo se encuentran en el África subsahariana (más del 50% de jóvenes son analfabetos, principalmente en países como Mali, Níger o Chad) y en el sudeste asiático.

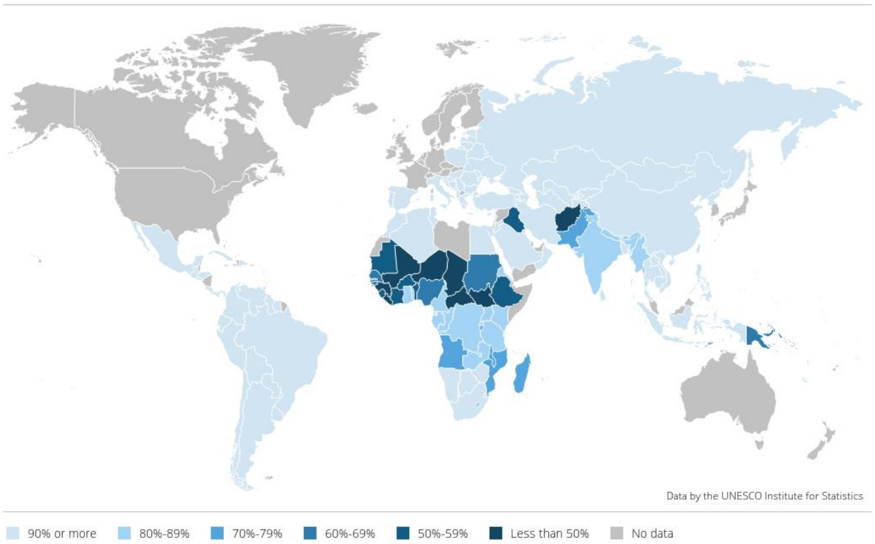


FIGURA 3[8]: Distribución global de la tasa de alfabetización entre los jóvenes de 15 a 24 años, sin diferencia en el género. La figura muestra la correlación entre altos niveles de analfabetismo y la pobreza de energía. Fuente: UNESCO. 2017.

La pobreza energética también tiene consecuencias negativas en la salud [5]. La Organización Mundial de la Salud estima que cada año, 3,8 millones de personas mueren prematuramente de enfermedades atribuibles a la contaminación del aire en las viviendas como resultado del uso de combustibles sólidos tradicionales como leña o carbón [9]. El uso de combustibles contaminantes para la iluminación de los hogares tiene consecuencias en la salud; de igual manera, el uso de biomasa sólida y carbón para cocinar entraña riesgos para la salud principalmente respiratorios, pues a menudo se cocina en un espacio reducido y cerrado que no dispone de la ventilación adecuada. La pobreza energética tiene otras consecuencias negativas en el área de la salud: se estima que el 60% de los sistemas de refrigeración utilizados en los centros de salud de África tienen un acceso a electricidad muy poco fiable, lo que resulta en una pérdida de casi la mitad de las vacunas. Además, se estima que el 70% de los dispositivos médicos eléctricos utilizados en los países en desarrollo presentan fallos, debidos principalmente a la mala calidad de las redes [1]. La Fig. 4 muestra la distribución en el mundo de muertes prematuras asociadas a la contaminación del aire en los hogares, IAP por sus siglas en inglés. Se aprecia que las áreas con un mayor índice de pobreza energética presentan un número mayor de muertes prematuras a causa de IAP.

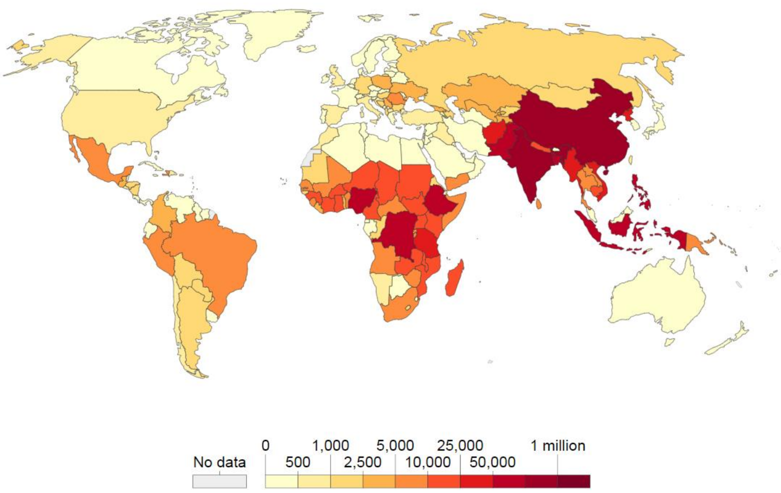


FIGURA 4: Distribución de muertes prematuras asociadas a la contaminación del aire en interiores [10]. La imagen muestra el número anual de muertes prematuras por enfermedades atribuidas a la contaminación del aire del hogar principalmente debido al uso de combustibles sólidos. Fuente: Instituto de Métrica de Salud y Evaluación. 2016 [10].

El acceso a electricidad tiene consecuencias sobre el objetivo de igualdad de género. En la mayoría de los países en desarrollo, es habitual que sean las mujeres las que sufren la pobreza energética de una forma más severa. El motivo de esta disparidad es que habitualmente es la mujer la encargada de realizar las tareas de recolección de biomasa y recogida de agua junto con las niñas [11], pasando varias horas al día dedicadas a estas tareas y teniendo que recorrer largas distancias. Este hecho tiene también consecuencias sobre la salud y sobre la educación de las niñas, que en muchos casos dejan de asistir a la escuela para poder desarrollar estas tareas [11].

El acceso a electricidad también está íntimamente relacionado con el problema del cambio climático, que es en gran medida consecuencia del uso abusivo de combustibles fósiles [12]. El cambio climático tiene un impacto negativo en todo el mundo, pero es mayor en las comunidades pobres que tienen menos recursos para adaptarse a él [13]. Por un lado, los países en desarrollo se ven afectados de manera desproporcionada por los desastres [14]: de los 30 países más vulnerables a los desastres naturales y el cambio climático, 26 son países en desarrollo. Además, el Banco Mundial estima que el cambio climático va a generar más de 100 millones de personas viviendo en pobreza extrema para el año 2030 (principalmente por la falta de medidas de protección contra desastres en los países en desarrollo) [15].

A través de la Declaración del Milenio de las Naciones Unidas, firmada en septiembre de 2000, los dirigentes mundiales se comprometieron a luchar contra la pobreza, el hambre, la enfermedad, el analfabetismo, la degradación del medio ambiente y la discriminación contra la mujer [16]. Entre los años 2000 y 2015, la aceptación de los Objetivos de Desarrollo del Milenio (MDGs por sus siglas en inglés) supuso una medida histórica y eficaz, consiguiendo la movilización mundial para luchar contra la pobreza [17]. Para continuar con las tareas iniciadas por los MDGs más allá de 2015, en 2012 se establecen los Objetivos de Desarrollo Sostenible [18] (SDGs por sus siglas en inglés) en la Conferencia de las Naciones Unidas sobre el Desarrollo Sostenible de Río de Janeiro, para continuar combatiendo la pobreza mundial. La adopción del Objetivo 7 (SDG 7), "garantizar el acceso a una energía asequible, fiable, sostenible y moderna para todos", tiene como meta acabar con la pobreza energética para 2030 [19] y reconoce el papel del acceso a la energía como clave para un desarrollo sostenible y para la lucha contra la pobreza. El SDG7 fija tres objetivos principales: garantizar el acceso universal a energía, duplicar la tasa mundial de mejora de eficiencia energética, y aumentar sustancialmente el porcentaje de la energía renovable en el conjunto de fuentes de energía. El acceso a energía está involucrado en otros SDGs: el acceso a la energía moderna como la electricidad es una posible solución a otros aspectos multidimensionales de la pobreza, tales como la educación (SDG4), la salud (SDG3) y el cambio climático (SDG13) [1,20]. Además, el acceso a la energía moderna promueve la igualdad de género y el empoderamiento de la mujer (SDG5) [21].

La Agencia Internacional de la Energía [1] realizó un estudio estableciendo los pasos a seguir para conseguir acceso universal a electricidad en el año 2030 siguiendo el SDG7: los sistemas descentralizados representan casi tres cuartas partes de los sistemas adicionales que habría que instalar para conseguir acceso universal a electricidad y, concretamente, la instalación de sistemas fotovoltaicos se presenta como la solución óptima.

C.2. Energía solar para la electrificación rural

Se define el Cinturón Solar [22] como la región del mundo más indicada para la instalación de un sistema solar, por ser la zona que recibe una mayor cantidad de radiación solar. La mayoría de los países en desarrollo están situados entre las latitudes 35 ° N y 35 ° S. Coincide así que la mayoría de la población mundial que no dispone de acceso a energía vive en lugares potenciales para la instalación de sistemas fotovoltaicos, tal y como se muestra en la Figura 5.

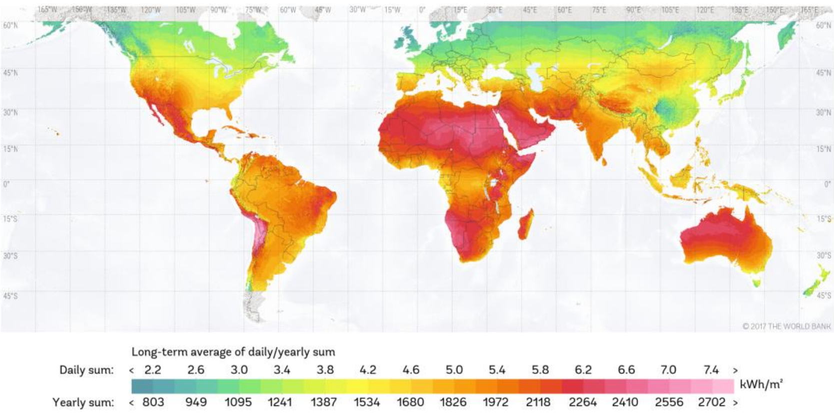


FIGURA 5: Distribución mundial de la irradiancia global [15]. Las zonas más apropiadas para la instalación de sistemas fotovoltaicos coinciden con las zonas de mayor pobreza energética (África subsahariana y sudeste asiático).

La capacidad mundial acumulada de energía solar ha experimentado un crecimiento exponencial en los últimos años. Según la Agencia Internacional de Energías Renovables, a finales de 2018 alrededor de 2.938 GW de la energía solar fotovoltaica producida provenía de sistemas sin conexión a red [23]. Más concretamente, casi 26 millones de hogares (100 millones de personas) tienen electricidad gracias a sistemas de energía renovable autónomos: 20 millones de hogares a través de sistemas fotovoltaicos autónomos, 5 millones de hogares a través de mini-redes, y 0,8 millones de hogares a través de pequeños sistemas eólicos [24]. En la Fig. 6 se muestra una clasificación de los sistemas fotovoltaicos autónomos y sus cargas típicas. Entre los hogares con sistemas fotovoltaicos no conectados a red encontramos soluciones diferentes [25], desde instalaciones muy pequeñas como son los sistemas pico-solares (SPS) a las soluciones de mayor tamaño como los SHSs (por su nombre en inglés "*Solar Home System*"). Por lo general, los SHSs, tienen una capacidad de 10-130 vatios pico, llegando hasta un máximo de 250 vatios en algunas instalaciones.

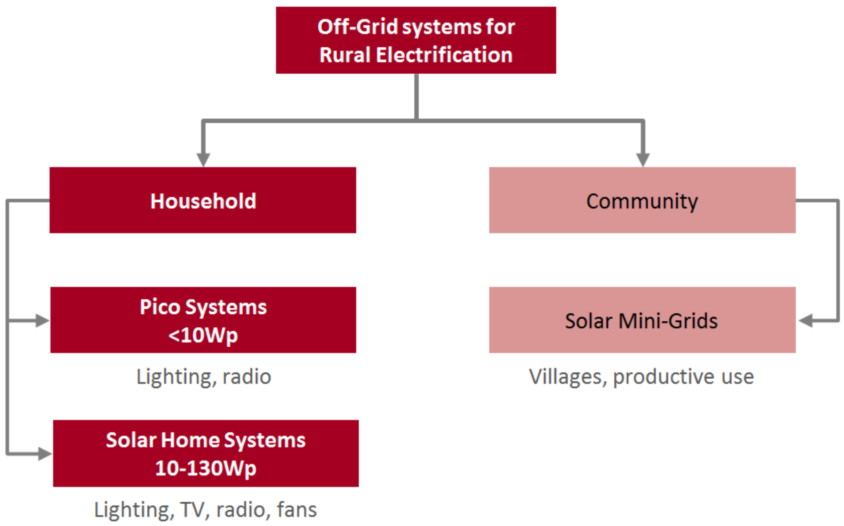


FIGURA 6: Tipos de sistemas sin conexión a red empleados en electrificación rural. La clasificación incluye los sistemas a nivel de hogar y de comunidad, incluyendo el sistema de carga más común para cada uno de los sistemas fotovoltaicos.

Los SHSs son sistemas fotovoltaicos aislados adecuados para aplicaciones residenciales [26]. En general, cuando hablamos de un SHS, hablamos de baja energía, es decir, de menos de 100 Wp. Los SHSs permiten la conexión de cargadores, pequeños electrodomésticos, luminarias, ordenadores o pequeñas bombas de agua [27].

A principios de 1990, los SHSs se presentaron como una solución económica para su instalación en programas de electrificación rural [69]. Desde entonces distintas instituciones han prestado su apoyo a las iniciativas de electrificación rural que promueven la instalación de SHSs en zonas rurales de países en desarrollo [28]. Por norma general, los SHSs son sólo una componente más de proyectos más grandes que abarcan objetivos de desarrollo tales como reformas del sector energético, la electrificación rural y el desarrollo rural.

La proliferación de los programas de electrificación rural ha fomentado la instalación de millones de SHSs en áreas remotas, principalmente en zonas rurales de Asia, África y América Latina. Tanto es así que en los últimos años, el mercado de los sistemas fotovoltaicos sin conexión a red se ha trasladado a los países en desarrollo. Fijándonos en la capacidad global acumulada de energía fotovoltaica a finales de 2018, las cifras son especialmente altas en países como India (843,11 MWp), China (387,80 MWp), Bangladesh (135,35 MWp), Kenia (36,84 MWp), Uganda (28 MWp), Burkina Faso (27MWp) y Tanzania (25,34 MWp) [23]. En estas regiones, la instalación de un SHS con un tamaño medio de 50 Wp es la solución de acceso a electricidad para 100.000 familias [29]. Encontramos los mercados más maduros en países como India (450.000 SHSs), China (150.000 SHSs), Kenia (120.000 SHSs), Marruecos (80.000 SHSs), México (80.000 SHSs) y Sudáfrica (50.000 SHSs) según Moner- Girona et al. [30], 2016.

Gracias a programas de electrificación rural como “Ligthing Global” [31] que apoyan el crecimiento sostenible de los países en desarrollo, millones de SHSs han sido instalados en todo el mundo:

a) En Asia, a través del programa “2005-2010 Village Electrification Programme”, 3,5 millones de personas han conseguido acceso a electricidad haciendo uso de energías renovables, gracias a la instalación de más de 400.000 SHSs [32] en China. En Bangladesh, la cifra de SHSs instalados entre 2003 y 2014 alcanzó los 3,2 millones de instalaciones beneficiando a 14 millones de bangladesíes, llevándose a cabo más de 50.000 instalaciones SHSs al mes [33]. En India, se estima que 239 millones de personas (siendo la población total de 1324 millones de personas) no tenían acceso a electricidad en 2016 [1]: esta cifra equivale aproximadamente a una cuarta parte de la población mundial sin acceso a la electricidad. India es uno de los países líderes en el área de mini-redes y sistemas fotovoltaicos autónomos, y ha realizado un tremendo esfuerzo de electrificación principalmente en las zonas rurales, pues desde el año 2000, 500 millones de personas han obtenido acceso a electricidad [1]. Miles [34] de SHSs han sido instalados a través del programa "Misión Solar Nacional" [35], siendo la promoción de los sistemas fotovoltaicos autónomos uno de los objetivos principales de la iniciativa. En India, las tres configuraciones más instaladas según Thrive™ Solar Energy Private Limited Corporación [36] son: módulo FV de 110Wp y batería de 75Ah, módulo FV de 250Wp y batería de 100Ah, y por último, módulo FV de 300Wp y batería de 120 Ah.

b) En África, los SHSs constituyen alrededor del 75% de la capacidad FV instalada en Tanzania [33]. Estos sistemas generalmente incluyen un módulo FV de 80-200Wp, una batería y un controlador de carga. Alrededor de 300.000 hogares de zonas rurales de Kenia tienen electricidad gracias a un SHS, según Kenia Renewable Energy Association [37]. En Kenia, la configuración más utilizada en las instalaciones de SHSs consta de un módulo FV de 25-30Wp. Generalmente, los sistemas revisados integran un módulo que oscila entre los 20W y los 120W, una batería de 30-100Ah y un controlador de carga.

c) En América Latina, el Proyecto de Electrificación Rural en Perú (2006) llevó a cabo la instalación de 7000 SHSs, dotando de acceso a electricidad a aproximadamente 31.500 personas de zonas rurales aisladas [15]. Este programa instaló módulos cristalinos de 60-80Wp, baterías de plomo-ácido de 100Ah y reguladores de carga de 10A. El sistema más instalado fue el de 80Wp según Acciona Microenergía Corporación [38]. En Brasil, el programa "Luz para todos" iniciado en 2003 [39] tenía como objetivo dar acceso universal a energía en Brasil. En 2016, 15,6 millones de brasileños se habían beneficiado de este programa, creándose más de 485.000 empleos [40] gracias a la instalación de sistemas FV. Los sistemas instalados utilizan módulos de 160Wp.

Las cargas típicas en hogares en zonas rurales de países en desarrollo suelen ser luminarias, televisores, ventiladores, cargadores o pequeños frigoríficos [41]. La Tabla I muestra típicas configuraciones de carga encontradas en la literatura.

TABLA I: SISTEMA TÍPICO INSTALADO Y CONFIGURACIÓN DE LA CARGA TÍPICA USADA EN PROGRAMAS DE ELECTRIFICACIÓN RURAL CON INSTALACIÓN DE SHSS

País	Módulo	Cargas
Bangladesh	10-350Wp	Luminarias, ventiladores y televisores LCD / LED [76]
India	10-200Wp	Luminarias, ventiladores y televisores [77]
Kenya	20-120Wp	Luminarias y TV / radio [78]
Tanzania	80-200Wp	Luminarias, radios, teléfonos móviles, televisores [79]
Peru	60-80Wp	Luminarias, cargador de teléfono celular, televisión / radio [80]

Muchos de estos países también fabrican los componentes necesarios para la instalación de los SHSs: baterías, controladores de carga y luminarias [47]. En general, todas estas iniciativas de electrificación rural utilizan módulos fotovoltaicos de silicio cristalino. En cuanto al otro componente clave de un SHS, la batería, la de plomo-ácido ha sido la más instalada según los estudios revisados. Por último, la mayoría de los SHSs utilizan reguladores de carga para proteger la batería, siendo el de tipo PWM el más empleado [48].

Los programas de electrificación rural tienen aún muchos desafíos por delante. Tras la revisión de los trabajos publicados sobre electrificación rural, a continuación recogemos los mayores retos encontrados:

1. Coste inicial muy alto [49]. Para una familia que viva en una zona rural de un país en desarrollo invertir 300€ en un sistema fotovoltaico es realmente difícil (podría ser comparable a comprar un coche nuevo en un país industrializado).

2. Falta de infraestructura financiera [49]. Por ejemplo, en el caso de América Latina, la infraestructura bancaria es pobre por lo que han sido

las propias instituciones las que han proporcionado a las familias microfinanciación [51].

3. Falta de conocimiento entre la población rural [49]. En muchas ocasiones el cliente no tiene experiencia previa con sistemas fotovoltaicos o ni siquiera ha oído hablar con anterioridad de este tipo de sistemas.

4. Falta de mantenimiento en los sistemas [50]: El mal mantenimiento de los sistemas y la falta de personal con conocimientos técnicos dan como resultado una reducción considerable en la vida útil de los sistemas fotovoltaicos debido al daño prematuro en los sistemas, principalmente por un mal uso de la batería. A menudo, los usuarios no son capaces de reparar fallos básicos en los sistemas. También es frecuente que la formación para realizar el mantenimiento de los sistemas no esté dirigido a las personas adecuadas [50]. Para solucionar esto, es necesario invertir recursos suficientes en el mantenimiento de los sistemas y en formación [49].

5. Fallos en equipos [52]: Las baterías y luminarias de tipo fluorescentes son los dos componentes que fallan con más frecuencia en los SHSs. Sobre todo el caso de la batería es realmente importante, pues suele ser la componente de sistema fotovoltaico que determina el tiempo de vida del mismo. Con la integración de reguladores de carga en el sistema FV podemos conseguir alargar la duración de la batería y por lo tanto, del sistema FV.

6. Falta de información sobre los programas de electrificación rural: La información disponible sobre las experiencias en los programas de electrificación previos con los SHSs es muy limitada. A menudo, es difícil acceder a la información y los datos se dispersan. Esta información es de gran valor para mejorar el diseño de nuevos proyectos. La creación de bases de datos con información de los programas de electrificación rural podrían facilitar el intercambio de datos [52].

7. Falta de monitorización: Nieuwenhout et al [50] realizaron una revisión sobre las experiencias previas con SHSs en países en desarrollo y su principal conclusión fue que no hay suficiente información disponible ni

sobre el rendimiento de los sistemas y ni sobre los proyectos. Es fácil encontrar información sobre la estructura organizacional de los proyectos, pero en muy pocos casos se describe (con cierto nivel de detalle) cómo se utilizan realmente los SHSs en los hogares. Se requiere más información para mejorar las actividades de despliegue y para mejorar la calidad de los sistemas. Es necesaria la monitorización de los sistemas tras la instalación del proyecto.

8. Falta de estandarización: Los estudios en campo han revelado que se requieren pruebas de laboratorio previas para comprobar que los sistemas cumplen con las normativas y los requisitos internacionales de estandarización como el IEC (Comisión Electrotécnica Internacional) y la PV-GAP (Programa Global de Aprobación para la energía fotovoltaica) [52].

C.3. Falta de monitorización en SHSs instalados en zonas rurales de países en desarrollo

De todos los retos mencionados en el apartado anterior, este trabajo se centra en el problema de la falta de monitorización de los SHSs instalados en las zonas rurales de países en desarrollo.

Se ha identificado la monitorización de los SHSs como uno de los factores principales que contribuyen en el éxito de un programa de electrificación rural [53], pues la monitorización los sistemas FV aumenta su vida útil y minimiza la probabilidad de fallo en las instalaciones fotovoltaicas. La monitorización de estos SHSs también ofrece información valiosa que puede ser utilizada en distintos campos de investigación. En el 2000, Nieuwenhout et al. [52] presentaron un trabajo titulado “Monitorización y evaluación de SHSs”, en el que analizaban los resultados tras la instalación de sistemas fotovoltaicos en hogares de zonas rurales de países en desarrollo. Tras realizar una extensa y profunda revisión de diferentes programas, su principal conclusión fue que no había suficiente información disponible sobre el rendimiento de los SHSs y los proyectos, y que este hecho ralentiza aún más el desarrollo y la difusión de los programas de electrificación rural. También, se presenta la falta de monitorización como un factor decisivo en el éxito del programa. El uso de sistemas de monitorización así como otras herramientas (encuestas a los usuarios por ejemplo) permitiría obtener un mayor nivel de información sobre los sistemas FV instalados. Además, es necesario que se continúe con la monitorización de los sistemas fotovoltaicos más allá de la etapa de instalación [50].

En 2014, Md. Zahidul Islam et al. [54] presentaron un estudio centrado en la situación actual, las perspectivas futuras y las limitaciones que presentan los SHSs instalados en Bangladesh. Detectaron la existencia de varios problemas, la mayoría de ellos consecuencia del mal uso por parte de los usuarios: inclinaciones de los módulos incorrectas o sombras, que en muchos casos produjeron puntos calientes en el módulo, en muchas ocasiones debido a la mala ubicación del módulo o a la mala limpieza. Además realizaron una evaluación de satisfacción de los usuarios. En la mayoría de los casos los usuarios no tenían una buena opinión sobre los proveedores y éste era el principal motivo por el cual no se planteaban aumentar el tamaño de su instalación. La falta de monitorización adecuada y por lo tanto, la imposibilidad de detectar problemas de operación y mantenimiento, que en la mayoría de casos son causados por malas prácticas de los usuarios finales, puede conducir a una reducción dramática de la vida útil de los sistemas [55]. Urmee et al. [53] en 2009 identificaron "el mantenimiento regular de los sistemas y su seguimiento" como factores decisivos que contribuyen en el éxito de los programas de electrificación rural, pues la aplicación de estas acciones aumenta la vida útil del sistema y ayudan a mejorar el nivel de confianza de los usuarios en el sistema. La monitorización de SHSs siguiendo las normativas internacionales permite evaluar el rendimiento del sistema y detectar fallos en su funcionamiento.

La monitorización de los SHSs es todo un reto: por la ubicación de las instalaciones se necesitan sistemas de monitorización que sean precisos, robustos, autónomos (permitiendo llevar a cabo la monitorización de forma remota), y todo ello a bajo coste. Se han identificado tres requisitos fundamentales que deberían de cumplir los registradores de datos que quieran emplearse en la monitorización de los SHSs:

a) *Requisito de bajo coste:* Por lo general, en los sistemas FV conectados a la red, los dispositivos de monitorización permiten medir los parámetros principales para llevar a cabo las acciones correctivas y de mantenimiento necesarias sin que los gastos asociados a la monitorización presenten un gran impacto económico en el coste total de la instalación. Sin embargo, en el caso de los SHSs, las instalaciones están limitadas por dos factores: tamaño y coste. El precio de los registradores de datos comerciales ha disminuido en los últimos años, pero todavía es demasiado alto y en algunos casos, incluso supera el precio del sistema fotovoltaico autónomo. Por ello, surge la necesidad de desarrollar sistemas de adquisición de datos que permitan monitorizar los SHSs, cumpliendo con la premisa de que sean sistemas de bajo coste.

b) *Cumplimiento de los estándares internacionales:* La medida de los parámetros eléctricos proporciona información sobre el consumo y la eficiencia de los SHSs. Los estándares internacionales establecen los requisitos de precisión de las medidas eléctricas. Estos estándares también especifican los parámetros climáticos que se deben medir así como la precisión en la medida de estos parámetros. Además estos estándares regulan otros detalles muy importantes de la monitorización como son el intervalo de muestreo, el intervalo de registro de los datos, los protocolos de sincronización a utilizar o la metodología de almacenamiento de los datos.

c) *Monitorización remota:* Generalmente, los SHSs están situados en lugares aislados por lo que poder realizar la monitorización de manera remota en una necesidad. Además, permite reducir el tiempo de respuesta ante fallos [56]. Centrándonos en los sistemas descentralizados, la aplicación de tecnologías inalámbricas en la monitorización parece ser el método de comunicación más apropiado: los SHSs comúnmente se encuentran en regiones remotas y de difícil acceso, generalmente en áreas sin acceso a las redes tradicionales de telecomunicaciones por cable. Por ello la tecnología de comunicación empleada en estos lugares debe ser capaz de funcionar de forma autónoma, sin necesidad de redes de comunicaciones de respaldo adicionales preinstaladas.

En general, como ya se ha indicado previamente, la mayoría de estos sistemas se encuentran en zonas rurales de Asia, África y América Latina. En los últimos años, se han desarrollado varios sistemas aplicables a la monitorización de SHSs ubicados en zonas remotas de países en desarrollo. También recientemente, se está siguiendo la tendencia de desarrollar diseños de bajo coste basados en software/hardware libre. Esta tendencia también se ha aplicado al desarrollo de equipos de monitorización. El uso de plataformas de hardware libre (Arduino™, Rapsberry™...) reduce considerablemente el coste final del diseño. Además, se ha identificado la monitorización de sistemas fotovoltaicos como una aplicación del IoT con mucho potencial. Por ello, la integración del IoT y el uso de herramientas de código abierto en la monitorización de los SHSs se presentan como la solución óptima que permitiría el desarrollo de sistemas de monitorización ad-hoc a bajo coste.

C.3.1. Sistemas de monitorización convencionales

Tras revisar la literatura publicada en los últimos 20 años sobre monitorización de sistemas fotovoltaicos, se concluye que es difícil realizar la monitorización de los SHSs principalmente porque a) los registradores de datos requeridos son demasiado caros en comparación con el coste total del sistema fotovoltaico, b) con frecuencia los registradores de datos dependen de HW adicional (PC o fuentes de alimentación externas) y c) el registrador de datos no sigue los estándares internacionales.

El uso de software comercial es uno de los principales inconvenientes encontrados en los intentos de monitorización revisados, pues aumenta el precio del registrador de datos, llegando incluso a superar el precio total del sistema fotovoltaico. El uso de equipos auxiliares para almacenar datos (ordenadores por ejemplo) es uno de los factores que también tiene un alto impacto en el coste final del sistema. M. Benghanem y A. Maafi [57] en 1998 desarrollaron un sistema de monitorización en tiempo real que utilizaba un ordenador central como servidor. El sistema empleaba un microprocesador MC68B09 que llevaba a cabo la adquisición de parámetros eléctricos y meteorológicos en sistemas fotovoltaicos. Tras la adquisición de los datos, los parámetros eran transmitidos al PC a través de una conexión serie RS232C.

Una vez allí, el tratamiento de los datos permitía estudiar el rendimiento del sistema fotovoltaico. El uso de hardware adicional (como el PC) aumentaba considerablemente el precio del sistema de monitorización. E. Koutroulis y K. Kalaitzakis [58] en 2003 presentaron un sistema integrado de adquisición de datos; el sistema fue diseñado para medir parámetros meteorológicos (temperatura, humedad, etc.) y eléctricos (tensión y corriente). El registrador de datos propuesto utilizaba una tarjeta DAQ, un convertidor ADC con una precisión de 12 bits y 8 canales dedicados a entradas/salidas digitales. Sin embargo, el uso de un software comercial para el procesado, la visualización y el almacenamiento de los datos recopilados junto con la dependencia de hardware externo (PC), aumentó el precio del sistema considerablemente.

Para monitorizar sistemas fotovoltaicos instalados en áreas remotas de países en desarrollo sin acceso a red eléctrica ni a redes de telecomunicación, que el sistema de adquisición de datos no necesite de una fuente externa para funcionar correctamente es crucial. Unos de los pioneros en el desarrollo de sistemas de monitorización para sistemas fotovoltaicos fueron R. Mukaro et al. [59] en 1998. El sistema de monitorización que fue desarrollado era de bajo coste, basado en un microcontrolador de 8 bits. Con 4 entradas analógicas, utilizaba un conversor analógico-digital para la realización de las medidas. Los datos eran almacenados en un ordenador portátil. El intervalo de muestreo escogido fue de 10 minutos y entre intervalos, se integró un sistema para minimizar el gasto de energía. Los resultados obtenidos se compararon con equipos de alta precisión (patrones) y se realizó un estudio de los errores obtenidos. Este sistema era adecuado para medir parámetros climáticos en estaciones meteorológicas remotas, especialmente en países en desarrollo. Sin embargo, otra vez, la necesidad de conectar el sistema a un PC era una gran desventaja. N. Forero et al. [60] en 2006 desarrollaron un sistema muy novedoso para monitorizar plantas solares fotovoltaicas. El sistema estaba diseñado para recopilar datos ambientales, y además podía medir el rendimiento de una pequeña planta solar fotovoltaica, obteniendo la curva I-V. El registrador de datos utilizaba una tarjeta de adquisición de datos de alta velocidad. El procesado y el almacenamiento de los datos se llevaba a cabo con la ayuda de un software específico. La necesidad de estar conectado a un PC es el principal inconveniente que presentaba este sistema.

Uno de los principales problemas encontrados durante la revisión de registradores de datos con aplicaciones fotovoltaicas es que por lo general, no se suelen evaluar los sistemas en términos de calidad. Las medidas de los sistemas desarrollados no suelen compararse con las medidas realizadas por otros sistemas de alta precisión. Los errores tampoco son evaluados y no suele aplicarse ningún tipo de estándar o normativa. En 2011, Purwadi et al. [61] desarrollaron un prototipo basado en un microcontrolador. El sistema se alimentaba por batería y estaba equipado con una memoria interna para el almacenamiento de los datos. El registrador de datos se instaló dentro de un sistema de alumbrado público (FV) situado en una zona remota de la Región de Yakarta (Indonesia). El prototipo empleaba herramientas de bajo coste: utilizaba un microcontrolador Atmel Atmega8, un reloj RTC (por sus siglas en inglés), sensores Dallas DS 1307 y una memoria EEPROM serial de 64kB. El datalogger proporcionaba información sobre la energía diaria utilizada, la energía total utilizada, el estado de carga/descarga de la batería y los errores del sistema FV. El registrador era de bajo consumo de energía, de bajo coste, portátil y fácilmente integrable en los sistemas de alumbrado público FV. Sin embargo, las medidas no se compararon con otros sistemas de adquisición de datos calibrados y de alta precisión, y tampoco se estudiaron los errores de las medidas. En 2008, Demirtas et al. [62] presentaron un sistema de adquisición de datos de bajo coste diseñado sobre un PIC 18F452 y un microcontrolador 18F2550. El sistema fue probado en un módulo solar de 2.5 kW y en un sistema eólico de 2.5 kW. Era de bajo consumo y de bajo coste. Integraba un conversor ADC de 10 bits y disponía de 8 entradas analógicas. Los parámetros medidos (corriente, voltaje, dirección del viento…etc) se visualizaban en una pantalla LCD. El principal inconveniente: el diseño no seguía ningún tipo de normativa internacional y la precisión del sistema no fue demostrada.

C.3.2. Aplicación del IoT y herramientas de SW/HW libre y su integración en la monitorización de SHSs

En los últimos años, la tendencia en el diseño de los sistemas de monitorización es utilizar herramientas de código abierto (software y hardware) y la integración del IoT. En la última década se ha producido un aumento exponencial del uso de herramientas de SW/HW libre. Han proliferado los proyectos basados en hardware libre (OSHW por sus siglas en inglés), y las nuevas plataformas de OSHW se han ido integrando de manera progresiva en el diseño de sistemas de adquisición de datos precisos y de bajo coste. En el caso de los proyectos dedicados a monitorización estudiados, se han utilizado microcontroladores y microprocesadores como Arduino™ UNO [63], Arduino™ Mega [64,65], PcDuino [66] o Raspberry PI [67,68,69].

Se han encontrado varios diseños dedicados a la monitorización de sistemas fotovoltaicos en la literatura publicada. En 2014, M. Fuentes et al. [63] desarrollaron un prototipo de bajo coste utilizando un Arduino™ UNO. El sistema estaba pensado para la monitorización de sistemas fotovoltaicos (SHS y sistema fotovoltaico conectado a micro-red) localizados en áreas remotas o regiones rurales de países en desarrollo. El registrador de datos cumplía con los requisitos de precisión establecidos por los estándares del IEC. El registrador tenía una resolución de 18 bits, incluía medidas de parámetros eléctricos y meteorológicos. El datalogger fue probado en condiciones meteorológicas adversas, durante el verano y el invierno en el sur de España. Los resultados indicaron que el sistema desarrollado era preciso y su rendimiento era comparable al de los sistemas comerciales. Sin embargo, presentó una serie de inconvenientes: los parámetros meteorológicos medidos eran insuficientes (solo se midieron temperaturas e irradiancia) y el rango de voltaje de entrada era muy limitado. Gad et al. [64] en 2015 desarrollaron un nuevo sistema de adquisición de datos para la medida de temperatura con aplicaciones en energía solar. El sistema de monitorización constaba de cuatro partes: una placa de control, un Arduino™ MEGA, la fuente de alimentación y la unidad de sensores. El registrador de datos almacenaba los parámetros medidos en una memoria local hasta que un operador los descargara in situ; esto es una gran desventaja para su aplicación en la monitorización de SHSs ubicados en regiones aisladas e inaccesibles. En 2018, Pereira et al. [67] desarrollaron un sistema de monitorización en tiempo real con almacenamiento en la nube para su aplicación en una planta fotovoltaica descentralizada. El diseño utilizaba la plataforma Raspberry PI. Eligieron esta plataforma por su pequeño tamaño y su bajo coste. El datalogger fue probado en la región noreste de Brasil y midiendo parámetros climáticos y eléctricos. El mayor inconveniente de este sistema es su conectividad. Utiliza Wi-Fi para la transmisión de los datos por lo que requiere de un módem o enrutador: a menudo esto no está disponible en las regiones rurales de países en desarrollo.

A raíz de la integración del IoT en los nuevos diseños, los proyectos han empezado a utilizar servicios de almacenamiento de datos en la nube. La aplicación del IoT tiene un gran potencial para la monitorización a gran escala de SHSs, pues permite la monitorización remota de los sistemas fotovoltaicos accediendo a los datos en tiempo real desde cualquier ordenador o Smartphone. Friansa et al. [70] en 2016 desarrollaron un registrador de datos para monitorizar el funcionamiento y rendimiento de las baterías integradas en micro-redes FV que integraba IoT. El sistema empleaba una Raspberry PI Modelo 2; con esta placa se llevaba a cabo la adquisición de datos que posteriormente eran enviados a un servidor en la nube. La toma de datos se llevaba a cabo según lo establecido en el estándar IEC61724. Los datos almacenados en la nube se procesaron y analizaron para generar información que los usuarios pudieran entender fácilmente.

Estos nuevos sistemas de monitorización necesitan conexión a Internet y, en general, lo más habitual es dotar al sistema con comunicaciones inalámbricas. Existe una amplia gama de tecnologías inalámbricas donde escoger: radiocomunicaciones de corto alcance (como ZigBee, Bluetooth y Wi-Fi) o protocolos de radio de mayor alcance (como Dash 7). En los sistemas de monitorización revisados, se encontró que la tecnología Zigbee (de corto alcance) es la tecnología más utilizada [71,72,73,74,75]. Algunas tecnologías no son adecuadas para la monitorización de SHSs debido a su corto alcance o a la necesidad de una red de respaldo (generalmente por cable) que no está disponible en muchas de las ubicaciones. Además, en los últimos años, la tendencia es utilizar servicios de almacenamiento de datos en la nube. El uso de plataformas gratuitas de almacenamiento en la nube permite diseñar un sistema de monitorización basado completamente en herramientas de código abierto, reduciendo los costes al máximo. En la literatura revisada, la plataforma de almacenamiento en la nube gratuita más utilizada es ThingSpeak™. Touati et al. [68] en 2016 utilizaron este servicio de almacenamiento en la nube. Propusieron un sistema de monitorización de bajo coste que permitía un acceso a los datos ubicuo. El sistema estaba compuesto por un microcontrolador, 6 sensores (con circuitos de acondicionamiento de señal) y módulos Zigbee para la transmisión de datos. En los últimos años, algunos proyectos [75, 20] utilizan aplicaciones web, que permite la distribución de los datos a través de Internet y el acceso a ellos a usuarios remotos.

El objetivo de esta tesis es realizar el diseño y desarrollo de un sistema de monitorización de bajo coste para la monitorización de SHSs, que sea adecuado para su instalación en áreas rurales de países en desarrollo. El registrador de datos tiene que ser diseñado específicamente para resolver los problemas descritos anteriormente que surgen en la monitorización de SHSs instalados en regiones aisladas de países en desarrollo. El diseño estará pensado para su implantación a nivel global, permitiendo la detección de errores y problemas de los sistemas FV. El objetivo de este trabajo es contribuir en el éxito de los programas de electrificación rural y permitir un mejor acceso a energía en las zonas rurales de los países en desarrollo.

C.4. References

[1] <http://www.un.org> (accessed 07.04.2018)

[2] “Energy Access Outlook 2017” report. International Energy Agency, 2017.

[3] “Off-grid solar market trends report 2016” report. World Bank Group, 2016.

[4] “World Energy Resources Solar 2016,” World Energy Council, 2016.

[5] R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, “Off-Grid Renewable Energy Systems: Status and Methodological Issues,” Irena, p. 29, 2015.

[6] T. Urmee, D. Harries, and A. Schlapfer, “Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific,” Renew. Energy, vol. 34, no. 2, pp. 354–357, 2009.

[7] F. D. J. Nieuwenhout, A. Van Dijk, V. A. P. Van Dijk, D. Hirsch, P. E. Lasschuit, and G. Van Roekel, “Monitoring and evaluation of experiences with applications of solar PV for households in developing countries” September, 2000.

[8] < http://solarone.me/2016/07/27/living-in-the-sun-belt-the-solar-power-potential-for-the-middle-east/ > (accessed 07.04.2018)

[9] < http://www.meteonorm.com/ > (accessed 08.04.2018)

[10]V.Salas. “Stand-alone photovoltaic systems”. In: The Performance of Photovoltaic (PV) Systems, 2016.

[11]C. Werner and A. Gerlach, “Global Installed Photovoltaic Capacity and Identification of Hidden Growth Markets,” no. October, 2014.

[12] M. Moner-Girona, S. Szabo and S. Bhattacharyya, “Off-Grid Photovoltaic Technologies in the Solar Belt: Finance Mechanisms and Incentives, Reference Module in Earth Systems and Environmental Sciences”, Elsevier, 2016.

[13] < https://www.lightingglobal.org/ > (accessed 09.02.2018)

[14] R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, “Off-Grid Renewable Energy Systems: Status and Methodological Issues”, International Renewable Energy Agency, 2015.

[15] < http://www.irena.org/ > (accessed 04.03.2018).

[16] “The Synergies between Mobile, Energy and Water Access: Africa”. Groupe Speciale Mobile Association (GSMA), 2014.

[17] < https://unu.edu > (accessed 08.01.2018).

[18] Recommendation ITU-T Y.2060

[19] < http://kerea.org > (accessed 08.01.2018).

[20] < http://www.worldbank.org > (accessed 08.01.2018).

[21] < https://www.acciona.com/es/ > (accessed 10.02.2018).

[22] Jäger-Waldau, “PV status report 2014”, JRC Science and Policy Reports, 2014.

[23] N.J. Williams, E. Ernest van Dyk, F.J. Vorster, “Monitoring solar home systems with pulse width modulation charge control". J Sol Energy Eng 2011.

[24] F. D. J. Nieuwenhout, A. Van Dijk, P. E. Lasschuit, G. Van Roekel, and V. A. P. Van Dijk, “Experience with Solar Home Systems in Developing Countries : A Review”, Progress in photovoltaics: Research and applications, vol. 474, no. June, pp. 455–474, 2001.

[25] M.Fuentes, M. Vivar, H. Hosein, J. Aguilera, E. Muñoz-Cerón, ‘Lessons learned from the field analysis of PV installations in the Saharawi refugee camps after 10 years of operation’, Renewable and Sustainable Energy Reviews, Vol 93, pp.100-109, 2018..

[26] IEC61724-1. Photovoltaic System Performance- Part 1: Monitoring. 1st Ed., IEC, Switzerland, Geneva, 2017.

[27] Benghanem, M., Maafi, A., “Data acquisition system for photovoltaic system performance monitoring, 1998 IEEE Transaction on Instrumentation and Measurement, vol.47, pp.30-33

[28] E. Koutroulis and K. Kalaitzakis, “Development of an integrated data-acquisition system for renewable energy sources systems monitoring”, Renew. Energy, vol. 28, no. 1, pp. 139–152, 2003.

[29] R. Mukaro, X. Carelse, and L. Olumekor, “First performance analysis of a silicon-cell microcontroller-based solar radiation monitoring system”, Sol. Energy, vol. 63, no. 5, pp. 313–321, Nov. 1998.

[30] N. Forero, J. Hernández, and G. Gordillo, “Development of a monitoring system for a PV solar plant”, Energy Convers. Manag., vol. 47, pp. 2329–2336, 2006.

[31] A. Purwadi, Y. Haroen, F. Y. Ali, N. Heryana, D. Nurafiat, and A. Assegaf, Prototype development of a Low Cost data logger for PV based LED Street Lighting System, Proc. 2011 Int. Conf. Electr. Eng. Informatics, no. July, pp. 1–5, 2011.

[32] M. Demirtas, I. Sefa, E. Irmak, I. Colak, Low-cost and high sensitive microcontroller based data acquisition system for renewable energy sources, in: Int. Symp. Power Electron. Electr. Drives, Autom. Motion SPEEDAM, 2008, pp. 196–199.

[33] B. Wichert, M. Dymond, W. Lawrance, T. Friese, "Development of a test facility for photovoltaic-diesel hybrid energy systems", Renew. Energy 22 (2001) 311–319.

[34] K. Papadakis, E. Koutroulis, K. Kalaitzakis, "A server database system for remote monitoring and operational evaluation of renewable energy sources plants", Renew. Energy 30 (2005) 1649–1669.

[35] M. Anwari, M. Dom, and M. I. M. Rashid, "Small Scale PV Monitoring System Software Design" Energy Procedia, vol. 12, pp. 586–592, 2011.

[36] A. Mahjoubi, R.F. Mechlouch, A. Ben Brahim, "Data acquisition system for photovoltaic water pumping system in the desert of Tunisia", Procedia Engineering. 33 (2012)268–277.

[37] R. Eke, A. Sertap Kavasoglu, N. Kavasoglu, "Design and implementation of a low-cost multi-channel temperature measurement system for photovoltaic modules", Measurement 45 (2012) 1499–1509.

[38] M.E.A. López, F.J.G. Mantiñan, M.G. Molina, "Implementation of wireless remote monitoring and control of solar photovoltaic (PV) system", in: Transm. Distrib. Lat. Am. Conf. Expo., 2012, pp. 1–6.

[39] G. M. Tina and A. D. Grasso, "Remote monitoring system for stand-alone photovoltaic power plants: The case study of a PV-powered outdoor refrigerator", Energy Convers. Manag, vol. 78, pp. 862–871, 2014.

[40] J.T. Devaraju, K.R. Suhas, H.K. Mohana, V.A. Patil, "Wireless portable microcontroller based weather monitoring station", Measurement 76 (2015) 189–200.

[41] F. Shariff, N.A. Rahim, W.P. Hew, "Zigbee-based data acquisition system for online monitoring of grid-connected photovoltaic system", Expert Syst. Appl. 42 (2015) 1730–1742.

[42] V. Villagrán, A. Montecinos, C. Franco, R.C. Muñoz, "Environmental monitoring network along a mountain valley using embedded controllers", Measurement 106 (2017) 221–235.

[43] K.H. Chao, C.T. Chen, "A remote supervision fault diagnosis meter for photovoltaic power generation systems", Measurement 104 (2017) 93–104.

[44] H. Rezk, I. Tyukhov, M. Al-Dhaifallah, A. Tikhonov, "Performance of data acquisition system for monitoring PV system parameters", Measurement 104 (2017) 204–211.

[45] R. I. S. Pereira, I. M. Dupont, P. C. M. Carvalho, and S. C. S. Jucá, "IoT embedded linux system based on Raspberry Pi applied to real-time cloud monitoring of a decentralized photovoltaic plant", Measurement, vol. 114, no. August 2017, pp. 286–297, 2018.

[46] M. Fuentes, M. Vivar, J. M. Burgos, J. Aguilera, and J. A. Vacas, "Design of an accurate, low-cost autonomous datalogger for PV system monitoring using ArduinoTM that complies with IEC standards", Sol. Energy Mater. Sol. Cells, vol. 130, pp. 529–543, Nov. 2014.

[47] H.E. Gad, H.E. Gad, "Development of a new temperature data acquisition system for solar energy applications", Renew. Energy 74 (2015) 337–343.

[48] N. Erraissi, M. Raou, N. Aarich, M. Akhsassi, and A. Bennouna, "Implementation of a low-cost data acquisition system for ' PROPRE . MA ' project", vol. 117, no. November 2017, pp. 21–40, 2018.

[49] A. J. Lewis, M. Campbell, and P. Stavroulakis, "Performance evaluation of a cheap, open source , digital environmental monitor based on the Raspberry Pi", Measurement, vol. 87, pp. 228–235, 2016.

[50] L. J. Claros-Marfil, J. F. Padial, and B. Lauret, "A new and inexpensive open source data acquisition and controller for solar research: Application to a water- flow glazing", Renewable Energy, vol. 92, pp. 450–461, 2016.

[51] Open Source Hardware Association, “Open Source Hardware (OSHW) Statement of Principles and Definition,” 2017. [Online]. Available: <http://www.oshwa.org/definition/>

[52] < https://www.arduino.cc/ > (accessed 09.04.2018)

[53] < https://www.parallax.com > (accessed 09.04.2018)

[54] < http://www.wildernesslabs.co/ > (accessed 09.04.2018)

[55] < https://www.adafruit.com/ > (accessed 09.04.2018)

[56] < http://www.ti.com > (accessed 09.04.2018)

[57] < https://beagleboard.org/ > (accessed 09.04.2018)

[58] < https://www.raspberrypi.org/ > (accessed 09.04.2018)

[59] < http://cubieboard.org/ > (accessed 09.04.2018)

[60] < https://apc.io/products/rock/ > (accessed 09.04.2018)

[61] < https://www.olimex.com > (accessed 09.04.2018)

[62] < https://es.rs-online.com > (accessed 09.04.2018)

[63] <http://www.geeetech.com > (accessed 09.04.2018)

[64] S. C. W. Krauter and T. Depping, “Remote PV-system monitored via satellite”, Sol. Energy Mater. Sol. Cells, vol. 82, pp. 139–150, 2004.

[65] P. Papageorgas, D. Piromalis, K. Antonakoglou, G. Vokas, D. Tseles, and K. G. Arvanitis, “Smart solar panels: In-situ monitoring of photovoltaic panels based on wired and wireless sensor networks”, Energy Procedia, vol. 36, pp. 535–545, 2013.

[66] B. Mitchell, “What is the Range of a Typical Wi-Fi Network?” 2016. < https://www.lifewire.com/range-of-typical-wifi-network-816564 > (Accessed January 31, 2017).

[67] S. Rosiek and F. J. Batlles,“A microcontroller-based data-acquisition system for meteorological station monitoring”, Energy Convers. Manag., vol. 49, no. 12, pp. 3746–3754, 2008.

[68] ICT facts and Figures 2016, International Telecommunication Union <https://www.itu.int> (accessed 08.01.2018).

[69] “Harnessing the Internet of Things for Global Development” report. ITU, 2016.

[70] “Sub-Saharan Africa Power Trends Power disruption in Africa” report, Deloitte, 2017

[71] < https://www.nist.gov/ > (accessed 10.04.2018).

[72] B. Prahlada Rao , B, P. Saluja, N. Sharma, A. Mittal, and S. V. Sharma, “Cloud Computing for Internet of Things & Sensing Based Applications”, 2012 Sixth International Conference on Sensing Technology (ICST), pp. 374–380, 2012.

[73] < http://www.kaaproject.org > (accessed 08.04.2018).

[74] < https://thingspeak.com > (accessed 08.04.2018).

[75] < http://www.sitewhere.org/ > (accessed 08.04.2018).

[76] < https://devicehive.com/#connect > (accessed 08.04.2018).

[77] < http://www.openiot.eu/?page_id=32 > (accessed 08.04.2018).

[78] K. Friansa, I. N. Haq, B. M. Santi, D. Kurniadi, and E. Leksono, “Development of Battery Monitoring System in Smart Microgrid Based on Internet of Things (IoT),” Procedia Engineering., vol. 170, pp. 482–487, 2017.

[79] F. Touati, M. A. Al-Hitmi, N. A. Chowdhury, J. A. Hamad, and A. J. R. San Pedro Gonzales, “Investigation of solar PV performance under Doha weather using a customized measurement and monitoring system”, Renew. Energy, vol. 89, pp. 564–577, 2016.

[80] A. López-Vargas, M. Fuentes and M. Vivar, "IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino™ With 3G Connectivity," in IEEE Sensors Journal, vol. 19, no. 2, pp. 679-691, 15 Jan.15, 2019.

Annex D

Capítulo 8: Resumen de Resultados y Conclusiones

En este apartado se presenta un resumen de los principales resultados y conclusiones de esta tesis que ha sido presentada como un compendio de artículos científicos (Capítulos 3-7).

La investigación realizada en este trabajo tiene por objetivo desarrollar un sistema de monitorización que sea robusto, autónomo y de bajo coste gracias a la integración de herramientas de SW/HW libre, resolviendo la problemática existente para la monitorización de sistemas fotovoltaicos autónomos instalados en regiones aisladas de países en desarrollo.

A lo largo de los diferentes capítulos se ha ido explicando con detalle el trabajo llevado a cabo, estableciendo los objetivos de cada capítulo y discutiendo los principales resultados obtenidos. En el Capítulo 3 se han recogido los resultados obtenidos tras la revisión de los desafíos que presenta la monitorización a gran escala de los sistemas fotovoltaicos autónomos instalados en zonas rurales de países en desarrollo. Los Capítulos 4, 5 y 6 recogen los resultados experimentales obtenidos. El Capítulo 7 presenta un estudio reciente sobre la integración de tecnologías IoT en países en desarrollo; las nuevas posibilidades que ofrece el IoT para combatir la pobreza (con un número creciente de artículos científicos publicados sobre este tema durante los últimos años de tesis doctoral) han sido también recogidas en este trabajo. A continuación se presenta un resumen de las conclusiones más relevantes de esta tesis, que son presentadas de manera conjunta con los principales resultados obtenidos.

En primer lugar, la revisión realizada en el Capítulo 3 ("*Current challenges for the advanced mass scale monitoring of Solar Home Systems and the potential of open-source tools and Internet of Things for solar monitoring applications: A review*") ha proporcionado información muy valiosa que ha sido utilizada como punto de partida en el diseño del nuevo sistema de adquisición de datos. Se estudiaron los desafíos a los que se enfrenta la monitorización a gran escala de los sistemas fotovoltaicos autónomos instalados en zonas rurales de países en desarrollo a través de programas de electrificación rural. Se identificó el principal reto actual: obtener una monitorización de calidad (medidas precisas que cumplan con los requisitos establecidos por los entándares internacionales) a bajo coste. Los sistemas de adquisición de datos comerciales disponibles en el mercado aplicables a la monitorización de los sistemas fotovoltaicos autónomos y las nuevas tendencias de diseño que aúnan la integración de IoT y las herramientas de SW/HW libre que permiten reducir los costes de diseño fueron estudiados. Fueron identificados los principales problemas de los sistemas de monitorización convencionales: el alto coste, la dependencia de hardware externo (ordenadores portátiles o fuentes de alimentación) y el incumplimiento de los requisitos establecidos por los estándares internacionales. Un diseño basado en herramientas de código abierto permite desarrollar un sistema de monitorización ad-hoc de altas prestaciones a coste muy reducido. Los sistemas fotovoltaicos susceptibles de monitorización generalmente están localizados en regiones aisladas de países en desarrollo: que la monitorización pueda realizarse de manera remota es una prioridad. Tras el estudio de las tecnologías de comunicación aplicables a la trasmisión de los datos medidos por el sistema de monitorización, el uso de comunicaciones móviles fue identificado como la mejor solución. Este estudio concluye que la integración del IoT y el uso de plataformas gratuitas de almacenamiento en la nube es una solución realmente ventajosa, pues permite la monitorización remota y en tiempo real de los sistemas fotovoltaicos y la visualización de los parámetros medidos por el sistema de monitorización desde un ordenador o Smartphone, todo ello a muy bajo coste.

En el Capítulo 4 ("*Low-Cost Datalogger Intended for Remote Monitoring of Solar Photovoltaic Stand-alone Systems Based on Arduino*^{TM}") se presenta la primera versión del sistema de monitorización desarrollado (Datalogger SD). Diseñado expresamente para la monitorización de sistemas fotovoltaicos autónomos, el sistema de monitorización es capaz de medir un amplio rango de parámetros meteorológicos: irradiancia, temperaturas, humedad, velocidad del viento horizontal y lluvia. Los parámetros eléctricos (voltaje y corriente) se miden haciendo uso de amplificadores, divisores de tensión y sensores de corriente de Efecto Hall, que permiten además de realizar medidas muy precisas, adaptar la señal. Integra un sistema de almacenamiento de datos basado en una tarjeta SD que permite guardar los datos medidos de manera autónoma requiriendo un mantenimiento mínimo. El sistema de monitorización hace uso de un display LCD para la visualización de las medidas. Un sistema interactivo formado por un display y varios pulsadores permite al usuario controlar algunos procesos internos del sistema como la sincronización del reloj o la extracción de datos de la tarjeta SD. El uso de herramientas de HW/SW libre permite cumplir con el objetivo de bajo coste, integrando como componente principal del diseño un Arduino^{TM} UNO. Se diseñaron técnicas específicas para la reducción del consumo de energía tanto en sensores como en el microcontrolador. Para la campaña experimental y con el objetivo de reproducir las condiciones reales de medida a las que estará sometido el sistema de monitorización, se realizó una revisión de los perfiles de consumo de energía diarios típicos de familias que viven en áreas rurales de países en desarrollo y las características más comunes de los sistemas fotovoltaicos utilizados por los programas más importantes de electrificación rural. Con todo esta información, se dimensionó y se instaló un sistema fotovoltaico autónomo (incluyendo el perfil diario de consumo y carga típica) para probar y validar el nuevo sistema de monitorización de bajo coste trabajando en condiciones reales (Figura 1).

FIGURA 1: SAPV instalación del sistema de Jaén: (a) módulo PV mono-cristalino, (b) controlador y (c) de la batería de plomo-ácido de carga.

Además, se diseñó y se instaló una estación meteorológica de bajo coste (Figura 2). Para validar el prototipo se utilizó un sistema de monitorización comercial de alta precisión que fue utilizado como patrón, de manera que ambos sistemas (prototipo y patrón) monitorizaron los mismos parámetros de manera simultánea para posteriormente obtener los errores de medida por comparación. Se puso en marcha una campaña de experimentación de más de un mes de duración en el Instituto IMDEA Agua, en Alcalá de Henares (Madrid, España) para la validación del sistema de monitorización. Los resultados de la campaña experimental mostraron que los parámetros meteorológicos medidos por el nuevo prototipo se ajustan perfectamente a los medidos por el sistema de monitorización de alta precisión utilizado como patrón. En cuanto a los resultados de las medidas eléctricas, los errores en las medidas de las tensiones y las corrientes están por debajo del 1%. Se demostró que el sistema de monitorización cumple con los requisitos de precisión establecidos por el estándar IEC61724 tanto en las medidas eléctricas como en las meteorológicas. El coste final del nuevo prototipo, incluyendo los sensores para la medida de los parámetros eléctricos (tensión y corriente) ascendió a 81 €, precio muy por debajo a los sistemas de monitorización comerciales encontrados en el mercado con similares características. Se concluyó que el nuevo prototipo basado en herramientas de código abierto cumplía con los requisitos de precisión y de bajo coste establecidos, y que el sistema era el adecuado para la monitorización de sistemas fotovoltaicos autónomos instalados en zonas rurales de países en desarrollo.

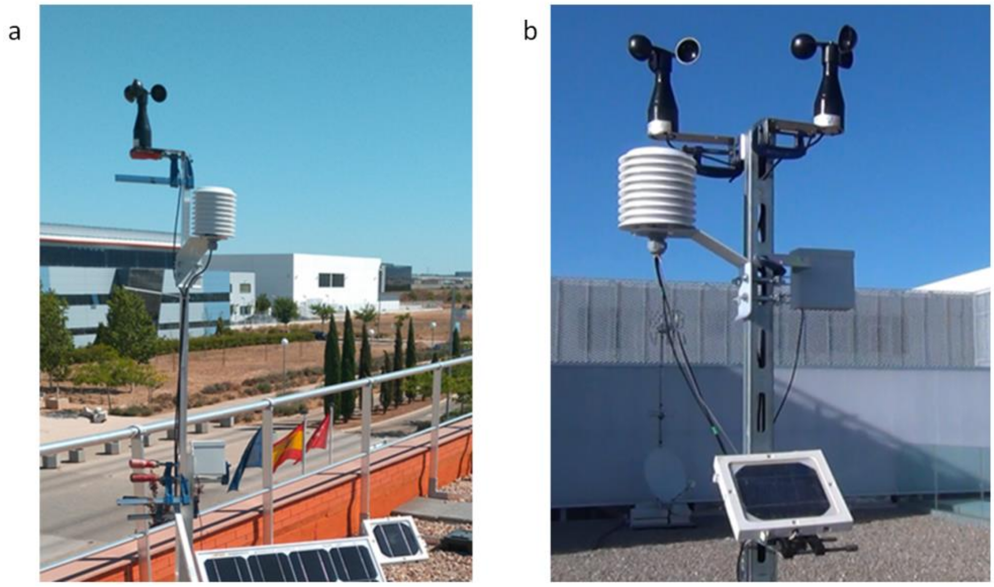


FIGURA 2: Las estaciones meteorológicas instaladas en Alcalá de Henares (a) y Linares (b).

La versión del prototipo “Datalogger SD” requería un mantenimiento mínimo. Sin embargo, este mantenimiento necesitaba de la intervención de un operario que recopilase los datos in situ de forma manual, lo que puede ser un inconveniente sobre todo en lugares de difícil acceso y además puede incrementar de manera considerable los gastos de mantenimiento y operación del sistema de monitorización. Es por ello que una versión más avanzada del sistema de monitorización (Datalogger 3G) que permita la monitorización en tiempo real del sistema fotovoltaico a través de una página web o un smartphone ha sido desarrollada y presentada en el Capítulo 5 (“*IoT Application for Real-Time Monitoring of Solar Home Systems Based on*

Arduino™ With 3G Connectivity”). Esta nueva versión utiliza también herramientas de SW/HW libre. En este capítulo, se ha llevado a cabo con éxito la integración en el sistema de monitorización de una tecnología inalámbrica para la transmisión de los datos, concretamente 3G. Se probaron dos tipos de almacenamiento de datos: un servidor dedicado (método convencional) y una plataforma de servicio de almacenamiento gratuito en la nube (aplicación de IoT). Ambas alternativas de almacenamiento permiten monitorizar el sistema fotovoltaico de forma remota. La integración de la plataforma IoT para el almacenamiento de datos en la nube permite el seguimiento de varios sistemas fotovoltaicos autónomos en tiempo real a través de una aplicación o web o a través del teléfono móvil a bajo coste. Este prototipo fue instalado en tres lugares distintos para estudiar el funcionamiento del sistema de monitorización en diferentes condiciones: Alcalá de Henares (Madrid, España), Linares (Jaén, España) y Oaxaca (Oaxaca, México). Los sistemas de monitorización estuvieron monitorizando parámetros eléctricos y meteorológicos durante una campaña de experimentación de 12 meses. Los resultados mostraron que tras la integración de la conectividad en el sistema, como se esperaba, el “Datalogger 3G” seguía midiendo correctamente los parámetros meteorológicos y eléctricos, cumpliendo con los requisitos de precisión establecidos en el estándar IEC61724. Durante el año que duró la campaña, solo se detectaron 4 errores por diferentes razones: un fallo de acceso, un fallo de red, un corte de alimentación y un fallo del equipo. Uno de los principales resultados en este trabajo fue la visualización de los datos a través de una página web protegida por contraseña. Tras dotar al sistema con conectividad 3G el coste del prototipo es de 141 €. El coste total del sistema es significativamente más bajo que el de los sistemas de monitorización comerciales, proporcionando medidas altamente precisas. Con este nuevo prototipo queda demostrado que los sistemas fotovoltaicos autónomos instalados en regiones aisladas de países en desarrollo pueden ser monitorizados de forma remota a través de un teléfono movil, y todo ello a bajo coste gracias a la integración de herramientas de código abierto (hardware libre y plataformas gratuitas de almacenamiento en la nube). La Figura 3 muestra los tres prototipos instalados en Alcalá de Henares (a), Oaxaca (b) y Linares (c).

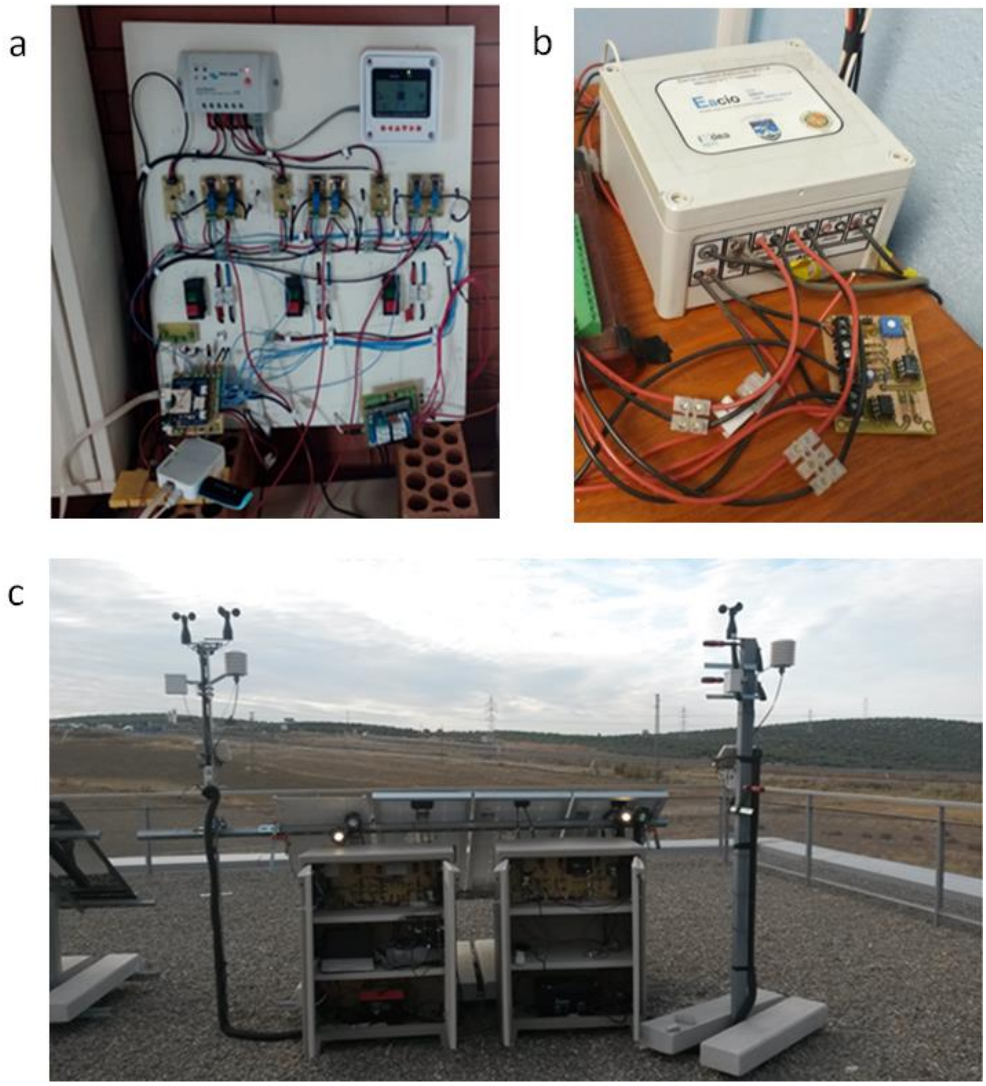


FIGURA 3: Asamblea prototipo final. (A) Versión con 3G instalado en Madrid (b) Versión con 3G instalado en Oaxaca (c) Versiones SD y 3G instalados en Linares.

Tras la evaluación de los fallos registrados en la campaña de experimentación presentada en el Capítulo 5, en el Capítulo 6 (“*Evaluation of long-term performance of a SHS monitoring system on harsh environments*”) se procede al desarrollo de optimizaciones y mejoras para el sistema. Se realizó la evaluación térmica del prototipo para garantizar su fiabilidad a largo plazo a través de dos campañas: una campaña de experimentación por ciclado controlado de temperaturas en espacio confinado (Experimentación 1) y la evaluación del sistema de monitorización trabajando en intemperie bajo condiciones ambientales extremas e incontroladas (Experimentación 2). Además, se diseñó y probó una nueva versión optimizada del sistema de monitorización (Datalogger SD+3G). La Tabla I muestra un resumen con todas las versiones del sistema de monitorización desarrolladas durante esta tesis con una breve descripción.

TABLA I: VERSIONES DEL DATALOGGER DESARROLLADAS EN ESTA TESIS

Versión	Descripción
Datalogger SD	Registrador de datos con un sistema de almacenamiento SD
Datalogger 3G	Registrador de datos con conectividad 3G
Datalogger SD + 3G	Registrador de datos con conectividad 3G y un sistema de almacenamiento de respaldo basado en una SD

Primero se sometió al prototipo “Datalogger 3G” a pruebas de estrés por temperatura controlada para simular las condiciones en las que se produjo el fallo de equipo (descrito en el Capítulo 5) que dejó al sistema de monitorización inoperativo. La temperatura ambiente registrada en los días previos al fallo de equipo superó los 40 ℃. Aunque se había instalado un sistema de refrigeración formado por dos ventiladores no fue suficiente y la temperatura en el interior del armario (donde se encontraba instalado el sistema de monitorización) superó los 47 ℃, superando las condiciones máximas de operación recomendadas para el sistema de conectividad del prototipo formado por un router y un módem. El sistema de monitorización dejó de funcionar y tras la inspección del sistema se confirmó que el sistema de conectividad del prototipo estaba inoperativo. En la Experimentación 1, durante el ensayo completo (20 ciclos) el sistema de monitorización funciono correctamente: realizó bien las medidas y envío datos de manera continua e ininterrumpida. Incluso las funciones más críticas, como son las funciones de conectividad y de transmisión de datos que además son las funciones más sensibles a las altas temperaturas, funcionaron correctamente. La campaña de experimentación descrita en el Capítulo 5 se extendió hasta 3 años sometiendo al sistema de monitorización a condiciones climáticas adversas. Este ensayo ofreció excelentes resultados. Se registraron muy pocos fallos y casi todos ellos tenían origen externo: corte de electricidad o caídas del servidor durante periodos cortos de tiempo (periodos en los que los datos medidos no quedaron registrados). Tras el estudio de estos resultados, se desarrolló el nuevo prototipo (versión Datalogger SD + 3G) que contaba con un nuevo sistema de almacenamiento de respaldo basado en una tarjeta SD para evitar la pérdida de datos en caso de no estar disponible el servidor. El prototipo “Datalogger SD + 3G” se instaló en Linares. Durante el verano de 2018, este sistema de monitorización estuvo funcionando ininterrumpidamente. Se alcanzaron temperaturas ambiente por encima de 40ºC. El sistema de monitorización se instaló dentro de un armario donde la temperatura era aún más alta: el registrador de datos trabajó a temperaturas de funcionamiento superiores a 48 º C. El sistema de monitorización realizó las medidas correctamente cumpliendo con los requisitos establecidos por el estándar IEC61724. No se registraron fallos ni error alguno en el funcionamiento del nuevo prototipo. Tras la evaluación del rendimiento a largo plazo del sistema de monitorización se concluyó que el sistema de monitorización es altamente fiable y robusto: se demostró que el sistema de monitorización está especialmente diseñado para su instalación en lugares con condiciones climáticas adversas.

Por último, durante los últimos años de la tesis doctoral el interés en las aplicaciones de IoT ha aumentado rápidamente, así como los artículos científicos publicado sobre este tema. El nuevo registrador de datos que ha sido presentado en esta tesis es una aplicación de IoT para los países en desarrollo. En este sentido, la fuerte demanda de tecnologías IoT ha creado una gran variedad de dispositivos de IoT que ya están disponibles, son asequibles y se pueden adaptar a los países en desarrollo. Por ello, en el Capítulo 7 (“*Challenges and Opportunities of the Internet of Things for Development (IoT4D) to Achieve the Sustainable Development Goals*”) se presenta una revisión de las posibilidades que tiene el IoT en los países en desarrollo para ayudar con el cumpliendo de los Objetivos de Desarrollo Sostenible de Naciones Unidas (SDGs por sus siglas en inglés). Se estima que alrededor del 85% de las implementaciones de IoT tienen el potencial de ayudar a cumplir los SDGs. Se han identificado y discutido los aspectos clave que permiten la implantación de IoT en los países en desarrollo: las infraestructuras, la conectividad, la falta de personal con conocimientos técnicos, condiciones ambientales o los sistemas financieros. Los resultados mostraron que uno de los principales retos para la expansión del IoT en los países en desarrollo es la conectividad. Los proyectos basados en herramientas de HW/SW libre generalmente no requieren altos costes iniciales, lo que permite una mayor difusión de este tipo de tecnología y además hace a esta área muy atractiva para la comunidad científica. Tras una revisión exhaustiva de la literatura publicada en este ámbito, se concluye que la combinación de tecnologías IoT de bajo coste y el prepago forma el escenario perfecto para una mayor difusión de IOT4D para cumplir con las metas fijadas por los SDGs.

Como resumen final, en el presente trabajo se ha confirmado la alta fiabilidad y robustez de un nuevo sistema de monitorización diseñado para el seguimiento de sistemas fotovoltaicos autónomos, demostrando su idoneidad para la instalación del sistema de monitorización en zonas rurales de países en desarrollo sin acceso a electricidad o redes de comunicación tradicionales, pudiendo trabajar bajo condiciones climáticas extremas.

Por último, atendiendo al potencial que tiene la instalación del sistema de monitorización en regiones aisladas de países en desarrollo, una de las líneas futuras de este trabajo es la creación de pequeñas redes que permitan monitorizar varios sistemas fotovoltaicos aislados utilizando un único registrador de datos. Por un lado, gracias al diseño HW del sistema de monitorización, se pueden apilar diferentes placas de manera que varios sistemas fotovoltaicos (ubicados lo suficientemente cerca para realizar guiado de cable) podrían ser monitorizados por un único registrador de datos actuando como nodo central. Otra línea futura fascinante es la creación de pequeñas redes utilizando tecnologías inalámbricas de bajo-medio alcance (Zigbee, LoRa) que permiten la monitorización de varios sistemas fotovoltaicos al mismo tiempo y el envío de los datos a la nube a través de un nodo central que utilice comunicaciones móviles. Ambas alternativas optimizan el uso de hardware y minimizan el coste final.