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Vampire: A smart energy meter for synchronous monitoring in a distributed computer system

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ABSTRACT

This paper presents the design and implementation of a low-cost system oriented to the synchronised and real-time surveillance and monitoring of electrical parameters of different computer devices. To measure energy consumption in a computer system, it is proposed to use, instead of a general-purpose wattmeter, one designed ad-hoc and synchronously collects the energy consumption of its various nodes or devices. The implementation of the devised system is based on the confluence of several technologies or tools widely used in the Internet of Things. Thus, this article the intelligent objects are the power meters, whose connections are based on the low-cost ESP32 microcontroller. The message transmission between devices is carried out with the standard message queuing telemetry transport (MQTT) protocol, the measurements are grouped in a database on an InfluxDB server that store the sensor data as time series, and Grafana is used as a graphical user interface. The efficiency of the proposed energy monitoring system is demonstrated by the experimental results of a real application that successfully and synchronously records the voltage, current, active power and cumulative energy consumption of a distributed cluster that includes a total of 60 cores.

1. Introduction

An electric energy meter is a device that continuously detects the energy consumed by any electrically powered appliance or system. The meter continuously reads voltage (in volts) and current (in amps) from which the energy consumed over a given time can be determined. In electronic meters, the detected information can be displayed on an LCD or LEC screen. If the meter allows data to be stored and transmitted through a secure data communication network, to be processed remotely, it is said to be "smart"; in particular, if the transmission is done through the Internet, the meter is considered as an intelligent object of the Internet of Things, also referred to as the "Internet of Energy" by some authors (IoE) [1].

As indicated below (Section 2), different types of wattmeters have been commercialised and described in the bibliography, which are fundamentally oriented to measure the consumption at homes or residential houses (including billing), at industrial factories and at energy grids. The present work, unlike previous work, deals with the conception and design of a custom low-cost meter able to capture and transmit the voltage, current and power factor of computer systems such as PCs, workstations, servers, and distributed computer systems, in general, for later analysis. The developed system allows the monitoring of multiple devices in a synchronised and independent way, which makes it suitable for accurately measuring, for example, the energy consumption of a program that is running in parallel on different servers in a computer cluster.

This system is based on the convergence of various conveniently coupled technologies. Indeed, the electrical data capture is carried out with a PZEM-004T board, implementing the connections by means of an ESP32 System-on-a-chip (SoC) where the transmission of messages is carried out with the standard MQTT (message queuing telemetry transport) protocol. MQTT is supported by any protocol that offers bi-directional ordered and lossless connections, and in particular TCP/IP. The measurements obtained are grouped as time series in an InfluxDB database, and Grafana is used as a graphical interface to visually consult data and graphs.

The main contribution of this work lies in the development and implementation of an original low-cost system specifically oriented to the synchronised and real-time surveillance and monitoring of electrical parameters of different computer devices. The presented system also

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includes a free cloud-based software application for the analysis of the captured data and graphical and textual presentation of the results.

After this brief introduction, the rest of the paper is structured as follows: Section 2 refers reviews the different works in the literature related to the topic addressed. Section 3 presents the design and characteristics of the proposed system. Then, Section 4 presents the appearance and functionality of the built system (data capture, calculation of power measurement metrics, meter configuration and messages transmission) and the user graphical user interface. Section 5 presents the experimental results. Finally, Section 6 provides the conclusions of the paper and Section 7 contains the bibliographical references.

2. Related work

There are a multitude of smart energy meters whose designs are focused on functions such as:

1 Measure the global power consumption at homes and residential houses [2–14].
2 Monitor individual consumption of different systems in smart homes (light, heating, cooling, and household appliances in general, etc.) [15–19].
3 Obtain information on the electrical consumption of corporate and commercial building or zones [20–24], even combining IoT and Blockchain utilities to provide a decentralised and secure recording mechanism [25,26].
4 Bill users for their electric consumption [27–37].
5 Controlling pre-paid and recharge systems [38–41].
6 Monitoring systems on renewable energy sources [10,42], as photovoltaic (PV) power plants [43–46].
7 Supervision in “smart grids”. According to the Institute of Standards and Technology (NIST) [47], the concept of smart grid or energy grid refers to the set of six aspects related to energy: bulk generation, transmission, distribution, customers, service providers, operations, and markets. This topic is highly relevant and for this reason it is widely discussed in the bibliography [2, 48-63].
8 Monitor energy consumption in Smart Cities [15,43,64]; such as, for example, public lighting [65–67].
9 Check the consumption and operation of other industrial applications [68], including, for example, functions such as monitoring of machines and motors [69–71] or smart irrigation systems [72].
10 Evaluate the energy consumption of the execution of software programs. In order to perform this function there are, on the one hand, software-based approaches that are based on estimating the energy consumption of a system from data obtained at run time [73–76], and, on the other hand, hardware-based approaches, based on physical power meters connected to the entire computer or its hardware components (processor, memory, graphical card or peripherals) [73,77-80].

In recent years, a large part of intelligent measurement systems have been framed within the context or technology of Internet of the Things (IoT) [13,20,34,48,54,60,61,71,81,82,53,83-86].

A relevant aspect to consider is the communications technology used [87]. One of the first options for very long distances is to use GSM (global system for mobile communication) [88–91]; but to obtain high capacity in data communication you can also use other wireless networks such as ZigBee [15,92,93], wireless fidelity (Wi-Fi) [15,52,83] or IPv6 over low-power wireless personal area networks (6LoWPAN) [94–96]. One option to cover long distances is to use LPWAN (low--power wide-area network) technologies [97–100] such as SigFox [101, 102], Narrowband Internet of Things (NB-IoT) [103–105] and Long Range (LoRa), LoRa standing out among these for being an open technology, not requiring a contract with the owner company or acquiring a SIM card [16,46,66,67,90,44,66,66,106-109].

Although the previously referenced systems are based on the same principles, their design approach is largely determined by their scope of application, which determines the functions to be performed (billing or not, harmonic analysis, etc.) and parameters such as levels of measurable voltage and current, sampling frequency, accuracy, data communication, etc. By processing and analysing the data obtained from the energy smart meters, it is possible to estimate parameters such as the energy load at any given moment and to bill the consumption based on the days of the week or the time of consumption, as well as to obtain consumption patterns or profiles. With this information it is possible, for example, to make comparisons to optimize energy consumption, forecast future loads, detect fraud and abnormal electricity consumption [110,111], establish electricity rate offers and design market strategies [112]. Also, to Identify in a non-intrusive way the energy consumption of the different systems (kettle, air conditioner, fridge, etc.) of a home by analysing the global information obtained by a single power meter [113].

Several good works have been published that carry out surveys or comparative studies on different types of meters, highlighting those of Rind [48], Suriyan [114], Sanchez-Sutil [66], Sadeeq [115], Karthick [20], Bedi [82], Alahakoon [112], Beaudin [116], Sun [2], Avancini [49], O’driscoll [68], Ageed [117], Viciana [21], Diouri [118], Baduta [119] and Islam [120]. These articles consider and compare parameters such as:

a) Meter sensor type (physical principles and nature of measurements captured);
b) measurement accuracy;
c) measurement frequency (granularity);
d) wireless technology used, GSM, Wi-Fi, LPWANN, etc.;
e) wireless network coverage: LAN (Local Area Network), MAN (Metropolitan Area Network), WAN (Wide Area Network), or Satellite network;
f) use of the cloud with real-time data access with proprietary or public server;
g) open source and low-cost hardware and software.

Obviously, the selection of these parameters depends on the specific application to be developed. The meter presented herein has been designed to be as simple as possible, considering that the fundamental objective is to measure the consumption of computer equipment. Thus, current measurements are made by taking two samples per second, in real time. It is not interesting to use a higher sampling frequency because computer equipment uses switched DC power supplies whose high-capacity capacitors filter instantaneous consumption (spikes), making it impossible to measure. Consequently, harmonic analysis is not considered.

As indicated in the Introduction, the main objective of this paper is the development and implementation of an original low-cost system specifically oriented to the synchronised and real-time surveillance and monitoring of electrical parameters of different computer devices.

The analysis of the previously referenced bibliography has served to verify the non-existence of a smart energy meter fully compliant with the global set of specifications required here but, however, it has been useful to introduce concepts and improvements in different aspects of the definition of the system proposed here (Section 3). As previously seen, there are a multitude of smart meters designed for general use applications, or for specific uses other than those required in this paper, but none covers the objective of synchronously and efficiently measuring the energy consumption of the different nodes of a distributed server system working in parallel at a low cost and efficiently of a distributed system of servers working in parallel. Some meters require a Raspberry Pi (a small single-board computer) [45,121], which is currently quite expensive, thus increasing the cost per unit. The Vampire can be used individually from anywhere with a Wi-Fi connection. Other

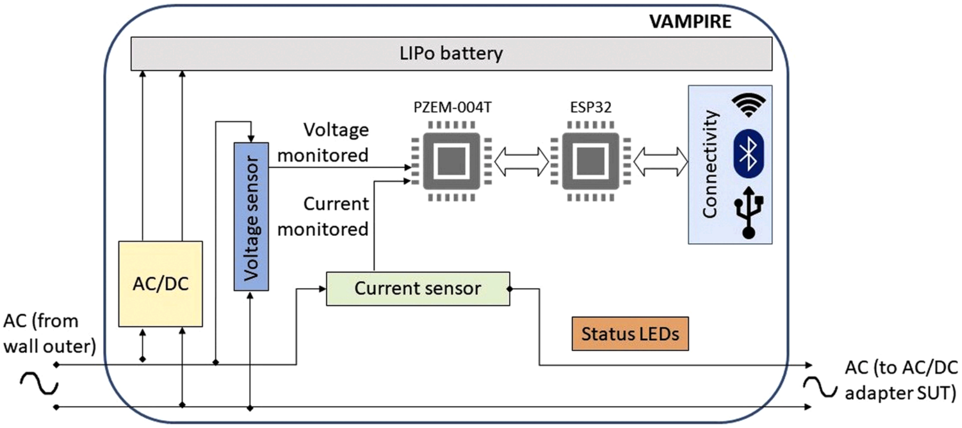


Fig. 1. Simplified schema of Vampire.

papers mention M2M (machine-to-machine communication), storage, and visualization, but they don't specify which programs they use for these purposes. In fact, they don't show any graphs where the real-time measurements of all the devices can be seen simultaneously.

Section 6 includes, as an example, experimental results that show the feasibility of the presented system for the analysis of energy consumption of a heterogeneous distributed system made up of 7 nodes running a High-Performance Computing (HPC) application.

It should be noted that there are low-cost power meters, but most of them do not send the information to a central node and only display the information on a screen. The ones with remote access usually require the use of a specific mobile application, and the time between samples cannot be controlled as it is predetermined by the manufacturer. Additionally, the sampling interval is often several seconds, the updates are asynchronous, and the precision is low.

The proposed system considers the importance of synchronization between all measurements and to control the time between samples for greater precision. Furthermore, it uses the existing wireless infrastructure with the Eduroam Wi-Fi network [122,123] as the firmware has been designed to accept specific certificates and authentication mechanisms that are not typically included in conventional devices. Moreover, and associated application has been developed that facilitates the data capture for each experiment, allowing users to easily set the start and end of their experiments and retrieve the obtained data at a later time.

3. Design and characteristics

The Vampire meter comprises the following elements (Fig. 1):

- Sensors, which depending on the design of the meter, can be of a different nature, based on different physical principles [119]: thermocouple heater based, electromagnetic radiation based, Hall-effect sensor-based [124,125], shunt based [126], and diode sensor-based. In Vampire, a precision shunt resistor of 1 mOhm is used as a transducer which converts current into voltage.
- Electronic module that provides the electrical measurements of the signals captured by the sensors. The Vampire uses the PZEM-004T board for this purpose, providing the following parameters in real time: RMS (Root Mean Square) voltage, RMS current, and calculates active power and total energy usage over time or accumulative power consumption in predetermined periods of time. The PZEM-004T [127–129] is a data acquisition and storage board containing a 16-bit A/D converter with differential inputs and programmable gain, and a SOP-24 V9881D energy measurement SoC chip what is especially useful to measure the voltage, current, power, energy, and frequency of an electrical signal [53,130].

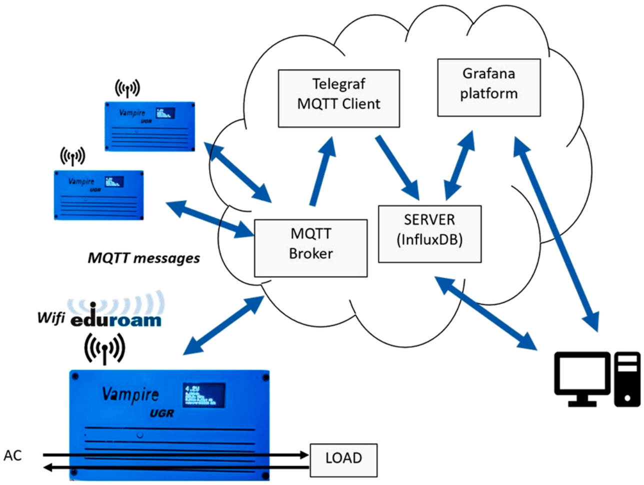
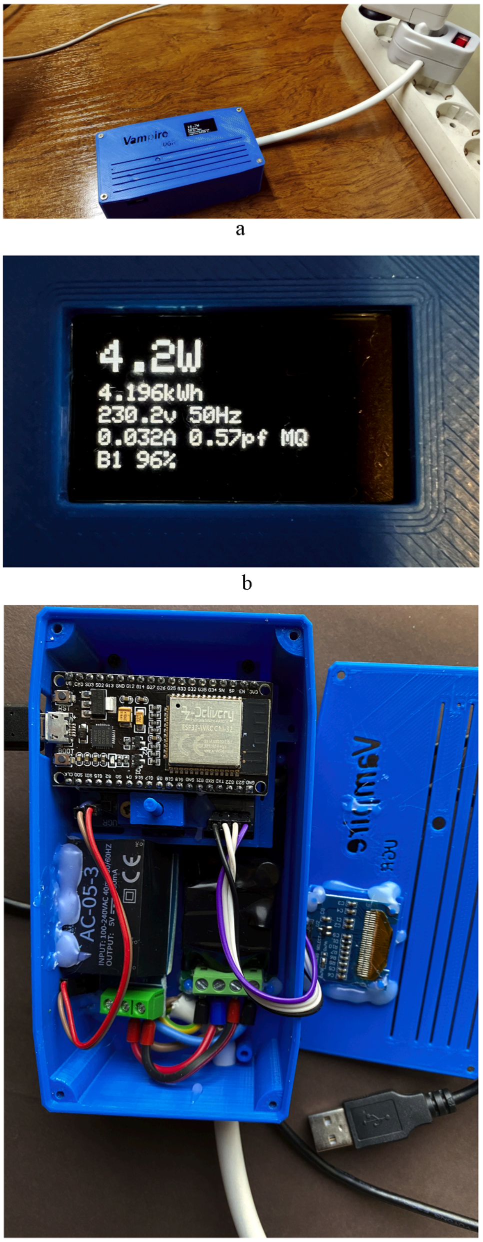


Fig. 2. Schematic of the complete system.

- A Main Control Unit (MCU) constituted by the ESP32 [131,132]. ESP32 is a family of low-cost, low-power SoC chips with 32-bit dual-core CPUs. The MCU makes it possible to access the outside of the meter via Wi-Fi, Bluetooth and USB, and has the ability to be updated over-the-air (OTA) updated. Also, it is responsible for transmitting the data in the form of time series through MQTT messages to a remote server. The MQTT (Message Queuing Telemetry Transport) [133] is a lightweight messaging protocol commonly used for IoT devices. It follows a publish-subscribe pattern, where there is a central messaging broker and multiple clients. The main function of the broker is to receive messages from publishers and distribute them to the clients. These messages are scalable with different quality of service (QoS) allowing great flexibility in their delivery. In the present case, the sensors act as MQTT publishers, and the server receives the data as an MQTT subscriber from all the sensors. The received data is then inserted into the real-time database, InfluxDB.
- OLED (Organic Light-Emitting Diode) technology screen on the meter itself that allows direct display of information concerning the status of the device and the measured values.

The Vampire works in combination with a remote server, interconnected by the Internet to the MCU, whose objective is to group and store all the measurements to process or visualize them online or offline (Fig. 2). The data received within the MQTT messages, as it is done in [53], is collected and stored using the InfluxDB application. InfluxDB is



a

b

c

Fig. 3. Different views and components of the Vampire meter.

an open-source database manager designed to store sensor measurements in the form of time series with which IoT, analytics, and cloud applications can be developed [134].

The graphical user interface shows in real time or off-line the measurements stored in the database, under different formats. In the present case, Grafana is used, which is a web-based data analysis and visualization tool, fully compatible with InfluxDB. With Grafana it is possible to setup custom dashboards, notifications, and alerts from the measurements.

The basic characteristics of the complete designed and built system are the following:

Electrical specifications. The system measures or generates the following electrical parameters with the accuracies indicated:
Input voltage: 80–260 V (± 0.1 V, 0.5%).
Intensity: 0–10A (± 1 mA, 0.5%).
Active Power: 0.4–2300 W (± 0.1 W, 0.5%).
Power factor: 0–1 (± 0.01, 1%).
Frequency: 45–65 Hz (± 0.1 Hz, 0.5%).
Energy: 0–9999 kWh (± 1W·h, 0.5%).

These design specifications have been made considering the purpose of the system conceived and the characteristics of the systems to be measured; Thus, for example, the maximum intensity indicated (10 A) is significantly lower than the one required by the computer equipment that is to be analyzed.

- Completely autonomous with measured and observable information in real time.
- Remote configuration and firmware upgrade.
- Allows the monitoring of multiple equipment in a synchronised and independent way (useful for measurements in computer clusters).
- Free and open system: Open-source software and hardware.
- Sampling frequency of 2 Hz (500 milliseconds between samples).
- 0.96″ OLED screen to view information concerning the device status and measurements.
- USB, Bluetooth and Wi-Fi connections. The Wi-Fi uses Eduroam as a gateway. Eduroam is an Internet access roaming service designed for users in research and higher education.
- InfluxDB database specifically for storing time series.
- User interface based on Grafana, allowing to display and monitor the measures of multiple devices in a synchronised way.

Fig. 3 shows different views of the meter. The external aspect of the Vampire when it is connected and ready to work is depicted in Fig. 3a. The system or device to be measured simply connects to the plug. Fig. 3b shows the meter`s OLED display, which provides in real-time the instantaneous power, cumulative energy consumed, voltage, frequency and power factor of the input signal, and the identification of the device. Finally, Fig. 3c shows the inside of the meter, where the ESP32 module and power supply can be easily seen on the left and center of the picture, respectively.

Regarding the internal software, the Vampire saves in its flash memory various information such as firmware update parameters, three Wi-Fi configurations, Eduroam certificate, configuration for access to the MQTT broker, URL addresses for updates, and parameters related to times (between consecutive measurement captures, delivery of MQTT messages, and watchdog). In addition, a set of Python Scripts has been developed to control the operation of the system and obtain the results in a user-friendly way. They perform the following functions:

1 Capture and transmit the data to the server. It should be noted that these scrips are executed in the MCU Meter.
2 From the captured samples, they calculate the Power Measurement Metrics:
  a Active Power in watts (W),
  b voltage in volts (V),
  c intensity in amps (A),
  d power factor, and
  e energy consumed in real time, in watts-hours (W·h).

The measured electricity values are captured every 500 ms, but the program can visualize the power metrics in larger intervals by grouping the average values of the samples (1.0 s, 1.5 s, 2.0 s, etc.). The 0.5 second sampling period is sufficient for the stated goal of measuring HPC processes with significant execution times, and a shorter period does not provide more accurate information for a particular moment in time due to the use of switching power supplies in equipment with large capacitors and inductors.

1 Configure the meter and access to Bluetooth and Wi-Fi.
2 Generate on the Vampire and transmit via Eduroam (Wi-Fi) MQTT messages containing the measures. These messages arrive at an MQTT broker contained in the server, where another program,

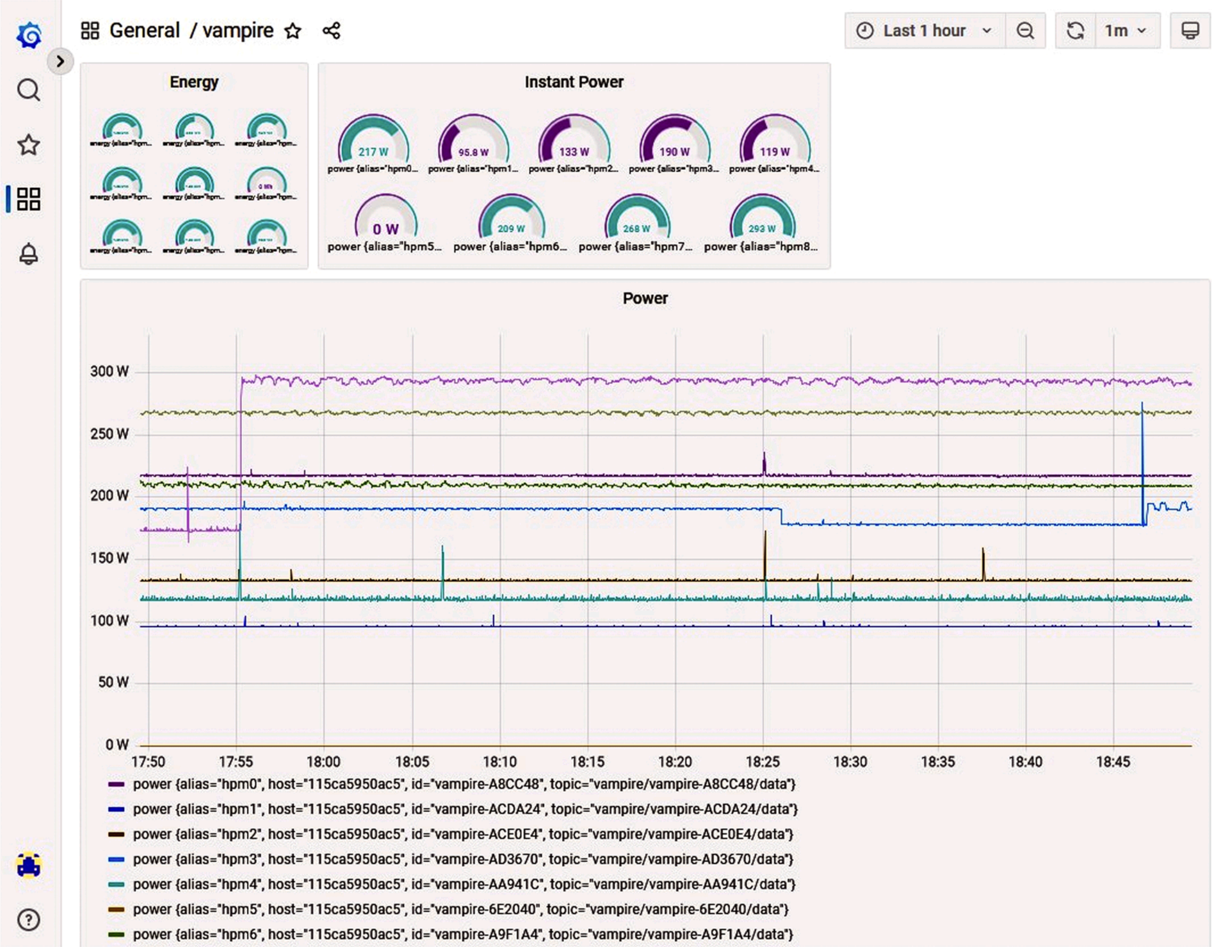


Fig. 4. Grafana dashboard used for Vampire monitoring. From top to bottom and left to right: active energy (W·h), instantaneous power (W), instantaneous power vs time, and device and experiment identifications.

Telegraf, extracts the measurements form the messages and stores them in the form of time series in the InfluxDB database (in accordance with Figure 2).

4. System use and user graphical interface

This section describes how to: configure the system (Section 4.1), manage the measurements obtained by the meter (Section 4.2), and finally interpret the user interface (Section 4.3).

4.1. Configuration

The initial vampire configuration can be achieved by accessing it in three different ways:

1) Via USB cable.

A program (vampire.py) automatically detects the connection port and opens a terminal session with the computer. The configuration program allows the following commands to be executed: help, set, get, reset, update, status. The 'set' command supports the inclusion of different configuration parameters.

1) Via Bluetooth connection:

In this case, the configuration is done from a computer or mobile device. Each of the Vampires located in each of the nodes of the distributed system has a specific identifier or name based on the last digits of its MAC address (vampire-xxxxxx) that allows them to be differentiated from each other.

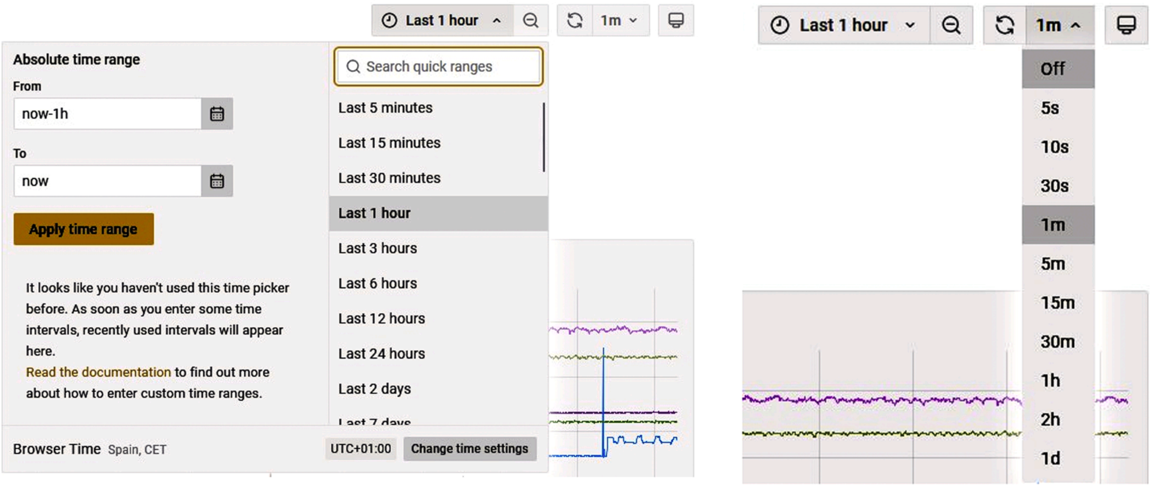
Once the meter is paired with the configurator device via Bluetooth, the same commands and parameters as in USB configuration can be transmitted to the device.

1) Through Wi-Fi with MQTT orders.

Remote commands are sent to the energy meter as MQTT messages. The interconnection with the server is made once the device has been assigned a Service Set Identifier (SSID) within the Wi-Fi network. Once active, the system automatically sends data to the cloud server. There is also a command to update the firmware while the device is connected to the Internet.

4.2. Measurement management

All measurement devices send data that are stored in the MQTT server. The set of measurements corresponding to a specific Vampire in a certain period of time is called an "experiment". Each experiment is identified by a username and a sequential number, and as parameters the initial and final timestamps are established, determining the interval for which the measurements are to be obtained. The measurements stored in the database can be analysed in more detail, obtaining, for example, average, maximum, and minimum magnitudes of voltage in a time-period using different aggregation scales. A script is also available



It looks like you haven't used this time picker before. As soon as you enter some time intervals, recently used intervals will appear here. Read the documentation to find out more about how to enter custom time ranges.

a

b

Fig. 5. Parameters associated with time: a) stored time intervals to be displayed; b) zoom of the time range to be displayed.

to be able to export the results in CSV (Comma-Separated Values) format. The defined commands are: start, stop, info, get, and list, which are compatible with the following options:

- -u user,
- -e experiment name,
- -d devices,
- -o output file,
- -p period (default 5 s) and
- -f csv format (default).

For example, the following command can be executed to start an experiment: "vampire start -u user -e experiment1".

4.3. Access to the graphic interface

As previously indicated, in order to visualize the data, the web-based Grafana application is used, with which the user can setup custom charts, graphs dashboards, alerts, and notifications when connected to supported data sources, regardless of where they are stored [121,135,136]. This interface also allows you to view the data history, which makes it easy to retrieve experiments and data of interest.

In Fig. 4 you can see, as an example, a screenshot of the design made for the Grafana interface corresponding to the results of the simultaneous measurements in 9 different devices.

In the top, the accumulated energy consumption up to a specified time (W·h) and the instantaneous power (W) are shown in real-time. In the central part the waveforms of the instantaneous power signals over time are shown. By clicking on each of its signals their different characteristics can be seen, and in the bottom part, the identifications of the Vampire used and the experiment being carried out are found the lower part. It also has menus to select parameters such as the stored time intervals to be displayed, zoom of the time range to be displayed, refresh rate of the displayed data, etc. (Fig. 5).

5. Experimental results

Different tests have been carried out to evaluate the Vampire. To analyze the precision of the meter, its measurements have been compared with those obtained by another existing commercial meter, called openZmeter (abbreviated, oZm) [21,137,138]. This device is an efficient low-cost smart energy meter that has been designed to meet the requirements of the IEC 61,000 4 30 international standard and was calibrated with a standard resistor and a precision multimeter.

Table 1
Comparative experimental results between the Vampire and openZmeter power measurements.

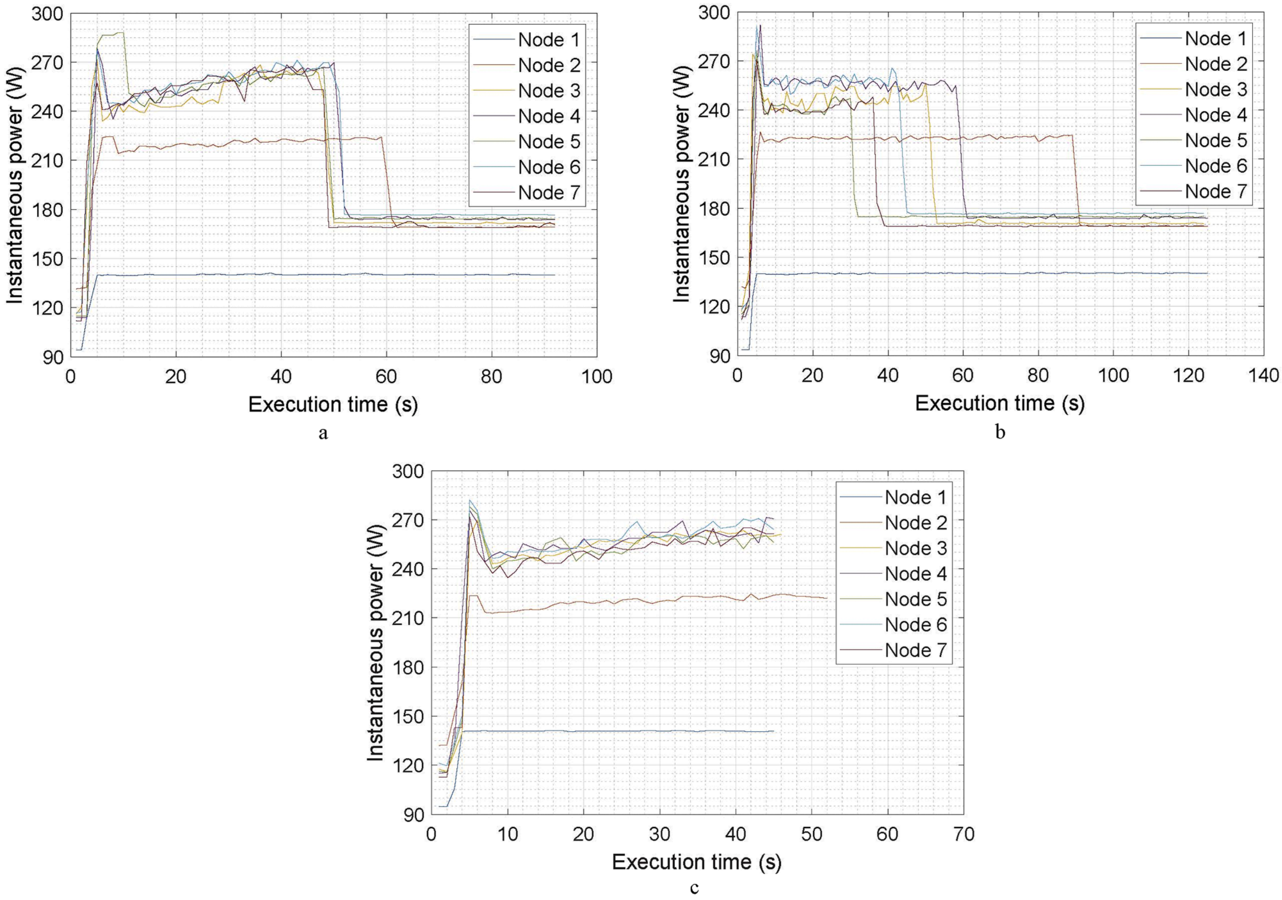
	Vampire	openZmeter	Difference (W)
Sampling frequency	2 Hz	15,625 Hz	
Linpack			
Time interval considered:	1014 s	1014 s	
Number of samples:	2028	15,844	
Average power:	32.89 ± 9.42 W	32.62 ± 9.65 W	0.27 W
4 W lightbulb			
Time interval considered:	725 s	727 s	
Number of samples:	1450	11,359	
Average power:	4.22 ± 0.04 W	4.06 ± 0.07 W	0.16 W
25 W lightbulb			
Time interval considered (s):	885	884	
Number of samples:	1770	13,812	
Average power:	24.9 ± 0.1 W	24.3 ± 0.1 W	0.6 W

Tests were carried out to measure, with both devices, the instantaneous power consumed in the following three cases: (a) executing the Linpack reference program [139] and (b) by two lightbulbs of known power (4 W and 25 W, respectively). The Linpack is a benchmark traditionally used as a reference application for comparative studies between the performance of different computer systems, and the version used here is the Linpack Xtreme released on Windows 10, version v1.1.5 [78,140]. In the present case, the energy consumption measurements made when solving a dense system of 20,000 linear equations.

Table 1 shows the results obtained, showing for each of the three cases (Linpack, 4 W lightbulb and 25 W lightbulb) and for each meter (Vampire and oZm), the time considered between two successive samples (sampling period, in seconds) the number of samples obtained for the measurements and the average power and standard deviation of those measurements (in watts). It can be seen that in all cases the differences between the average powers obtained by the two meters are less than 1 watt. The small fluctuations observed can be attributed to the fact that the thousands of instantaneous measurements obtained are not synchronized between the two meters to the millisecond. Furthermore, with a constant load, as is the case with the two lightbulbs, the standard deviations of the measurements are ±0.04 and ±0.01 which are within the precision range of ±0.1 W guaranteed by the manufacturer of the PZEM-004T board (in Section 3). It is considered that the small differences between the average values are due to the fact that the LEDs include small switched sources, therefore not behaving as pure resistive

Table 2
Characteristics of the cluster used in the experiments.

Node	CPU				RAM memory	
	Model	Total cores/threads	Thermal Design Power, TDP (W)	Frequency (MHz)	Frequency (MHz)	Size (GB)
Master	2x Intel Xeon E5–2620 v2	12/24	160	2100	1600	32
1	1x Intel Xeon E5–2620 v4	8/16	85		2133	
2	2x Intel Xeon ES-2620 v4	16/32	170			
3 to 7	2x Intel Xeon Silver 4214	24/28	170	2200	2933	64



a

b

c

Fig. 6. Comparison of instantaneous power between the different workload distributions when using 7 computing nodes.

loads. Note that the standard deviations obtained from the power consumption in the execution of the Linpack (±9.42 and ±9.65 W) have a high value, corresponding to the fact that the load is not constant, since the power consumption depends on the instructions that are running at any moment (not all consume the same amount of power) and the specific hardware resources in use (number of active cores, for example).

Among other real-world experiments, the Vampire have been used to measure the energy consumption of programs for EEG classification [141]. The dataset includes 178 EEG signals for training and another 178 for testing, each with 3600 features, reported by the BCI laboratory of the University of Essex and corresponds to Brain Computer Interface (BCI) signals [142].

The application is based on the implementation of the K-nearest neighbours (KNN) algorithm to identify within the EEG signals three different motor-imagery movements (left hand, right hand, and feet). Therefore, the KNN algorithm deals with a 3-class classification problem. KNN has been chosen for two reasons: the first, because it is the method that currently obtains the best precision with the databases discussed here [141]. Secondly, because when testing different workload distributions and input parameters, such as the number of neighbours (K), the energy consumption of the procedure could vary. In this sense, it is interesting to study to what extent these parameters are capable of influencing the total energy consumption of the procedure and if the wattmeter is capable of recording them in case the differences are minimal.

On the other hand, the application has been parallelized with C++ and the OpenMP library. OpenMP is a de facto standard for multi-core CPUs in shared-memory systems via multi-threading, providing a flexible and simple tool for developing portable and scalable parallel applications [143,144]. For the experiments carried out in this work, the application has been executed on a 7-node heterogeneous cluster whose characteristics are shown in Table 2.

Given the nature of the problem, all worker nodes (Wk1, …, Wkn) execute the same task in parallel, but with data blocks of different computational load. The workload can be assigned to nodes in the following ways:

a) Static contiguous distribution. Consecutive blocks of data are assigned to each of the nodes: For example, worker Wk1 executes the task with data T1, T2 and T3. In parallel, worker Wk2 executes data

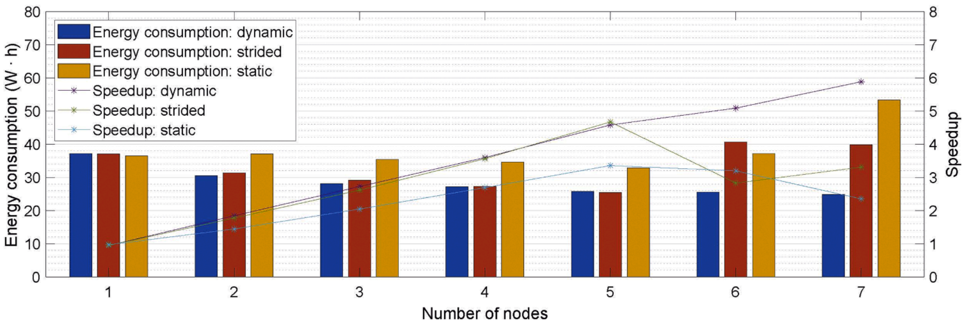


Fig. 7. Energy consumption and speedup of each distribution when increasing the number of computing nodes.

blocks T4, T5 and T6, while Wk3 executes data blocks T7, T8, and T9, and so on.

b) Static strided distribution. Wk1 is assigned, for example, blocks T1, T4 and T7, while Wk2 is assigned blocks T2, T5, and T8, and Wk3 is assigned blocks T3, T6 an T9.
c) Dynamic distribution. As the execution time of each task depends on the data and the specific processor of each node (it is a heterogeneous system), the execution of some tasks will take longer than others. With dynamic allocation, each node (Wk) is assigned a new block of data as soon as it becomes free without waiting for the other nodes to complete theirs.

The energy measurement system presented has been used to compare the evolution of time and total energy consumption as a function of the workload. Figs. 6 and 7 show graphs of the results obtained with the Vampire meters and their effectiveness. Specifically, Fig. 6 plots the instantaneous power over the time when executing the KNN algorithm according to the distribution of the workload used. On the other hand, Fig. 7 shows the energy consumption (in W·h) and the speedup obtained as a function of the number of nodes in the distributed system and the workload used.

It can be seen that the results are fully satisfactory since they allowed the measurement of the energy efficiency of a bioengineering application capable of exploiting the qualities of distributed and heterogeneous parallel platforms considering energy efficiency as a fundamental parameter, unlike other works that focus only on the accuracy of the results and on the execution time. The figures show the result of the entire process, revealing its correct functioning which involves the capture of energy consumption measurements, their inclusion in MQTT messages, their retransmission with the Wi-Fi network, their reconstruction into the form of time series in the InfluxDB database, and its graphical presentation accessible in Grafana.

6. Conclusions

The system developed, called "Vampire", periodically takes current samples from an electrical conduction line that supplies a load, transmits them to a server and from them various electrical parameters are obtained and displayed. Vampire has been projected for synchronous monitoring of the energy consumption in a multi-node computer system.

The implementation of the devised system is based on the confluence of various technologies and tools. Indeed, the PZEM-004T has been used as a current and input voltage meter with an accuracy of 0.5% and a resolution of 0.001 A and 0.1 V, respectively. The transmission of sensor data is carried out as messages with the standard MQTT protocol using the low-cost ESP32 microcontroller. The sensor data are grouped, stored and processed as time series in the InfluxDB database, a graphical user interface in the Grafana platform has been designed, and a Python application simplifies the time mark captures and retrieval of data.

To verify the efficiency of the Vampire, its results were compared to the measurements obtained by openZmeter. For this comparison, two different were carried out. One of them measures the consumption of two bulbs of known power, while the other analyses the consumption of the computer after running the Linpack reference program.

The results obtained in a real application consisting of the classification of EEG signals to identify imagery movement of a person have also been shown. Classification is performed by running a parallelised version of the KNN algorithm on a distributed and heterogeneous parallel platform of 7 nodes of a cluster, with a total of 60 cores. The objective of this study was to compare the results obtained in various distributed configurations considering as fundamental parameters the accuracy of the results, the energy efficiency, and the execution time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] A. Alsalemi, Y. Himeur, F. Bensaali, A. Amira, An innovative edge-based Internet of energy solution for promoting energy saving in buildings, Sustain. Cities Soc 78 (2022), 103571.
[2] Q. Sun, H. Li, Z. Ma, C. Wang, J. Campillo, Q. Zhang, J. Guo, A comprehensive review of smart energy meters in intelligent energy networks, IEEE Internet Things J. 3 (4) (2015) 464–479.
[3] Y.Y. Chen, Y.H. Lin, C.C. Kung, M.H. Chung, I.H. Yen, Design and implementation of cloud analytics-assisted smart power meters considering advanced artificial intelligence in demand-side management for smart homes, Sensors 19 (9) (2019) 2047.
[4] G. Alkawsi, N.A. Ali, Y. Baashar, The moderating role of personal innovativeness and users experience in accepting the smart meter technology, Applied Sciences 11 (8) (2021) 3297.
[5] S.H. Mir, S. Ashruf, Y. Bhat, N. Beigh, Review on smart electric metering system based on GSM/IOT, Asian J. Electr. Sci. 8 (1) (2019) 1–6.
[6] J.C. Hernandez, F. Sanchez-Sutil, A. Cano-Ortega, C.R. Baier, Influence of data sampling frequency on household consumption load profile features: a case study in Spain, Sensors 20 (21) (2020) 6034.
[7] A. Molina-Garcia, J.A. Fuentes, E. Gomez-Lazaro, A. Bonastre, J.C. Campelo, J. J. Serrano, App. of wireless sensor network to direct load control in residential areas, 2007 IEEE Int. Sym. Indus. Electr. (2007) 1974–1979.

[8] E.L. Medeiros, E.G. Costa, G.R. Lira, A.C. Alves, C.V. Diniz, A low cost power quality meter over the internet, in: 2016 17th Int. Conf. on Harmonics and Quality of Power (ICHQP), 2016, pp. 986–991.

[9] A. Cano-Ortega, F. Sánchez-Sutil, J.C. Hernández, Smart meter for residential electricity consumption with TLBO algorithm for, LoRaWAN. Electrical Engineering (2023) 1–20.

[10] M.H. Islam, T.I. Talukder, F.T.Z. Saima, M.N.I. Rimon, J. Ali, An IoT-based smart energy meter with real-time power tracking system: a review, in: 2021 6th Int. Conf. on Smart and Sustainable Technologies, IEEE, 2021, pp. 01–05.

[11] P. Vispute, M. Khan, IoT based energy meter reading system, Available at SSRN 4050198 (2022). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4050198.

[12] S. Kshirsagar, S. Kshirsagar, Iot Based Smart Energy Meter (2021). Available at SSRN 3936289.

[13] T.D.L. Nguyen, N.D. Tran, T.H. Tran, Single-phase smart energy meter—IoT based on manage household electricity consumption service, in: Intelligent Comp. in Eng.,: Proc. of RICE 2019, Springer, 2020, pp. 1185–1193.

[14] H.A. Alajmi, R.R.A. Alsaidi, O.A.S. AL-shibli, S. Ramadoss, Implementation of IOT based smart energy meter in Oman, J. Student Research (2019).

[15] S. Muralidhara, N. Hegde, P.M. Rekha, An internet of things-based smart energy meter for monitoring device-level consumption of energy, Communist Chin. Sci. Abstr. 87 (2020), 106772.

[16] F. Sanchez-Sutil, A. Cano-Ortega, Smart plug for monitoring and controlling electrical devices with a wireless communication system integrated in a LoRaWAN, Expert Syst Appl 213 (2023), 118976.

[17] A. Molina-Garcia, J.A. Fuentes, E. Gómez-Lázaro, A. Bonastre, J.C. Campelo, J. J. Serrano, Development and assessment of a wireless sensor and actuator network for heating and cooling loads, IEEE Trans Smart Grid 3 (3) (2012) 1192–1202.

[18] R.T. Mathew, S. Thattat, K.V. Anirudh, V.P. Adithya, G. Prasad, Intelligent energy meter with home automation, in: 2018 3rd International Conference for Convergence in Technology (I2CT), IEEE, 2018, pp. 1–4.

[19] M.N. Meziane, P. Ravier, G. Lamarque, J.C. Le Bunetel, Y. Raingeaud, Accuracy comparison of low-cost energy meters for home electrical consumption assessment, in: 2016 IEEE 16th International Conference EEEIC, IEEE, 2016, pp. 1–6.

[20] T. Karthick, K. Chandrasekaran, Design of IoT based smart compact energy meter for monitoring and controlling the usage of energy and power quality issues with demand side management for a commercial building, Sustain. Energy, Grids Netw (2021).

[21] E. Viciana, A. Alcayde, F.G. Montoya, R. Baños, F.M. Arrabal-Campos, A. Zapata-Sierra, F. Manzano-Agugliaro, OpenZmeter: an efficient low-cost energy smart meter and power quality analyzer, Sustainability 10 (11) (2018) 4038, https://doi.org/10.3390/su101.

[22] C. Roach, Estimating electricity impact profiles for building characteristics using smart meter data and mixed models, Energy Build 211 (2020), 109686.

[23] S. Araya, N. Rakesh, Review on design of residential IoT based smart energy meters, Int J 6 (7) (2019) 3018.

[24] A. Shapiro, A. Balamurugan, D.S. Kumar, G. Swaminathan, IoT based smart energy meter, Sensors 1 (2019) 4.

[25] N. Bhalaji, EL DAPP-An electrıcıty meter trackıng decentralızed applıcatıon, Journal of Electronics 2 (01) (2020) 49–71.

[26] Z. Huang, K. Suankaewmanee, J. Kang, D. Niyato, N.P. Sin, Development of reliable wireless communication system for secure blockchain-based energy trading, in: 2019 16th Int. Joint Conf. JCSSE, IEEE, 2019, pp. 126–130.

[27] H.R. Tan, C.H. Lee, V.H. Mok, Automatic power meter reading system using GSM network, in: 2007 International Power Engineering Conference (IPEC 2007), IEEE, 2007, pp. 465–469.

[28] M.M. Islam, M. Ahmad, M.A. Islam, A.F. Mitul, M.F. Malek, M.A. Rashid, Electronic energy meter with remote monitoring and billing system, in: 2012 7th Int. Conf. on Electrical and Computer Eng, IEEE, 2012, pp. 240–243.

[29] M.R. Balwani, K. Thirumala, V. Mohan, S. Bu, M.S. Thomas, Development of a smart meter for power quality-based tariff implementation in a smart grid, Energies 14 (19) (2021) 6171.

[30] N.S. Srivatchan, P. Rangarajan, A novel low-cost smart energy meter based on IoT for developing countries' micro grids, Concurr Comput 32 (4) (2020) e5042.

[31] F.R. Clenitiaa, E. Ilakya, G.S. Preetha, B. Meenakshi, Enhanced digital energy meter, in: 2017 International Conference on Computation of Power, Energy Information and Commuincation (ICCPEIC), IEEE, 2017, pp. 588–591.

[32] C. Komathi, S. Durgadevi, K.T. Sundari, T.S. Sahithya, S. Vignesh, Smart energy metering for cost and power reduction in house hold applications, in: 2021 7th Int. Conf. on Electrical Energy Systems (ICEES), 2021, pp. 428–432.

[33] G.M. Jasim, K.K. Abdalla, Single phase energy smart meter system design and implementation using RFID and based on IoT, in: IOP Conference Series: Materials Science and Engineering 1090, IOP Publishing, 2021, 012093.

[34] N.A. Abd Razak, R.A Ramlee, Smart energy meter based on internet of things (IoT), INOTEK 2021 1 (2021) 97–98.

[35] C.M. Barathi, N.S. Ashok, Y.N.J. Rajan, T.A. Theepak, IOT based smart energy meter, IJARTET 6 (2019) 48–52.

[36] F. Saleh, S. Kaur, J. Kaur, IOT-based electric energy monitoring smart energy meter, J. Engineer. Des. Analy. (2019).

[37] P. Singhal, S. Upadhyay, S.A.P. Upadhyay, IoT Based Smart Energy Meter (2019).

[38] V. Preethi, G. Harish, Design and implementation of smart energy meter, in: 2016 International Conference on Inventive Computation Technologies (ICICT) 1, IEEE, 2016, pp. 1–5.

[39] N. Al Khafaf, A.A. Rezaei, A.M. Amani, M. Jalili, B. McGrath, L. Meegahapola, A Vahidnia, Impact of battery storage on residential energy consumption, Renew Energy 182 (2022) 390–400.

[40] L. Pujari, IoT based smart energy meter monitoring and controlling system, International Journal of Advance Research, Ideas and Innovations in Technology, 4 (2018) 2126–2128.

[41] M. Rupesh, N. Selvan, IOT Based Smart energy meter design for home with energy consumption limit, in: Proc. 1st Int. Conf. on Computing, Communication and Control System, I3CAC 2021, Bharath University, Chennai, India, 2021.

[42] M. Anisah, Y. Wijanarko, R. Maulidda, J. Al Rasyid, D.P. WP, M.D. Ramadhan, M. Noviansah, Impl. of Smart Grid System for Alternative Energy Power Plants Sources, in: Int. Conf. FIRST-T1-T2, Atlantis Press, 2022, pp. 227–231.

[43] Z. Chen, C.B. Sivaparthipan, B. Muthu, IoT based smart and intelligent smart city energy optimization, Sustain. Energy Technol. Assessm. 49 (2022), 101724.

[44] J.M. Paredes-Parra, A.J. García-Sánchez, A. Mateo-Aroca, Á. Molina-García, An alternative internet-of-things solution based on LOra for PV power plants: data monitoring and management, Energies 12 (5) (2019) 881.

[45] J.M. Paredes-Parra, A. Mateo-Aroca, G. Silvente-Niñirola, M.C. Bueso, Á. Molina-García, PV module monitoring system based on low-cost solutions: wireless raspberry application, Energies 11 (11) (2018) 3051.

[46] F. Sanchez-Sutil, A. Cano-Ortega, J.C. Hernandez, C. Rus-Casas, Development and calibration of an open source, low-cost power smart meter prototype for PV household-prosumers, Electronics (Basel) 8 (8) (2019) 878.

[47] A. Gopstein, C. Nguyen, C. O'Fallon, N. Hastings, D. Wollman, NIST Framework and Roadmap For Smart Grid Interoperability Standards, Department of Commerce. National Institute of Standards and Technology, Gaithersburg, MD, USA, 2021 release 4.0.

[48] Y.M. Rind, M.H. Raza, M. Zubair, M.Q. Mehmood, Y. Massoud, Smart energy meters for smart grids, an internet of things perspective, Energies 16 (4) (2023) 1974.

[49] D.B. Avancini, J.J. Rodrigues, S.G. Martins, R.A. Rabêlo, J. Al-Muhtadi, P. Solic, Energy meters evolution in smart grids: a review, J Clean Prod 217 (2019) 702–715.

[50] F. Al-Turjman, M. Abujubbeh, IoT-enabled smart grid via SM: an overview, Future Gener. Comp. Syst. 96 (2019) 579–590.

[51] R. Morello, C. De Capua, G. Fulco, S.C. Mukhopadhyay, A smart power meter to monitor energy flow in smart grids: the role of advanced sensing and IoT in the electric grid of the future, IEEE Sens J 17 (23) (2017) 7828–7837.

[52] B.K. Barman, S.N. Yadav, S. Kumar, S. Gope, IOT based smart energy meter for efficient energy utilization in smart grid, in: 2018 2nd Int. Conf. on power, energy and environment: towards smart technology (ICEPE, IEEE, 2018, pp. 1–5.

[53] K. Chooruang, K. Meekul, Design of an IoT energy monitoring system, in: 2018 16th International Conference on ICT and Knowledge Engineering (ICT&KE), IEEE, 2018, pp. 1–4.

[54] F. Abate, M. Carratù, C. Liguori, V. Paciello, A low cost smart power meter for IoT, Measurement 136 (2019) 59–66.

[55] D.B. Avancini, J.J. Rodrigues, R.A. Rabêlo, A.K. Das, S. Kozlov, P. Solic, A new IoT-based smart energy meter for smart grids, Int. J. Energy Res. 45 (1) (2021) 189–202.

[56] S. Saha, S. Mondal, A. Saha, P. Purkait, Design and implementation of IoT based smart energy meter, in: 2018 IEEE Applied Signal Processing Conf. (ASPCON), IEEE, 2018, pp. 19–23.

[57] D. Gallo, C. Landi, M. Luiso, G. Bucci, E. Fiorucci, Low cost smart power metering, in: 2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), IEEE, 2013, pp. 763–767.

[58] P.K. Chakravarthi, D. Yuvaraj, V. Venkataramanan, IoT-based smart energy meter for smart grids, in: 2022 6th int. Conf. on devices, circuits and systems (ICDCS), IEEE, 2022, pp. 360–363.

[59] D.M. Jaiswal, M.P. Thakre, Modeling & designing of smart energy meter for smart grid applications, Global Trans. Proc. 3 (1) (2022) 311–316.

[60] G. Mehta, R. Khanam, V.K. Yadav, A novel iot based smart energy meter for residential energy management in smart grid infrastructure, in: 8th Int. Conf. on Signal Processing and Integrated Networks (SPIN), IEEE, 2021, pp. 47–52.

[61] C. Santhosh, S.A. Kumer, J.G. Krishna, M. Vaishnavi, P. Sairam, P. Kasulu, IoT based smart energy meter using GSM, Mater. Today: Proc. 46 (2021) 4122–4124.

[62] M.G. Hudedmani, S. Kadapatti, S.G.S. Rashinkar, V. Yadave, IoT based smart energy meter for smart grid applications, Int. J. Adv. Sci. Eng. (2019).

[63] H. Cabrera, J. Torres, A.S. Morales, G. Ramírez, Integration of Industrial Power Quality Analyzer and Open Source Hardware and Software Solution for Microgrids Monitoring. 2019 IEEE CHILECON, IEEE, 2019, pp. 1–6.

[64] M. Piechowiak, P. Zwierzykowski, B. Musznicki, LoRaWAN metering infrastructure planning in smart cities, Appl. Sci. 13 (14) (2023) 8431.

[65] F. Sánchez Sutil, A. Cano-Ortega, Smart public lighting control and measurement system using LoRa network, Electronics (Basel) 9 (1) (2020) 124.

[66] F. Sanchez-Sutil, A. Cano-Ortega, Smart regulation and efficiency energy system for street lighting with LoRa LPWAN, Sustain Cities Soc 70 (2021), 102912.

[67] F. Sanchez-Sutil, A. Cano-Ortega, Development and implementation of a PQ analyser to monitoring public lighting installations with a LoRa wireless system, IoT 22 (2023), 100711.

[68] E. O'driscoll, G.E O'donnell, Industrial power and energy metering-a state-of-the-art review, J Clean Prod 41 (2013) 53–64.

[69] A. Cano-Ortega, F. Sánchez-Sutil, Monitoring of the efficiency and conditions of induction motor operations by smart meter prototype based on a LoRa wireless network, Electronics (Basel) 8 (9) (2019) 1040.

[70] F. Sánchez-Sutil, A. Cano-Ortega, Design and testing of a power analyzer monitor and programming device in industries with a lora lpwan network, Electronics (Basel) 10 (4) (2021) 453.

[71] A.K.M. Masum, S. Manzur, M.K.A. Chy, S.I. Khan, M.G.R. Alam, S.T. Reza, An IoT based smart energy meter for the idle use of electricity, in: 1st Int. Conf. on Adv. in Science, Eng. and Rob.Tech. (ICASERT), IEEE, 2019, pp. 1–6.

[72] F. Sánchez-Sutil, A. Cano-Ortega, Smart control and energy efficiency in irrigation systems using lorawan, Sensors 21 (21) (2021) 7041.

[73] J. Mancebo, C. Calero, F. García, M.Á. Moraga, I.G.R. de Guzmán, FEETINGS: framework for energy efficiency testing to improve environmental goal of the software, Sustain Comput 30 (2021), 100558.

[74] A. Bourdon, A. Noureddine, R. Rouvoy, L. Seinturier, Powerapi: A software Library to Monitor the Energy Consumed At the Process-Level, 2013, ERCIM News, 2013, p. 92.

[75] G. Kalaitzoglou, M. Bruntink, J. Visser, A practical model for evaluating the energy efficiency of software applications. ICT For Sustainability 2014 (ICT4S-14), Atlantis Press, 2014, pp. 77–86.

[76] E. Jagroep, J.M.E. van der Werf, S. Jansen, M. Ferreira, J. Visser, Profiling energy profilers, in: Proceedings of the 30th annual ACM symposium on applied computing, 2015, pp. 2198–2203.

[77] J. Mancebo, F. Garcia, C. Calero, A process for analysing the energy efficiency of software, Inf Softw Technol 134 (2021), 106560.

[78] B. Prieto, J.J. Escobar, J.C. Gómez-López, A.F. Díaz, T. Lampert, Energy efficiency of personal computers: a comparative analysis, Sustainability 14 (19) (2022) 12829.

[79] T. Johann, M. Dick, S. Naumann, E. Kern, How to measure energy-efficiency of software: metrics and measurement results, 2012 First International Workshop on Green and Sustainable Software (GREENS) (2012) 51–54.

[80] A. Guldner, M. Garling, M. Morgen, S. Naumann, E. Kern, L.M. Hilty, Energy consumption and hardware utilization of standard software, New Trends Environ. Inform. (2018) 251–261.

[81] L.A. Kumar, V. Indragandhi, R. Selvamathi, V. Vijayakumar, L. Ravi, V. Subramaniyaswamy, Design, power quality analysis, and implementation of smart energy meter using IoT, Communist Chin. Sci. Abstr. 93 (2021), 107203.

[82] G. Bedi, G.K. Venayagamoorthy, R. Singh, R.R. Brooks, K.C. Wang, Review of Internet of Things (IoT) in electric power and energy systems, IEEE Internet Things J 5 (2) (2018) 847–870.

[83] W. Hlaing, S. Thepphaeng, V. Nontaboot, N. Tangsunantham, T. Sangsuwan, C. Pira, Implementation of WiFi-based single phase smart meter for IoT, 2017 (iEECON) (2017) 1–4.

[84] D.S.A. Joshi, S. Kolvekar, Y.R. Raj, S.S. Singh, IoT based smart energy meter, Bonfring Int. J. Res. Commun. Engineer. 6 (Special Issue) (2016) 89–91.

[85] T.M. Serrano, L.C. da Silva, L. Pereira, F. Andreoli, T. Ji, F. Fruett, A low-cost smart plug with power quality and energy analyzer features, in: 2019 Int. Conf. on SEST, IEEE, 2019, pp. 1–6.

[86] A.S. Mustafa, S. Shree, A. Bokhari, P. Anitha, S. Babitha, N. Sayedi, IoT based smart talking energy meter (ISTEM), Int. J. Res. Engineer. 2 (4) (2019). Science and Management.

[87] F.M. Dahunsi, H. Ijadunola, A.O. Melodi, A.A. Ponnle, Analysis of GSM, Wi-Fi and LPWAN communication technologies for Smart energy metering circuits, in: 4th Int. Conf. NIGERCON, 2022, pp. 1–5.

[88] K. Ashna, S.N. George, GSM based automatic energy meter reading system with instant billing, in: 2013 Int. Mutli-Conf. on Automation, Computing, Communication, Control and Compressed Sensing (iMac4s), 2013, pp. 65–72.

[89] A.S. Metering, S. Visalatchi, K.K. Sandeep, Smart energy metering and power theft control using arduino & GSM, in: 2017 2nd international conference for convergence in technology (I2CT), IEEE, 2017, pp. 858–961.

[90] C. Santhosh, S.A. Kumer, J.G. Krishna, M. Vaishnavi, P. Sairam, P. Kasulu, IoT based smart energy meter using GSM, Mater. Today: Proc. 46 (2021) 4122–4124.

[91] A.A. Adhau, N.M. Patel, A.T. Zaidy, S.L. Patil, A.S. Deshpande, Low cost electricity meter reading system using GSM, in: 2013 International Conference on Energy Efficient Technologies for Sustainability, IEEE, 2013, pp. 1251–1255.

[92] S.S. Chowdary, M.A. Abd El Ghany, K. Hofmann, Iot based wireless energy efficient smart metering system using zigbee in smart cities, in: 2020 7th Int. Conf. on IoT: Systems, Management and Security (IOTSMS), IEEE, 2020, pp. 1–4.

[93] A.R. Alzaga, K.R. Caguete, M.E.N. De Vera, K.K.E. Villarino, G.V. Magwili, M. C Pacis, Development of a power demand meter for residential loads using ZigBee, in: 2023 15th Int. Conf. on CCAE, 2023, pp. 130–133.

[94] C. Gomez, J. Paradells, C. Bormann, J. Crowcroft, From 6LoWPAN to 6Lo: expanding the universe of IPv6-supported technologies for the Internet of Things, IEEE Commun. Mag. 55 (12) (2017) 148–155.

[95] M.N. Sahana, S. Anjana, S. Ankith, K. Natarajan, K.R. Shobha, A. Paventhan, Home energy management leveraging open IoT protocol stack. 2015 IEEE Recent Advances in Intelligent Computational Systems (RAICS), 2015, pp. 370–375.

[96] E.J. Sebastian, A. Yushev, A. Sikora, M. Schappacher, J.A. Prasetyo, Performance investigation of 6Lo with RPL mesh networking for home and building, in: 2016 3rd Int. Symp. on Wireless Systems in Conf. IDAACS-SWS, 2016, pp. 127–133.

[97] K. Mekki, E. Bajic, F. Chaxel, F. Meyer, Overview of cellular LPWAN technologies for IoT deployment: sigfox, LoRaWAN, and NB-IoT, in: 2018 ieee int. conf. on pervasive computing and communications workshops, 2018, pp. 197–202.

[98] G. Stanco, A. Botta, F. Frattini, U. Giordano, G. Ventre, On the performance of IoT LPWAN technologies: the case of Sigfox, LoRaWAN and NB-IoT, in: ICC 2022-IEEE Int. Conf. on Communications, IEEE, 2022, pp. 2096–2101.

[99] M. Pérez, F.E. Sierra-Sánchez, F. Chaparro, D.M. Chaves, C.I. Paez-Rueda, G. P. Galindo, A. Fajardo, Coverage and Energy-Efficiency Experimental Test Performance For a Comparative Evaluation of Unlicensed LPWAN, 10, IEEE, 2022, pp. 97183–97196.

[100] G. Conti, D. Jimenez, A. Del Rio, S. Castano-Solis, J. Serrano, J. Fraile-Ardanuy, A multi-port hardware energy meter system for data centers and server farms monitoring, Sensors 23 (1) (2022) 119.

[101] M.I. Nashiruddin, A. Yusri, Sigfox network planning for smart metering based on IoT for dense urban scenario, in: 2020 8th Int. Conf. on Information and Communication Technology (ICoICT), IEEE, 2020, pp. 1–6.

[102] E. Saavedra, G. del Campo, A. Santamaria, A novel, self-powered, non-intrusive, sigfox-enabled smart meter for challenging scenarios, in: 2020 16th International Conference on Intelligent Environments, IEEE, 2020, pp. 115–118.

[103] R.S. Balan, M.S. Gouri, T. Senthilnathan, S.R. Gondkar, R.R. Gondar, J.L. Zeema, R. Jothikumar, Development of smart energy monitoring using NB-IOT and cloud, Measurement (2023), 100884.

[104] E.M. Migabo, K.D. Djouani, A.M. Kurien, The Narrowband Internet of Things (NB-IoT) Resources Management Performance State of art, challenges, and Opportunities, 8, IEEE Access, 2020, pp. 97658–97675.

[105] M. Pennacchioni, M.G. Di Benedette, T. Pecorella, C. Carlini, P. Obino, NB-IoT system deployment for smart metering: evaluation of coverage and capacity performances, in: 2017 AEIT International Annual Conference, 2017, pp. 1–6.

[106] P. Kanakaraja, S. Upadhyay, S.K. Kotamraju, G.V.S. Suneela, R. Neelesh, Design and implementation of smart energy meter using LoRa-WAN and IoT applications, in: Journal of Physics: Conference Series 1804, IOP, 2021, 012207.

[107] A. Marahatta, Y. Rajbhandari, A. Shrestha, A. Singh, A. Thapa, F. Gonzalez-Longatt, S. Shin, Evaluation of a lora mesh network for smart metering in rural locations, Electronics (Basel) 10 (6) (2021) 751.

[108] F. Sánchez-Sutil, A. Cano-Ortega, J.C. Hernández, Design and implementation of a smart energy meter using a LoRa network in real time, Electronics (Basel) 10 (24) (2021) 3152.

[109] I. Enriko, A.Z. Abidin, A.S. NooR, LoRaWAN Implementation for Smart Electric Meter in Rural Area, Int. J. Comput., Inf., Syst. Sci., Eng. 38 (5) (2022).

[110] X. Xia, Y. Xiao, W. Liang, J. Cui, Detection methods in smart meters for electricity thefts: a survey, Proc. IEEE 110 (2) (2022) 273–319.

[111] W. Li, T. Logenthiran, V.T. Phan, W.L. Woo, A novel smart energy theft system (SETS) for IoT-based smart home, IEEE Internet Things J 6 (3) (2019) 5531–5539.

[112] D. Alahakoon, X. Yu, Smart electricity meter data intelligence for future energy systems: a survey, IEEE Trans. Ind. Inf. 12 (1) (2015) 425–436.

[113] R. Gopinath, M. Kumar, C.P.C. Joshua, K. Srinivas, Energy management using non-intrusive load monitoring techniques-State-of-the-art and future research directions, Sustain. Cities Soc 62 (2020), 102411.

[114] K. Suriyan, N. Ramalingam, M.K. Jayaraman, R. Gunasekaran, Recent Developments of Smart Energy Networks and Challenges, Smart Energy and Electric Power Systems, 2023, pp. 37–47.

[115] M.A. Sadeeq, S. Zeebaree, Energy management for internet of things via distributed systems, J. Appl. Sci. Technol. Trends 2 (02) (2021) 59–71.

[116] M. Beaudin, H. Zareipour, Home energy management systems: a review of modelling and complexity, Renew. Sustain. Energy Rev. 45 (2015) 318–335.

[117] Z.S. Ageed, S.R. Zeebaree, A. Ahmed, A state of art survey for intelligent energy monitoring systems, Asian Journal of Research in Computer Science 8 (1) (2021) 46–61.

[118] M.E.M. Diouri, ... Dolz, E.S Quintana-Ortí, Solving some mysteries in power monitoring of servers, in: Energy Efficiency in Large Scale Distributed Sys.: COST IC0804 Eur. Conf., EE-LSDS, Vienna, Springer, 2013, pp. 3–18.

[119] A. Babuta, B. Gupta, A. Kumar, S. Ganguli, Power and energy measurement devices: a review, comparison, discussion, and the future of research, Measurement 172 (2021), 108961.

[120] M.H. Islam, T.I. Talukder, F.T.Z. Saima, M.N.I. Rimon, J. Ali, An IoT-based smart energy meter with real-time power tracking system: a review, in: 2021 6th Int. Conf. on Smart and Sustainable Technologies (SpliTech), IEEE, 2021, pp. 01–05.

[121] M.D. Mudaliar, N. Sivakumar, IoT based real time energy monitoring system using Raspberry Pi, Internet of Things 12 (2020), 100292.

[122] M. Milinović, Eduroam Policy Service Definition, Technischer Bericht, GEANT, 2012, pp. 12–192.

[123] Wierenga, K., Winter, S., & Wolniewicz, T. (2015). The eduroam architecture for network roaming (No. rfc7593).

[124] D. Bansal, K. Gupta, M.C. Sharen Ganesh, J. Goyal, K. Tharani, S. Sharma, Smart energy meter based on hall effect current sensing techniques with IoT modules, J. Inform. Optimiz. Sci. 43 (1) (2022) 225–231.

[125] D. Kanellakos, R. Schuck, A. Todd, Hall effect wattmeters, IRE Trans. Audio (1) (1961) 5–9.

[126] Z. Jagun, A. Okandeji, F. Onaifo, P. Alao, Design analysis of a microcontroller based wireless wattmeter, Equity J. Sci. Technol. 7 (2) (2021) 9. -9.

[127] PZEM-004T V3.0 User manual and datasheet: https://innovatorsguru.com/wp-content/uploads/2019/06/PZEM-004T-V3.0-Datasheet-User-Manual.pdf.

[128] PZEM-004T characteristics: https://innovatorsguru.com/pzem-004t-v3/.

[129] PZEM-004T original scheme: https://github.com/TheHWcave/Peacefair-PZEM-004T-/blob/main/PZEM004T-orig.pdf.

[130] SDIC SD3004 Energy Measurement S.O.C. 2012. http://pdacontroles.com/wp-content/uploads/2018/02/sd3004_datasheet_v0.2c.pdf.

[131] ESPRESSIF ESP32. https://www.espressif.com/en/products/socs/esp32.

[132] M. Babiuch, P. Foltýnek, P. Smutný, Using the ESP32 microcontroller for data processing, in: 2019 20th International Carpathian Control Conference (ICCC), IEEE, 2019, pp. 1–6.

[133] U. Hunkeler, H.L. Truong, A. Stanford-Clark, MQTT-S—a publish/subscribe protocol for wireless sensor networks, in: 3rd Int. Conf. on Comm. Systems

Software and Middleware and Workshops (COMSWARE'08, IEEE, 2008, pp. 791–798.
[134] InfluxData. The modern engine for metrics and events. Available: https://www.influxdata.com/.
[135] M. Chakraborty, A.P. Kundan, Grafana. In Monitoring Cloud-Native Applications: Lead Agile Operations Confidently Using Open Source Software, Apress, Berkeley, CA, 2021, pp. 187–240.
[136] G. Labs. Grafana; the analytics platform for all your metrics. Available: https://grafana.com/.
[137] openZmeter. Smart metering and power quality analysis for the people. https://openzmeter.com/.
[138] A.J. Christe, S. Negrashov, P.M. Johnson, Design, implementation, and evaluation of open power quality, Energies 13 (15) (2020) 4032.
[139] Top500, The Linpack benchmark. Available online: https://www.top500.org/project/linpack/ (accessed on 12 July 2023).
[140] Linpack Xtreme, TechPowerUp, 2023, 31 December 2020 Version. Available online, https://www.techpowerup.com/download/linpack-xtreme/(accessed. on 12 July.
[141] J.J. Escobar, F. Rodríguez, B. Prieto, D. Kimovski, A. Ortiz, M. Damas, A distributed and energy-efficient KNN for EEG classification with dynamic money-saving policy in heterogeneous clusters, Computing (2023) 1–24.
[142] J. Asensio-Cubero, J.Q. Gan, R. Palaniappan, Multiresolution analysis over simple graphs for brain computer interfaces, J. Neural. Eng 10 (4) (2013), 046014.
[143] E. Ayguadé, N. Copty, A. Duran, J. Hoeflinger, Y. Lin, F. Massaioli, G. Zhang, The design of OpenMP tasks, IEEE Trans. Parallel Distrib. Syst. 20 (3) (2008) 404–418.
[144] L. Dagum, R. Menon, OpenMP: an industry standard API for shared-memory programming, IEEE Comput. Sci. Engineer. 5 (1) (1998) 46–55.

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