

Design of a Smart Electricity Meter for Mini-Grids Operation

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Abstract

Accurate measurement of electrical consumption is one of the challenges faced by energy suppliers in managing their electricity networks. To address this issue, this study focuses on the design of a smart electricity meter capable of accurately measuring the electrical parameters of subscribers to enable these suppliers to easily manage their electricity network. The proposed system incorporates voltage and current sensors supplying the value of these parameters to the ESP 32 microcontroller, which in turn induces actions to determine consumption data. The GSM SIM 800 module used transmits this data to a database that can be consulted on the supplier's desktop GIC application and also enables subscribers to recharge their meters and find out as many times as they like about the electricity consumption status of their installation. The results of real-life tests show that the device accurately measures electrical parameters (in compliance with ISO/CEI 17025: 2017). Customers can also interact with their meter via their mobile phone. All this means that the meter holds great promise in terms of customer satisfaction and supplier autonomy in managing their network.

Keywords

Counting System, GSM SIM 800 Module, ESP 32, Desktop GIC Application

1. Introduction

The exponential increase in energy demand in the 21st century is mainly due to population growth, global economic expansion and increased urbanization [1]-[3]. Fossil energy resources, although limited and polluting, are the main source of energy used to produce electricity [4]. As a result, in order to satisfy energy

demand, these resources are gradually being depleted. It is therefore important to incorporate other energy sources into the energy mix, in particular renewable energies, in order to meet the energy challenges facing the world [5]. This is easily understood by the fact that governments are being encouraged to put in place new policies and strategies to promote sustainable development. By way of illustration, in 2015, the United Nations adopted the Sustainable Development Goals (SDG), goals 7, 12 and 13 of which relate respectively to clean energy, responsible consumption and the fight against climate change [6]. These goals aim to promote sustainable energy systems that foster economic development while reducing environmental impact. While renewable energies play a key role in the energy transition, the integration of these energy sources requires efficient management of consumption, which underlines the importance of electricity meters. The evolution of electricity meters began with electromechanical meters, based on a disc rotating at a speed proportional to the electricity consumed. The calculation of electricity consumption by energy supply companies and the preparation of bills using the old traditional meters are now proving ineffective. These methods have a number of limitations, including a complete reliance on manual readings, increased exposure to human error, and significant time taken to collect and process data over a large area. They also increase the risk of energy theft and deprive consumers of regular, accurate monitoring of their energy consumption. As a result, electronic meters offering more accurate measurements and additional functionalities have emerged. Equipped with sensors, they measure the instantaneous current and voltage over a period of time to assess the energy consumed. However, they are unable to transmit consumption data to the subscriber and/or supplier in real time due to the lack of a communication protocol. This has finally given way to smart electricity meters (CEI). These meters are measuring devices used by utilities to transmit billing data to customers while ensuring the operation of electricity networks. Their ability to be read and controlled remotely makes them a prime target for businesses, helping to reduce labor costs [7]. Smart meters offer a number of important benefits. Firstly, they allow users to access detailed information about their energy consumption, making it easier to adjust their habits to save money, improve energy efficiency and promote sustainability. In addition, the ability to monitor and manage meters remotely helps service providers to reduce operating costs, minimize human error and enhance network security [8]. In addition, smart meters are transforming homes into intelligent environments with the ability to monitor appliance consumption in real time and use a centralized management system to optimize consumption [9] [10]. The integration of these meters into an Advanced Metering Infrastructure (AMI), combined with Home Area Networks (HAN), Wide Area Networks (WAN) and Neighborhood Area Networks (NAN), enables major advances over Automatic Meter Reading (AMR) and Meter Management (AMM) technologies [11]. **Figure 1** shows the complete architecture of a smart grid. This network integrates energy sources, including solar energy. It also encompasses various loads, such as smart homes, connected

buildings as well as a data center responsible for overseeing the entire infrastructure. This architecture must meet several interconnected requirements: data privacy and security, reliability, durability, quality of service (QoS), and coverage. These criteria, which are interdependent, are essential to ensure the secure transmission of information.

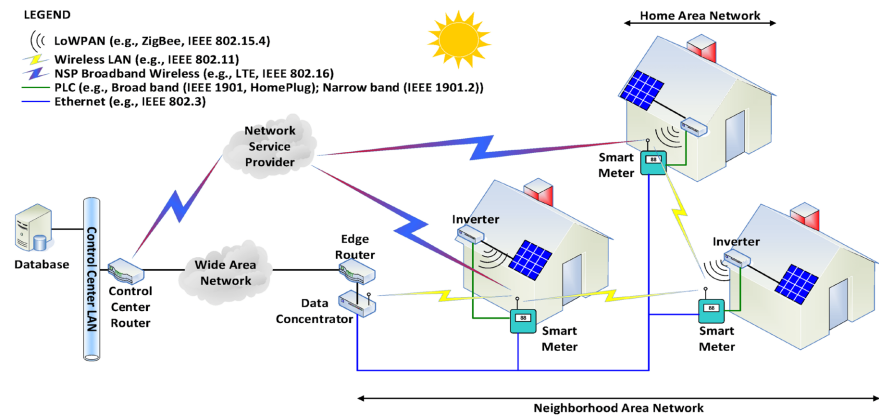


Figure 1. Smart grid infrastructure [12].

The pooled meters send their data to a local hub which then transmits it to the servers via a terrestrial connection for storage, processing, and billing. This process underscores the importance of the network's communication capabilities. To this end, the integration of technologies and applications such as analytics, real-time monitoring and dynamic pricing generates a considerable volume of data that flows through these channels. It is therefore essential to assess the available communication technologies to identify the most suitable one for smart grids. Smart meters communicate using a variety of technologies. Two main types of technology can be considered: wired and wireless. Wired technologies generally offer greater transmission capacity and cover longer distances, while wireless technologies, although often less expensive, may be more suitable for hard-to-reach areas [13]. Here's an overview of the main technologies:

- IOT (Internet of Things) which connects various devices in an integrated system, optimizing energy management and preventing electrical incidents.
- Bluetooth and Bluetooth Low Energy (BLE): this short-range wireless technology (around 10 meters) is economical and consumes little energy. It can facilitate local wireless access to smart meters and other smart grid components [14].
- ZigBee: a wireless technology, based on the IEEE 802.15.4 standard and specially designed for sensor networks and home automation applications. Some variants of ZigBee, such as ZigBee Smart Energy Profile (SEP) and Z-Wave, allow wireless mesh networks to be created by turning each node into a router, thus extending the range of the network [15].
- Wi-Fi: Designed for short-range communications of up to 250 meters, Wi-Fi does not meet low power consumption requirements. It operates in the 2.4 or

5 GHz frequency bands [14].

- LoRa (Long Range) is a wireless communication technology enabling long transmission distances with low energy consumption.
- Cellular networks : Cellular networks offer wide coverage and high data rates, making them suitable for connecting smart meters and other smart devices [8] [14]. The GSM network, for example, is a cellular network technology that enables mobile communication over long distances by connecting mobile devices to networks via geographical cells managed by telecommunications towers.
- Power line communication (PLC): This wired technology uses existing power lines to transmit data at speeds of up to 3 Mbps.
- Finally, digital subscriber line (DSL) and fiber-optic technologies offer high-speed data transmission capabilities over voice telephony networks or fiber-optic cables. They are particularly suitable for connecting intelligent network elements in home area networks (HAN) and wide area networks (WAN).

In some studies, such as those of Geno and al., have sought to improve electro-mechanical meters in order to facilitate the billing process. In their improvement, they have used a GSM SIM 900 module for communication and charging. The system's overcurrent protection is provided by a current sensor and a relay that work together [16] [17]. Aghillas *et al.* prototyped power and current acquisition using Hall effect current sensors. Indeed, the device based on an Arduino board to perform the calculation of power and current; Wireless communication that allowed them to transmit and display the values on a smartphone [18]. Admane *et al.* [19] improved electromechanical meters by using the Arduino Atmega board as a microcontroller and the GSM module as a communication technology. However, other researchers have used the Raspberry Pi3 as a server in addition to the aforementioned components that transmits energy consumption data on a web page. Djebiri *et al.* developed the in-house design of an electric meter using voltage and current sensors and an ESP32 microcontroller. An Android smartphone application capable of synchronizing data with the ESP32 card is developed to allow the subscriber to interact with the meter [20]. The system proposed by Al-Sehail *et al.* allows the exchange of information between the consumer and the public service, where the consumer can access their data through a web page: issuance of a monthly invoice and sending to the consumer by e-mail and SMS as well as disconnecting from the power source in the event of non-payment of the invoice by the consumer [21]. Bhavani *et al.* have implemented smart energy meters using GSM technology for domestic consumers. To have a variable billing system, the meter integrates the Wireless PeakHour, Timing Update (WPTU) and Wireless Tariff Update (WTU) systems [22]. Abdul *et al.*'s work focused on modeling of Arduino-based Prepaid Energy Meter using GSM Technology. Indeed, the work aims to collect data on the energy consumed by a subscriber via a wireless communication system (based on GSM technology) called AMR (Automatic Meter Reading) [23]. Syed *et al.* worked on modelling of Arduino Based Pre-Paid Energy Meter Using GSM Technology. The authors designed and modeled an energy

charging system for prepaid metering to reduce common errors in energy billing in India. These errors, related to electromechanical meters, human intervention and data processing, increase costs and management complexity. The integration of a GSM module will allow users to recharge their electricity credit remotely, improving the accessibility and efficiency of the system [24]. Henry Erialuode Amhenrior, on the other hand, made an electromechanical meter smart by developing an application to visualize the data [25]. This article highlights a smart electricity meter using the GSM network, via the SIM800 module, to ensure real-time charging and communication even in remote areas. Unlike models requiring complex applications, this meter allows simple interaction via SMS, making it accessible to users without a smartphone. It also incorporates an SD card reader to save data in the event of a power outage, a rare feature in existing solutions often limited to real-time transmissions. The GIC platform, developed with modern tools (Flutter, Figma and others), centralizes management by allowing detailed monitoring of consumption and recharging. In addition, by using cost-effective components such as the ESP32, this system is ideally suited to low-resource contexts.

2. Materials and Methods

Setting up the system requires several elements to interact.

2.1. Materials

2.1.1. System Design

Table 1 below provides information on the electronic components used.

Table 1. Electronic components used.

Electronic components	Parameters	Specifications
NodeMCU: ESP32-DEVKITC	Clock frequency	240 MHz
	Wifi	2.4 GHz to 150 Mbps/s
	Bluetooth	BLE (Bluetooth Low Energy) and Bluetooth
	Serving temperature	-40 °C to 125 °C
Current sensor	Measuring range	0 - 100 A
	Sensitivity	0.02 A
	Precision	0.5%
	Resolution	1 mA
PZEM-004T module	Measuring range	80 - 260 V
	Supply voltage	5 V
	Precision	0.5%
	Resolution	0.1 V
GSM SIM 800 module	Size	7.5 (cm) × 2.4 (cm)
	GSM	850, 900, 1800, 1900 MHz
	RAM	32 Mbit
	Supply voltage	3.7 - 4.2 V
	Current Consumption	1 mA

Continued

	Operating temperature range	-40° - 85°
	Size	2.5 cm × 2.3 cm
Relay SRD-05VDC-SL-C	Maximum contact current	30 A
	Maximum contact voltage	250V AC
	Coil resistance	100 Ω
	Coil voltage	5V DC
SD reader	Supply voltage	4.5 V (min), 5 V (typical), 5.5 V (max)
	Current Consumption	0.2 mA (min), 80 mA (typique), 200 mA (max)
	Card supported	Micro SD card (≤2 G), Mirco SDHC card (≤32 G)
	Size	42 (mm) × 24 (mm) × 12 (mm)
Resistor	Value of resistance	1 K
	Tolerance	± 1%
	Temperature coefficient (ppm/°C) :	±50 - ±100 (ppm: part per million)
LED	Intensity	10 mA
	Brightness	High
	Lifespan	Long
LCD display	Pin definition	GND. VCC. SDA. SCL
	Backlight	Green with black color
	Supply voltage	5V
	Size	60 (mm) × 99 (mm)
Wattmeter	Display interface	Large screen LCD
	AC measuring voltage range	80 V - 260 V
	Current range	0 - 100 A
	Power range	0 - 22 kW
	Energy range	0 - 999 kWh
	Frequency range	45 - 65 Hz
	Factor range	0 - 1 PF

2.1.2. Design of the Desktop GIC Application

To design GIC application, the name given to the desktop application developed, we used Dart, a programming language, in Flutter FrameWork to develop the platform, and Figma enabled us to implement the application model.

2.2. Methods

This study required the development of a working methodology. It covers various aspects such as the choice of electronic components, the calibration of sensors and the implementation of the device.

2.2.1. Calibration of the Power Meter

To ensure the accuracy of the values, we calibrated the wattmeter. We applied the known voltage, current, load and frequency to the wattmeter, then compared the measurements displayed with those of the reference devices (the standard voltme-

ter and ammeter). If the differences exceeded the tolerances, we adjusted the parameters of the wattmeter using its potentiometer.

2.2.2. Project Ecosystem

Three players are involved in the project ecosystem. These are the customer, the supplier and the meter itself. The customer recharges his meter using his mobile phone. Electricity will then be available at the customer's home, and at the same time, consumption data will be sent to a database via the GSM network for viewing by the supplier on a platform (Figure 2).

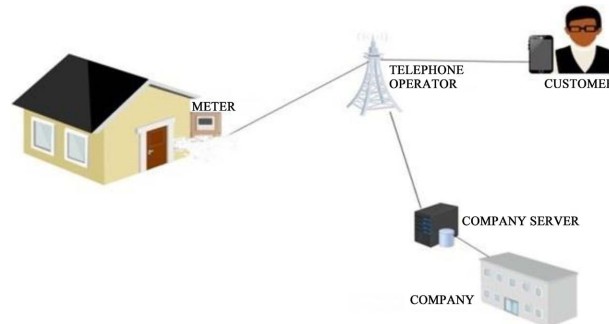


Figure 2. Project ecosystem.

2.2.3. How the System Works

Initially, the subscriber sends money to recharge his meter using his mobile phone. Thanks to the GSM SIM 800L module, the ESP 32 processes the message and converts the amount into a given quantity of kilowatt-hours. The subscriber then has access to the electrical energy in his concession. The consumption data for the installation is measured by the PZEM-004T module, displayed on the LCD screen and sent to a database for viewing by the supplier on the GIC platform. The system is equipped with an SD reader that holds a memory card. The data is stored on this memory so that it is not lost in the event of a power cut. The relay also switches the customer's installation off and on again. The metering system is summarized in the following diagram. This diagram includes all the electronic components that interact in the system (Figure 3).

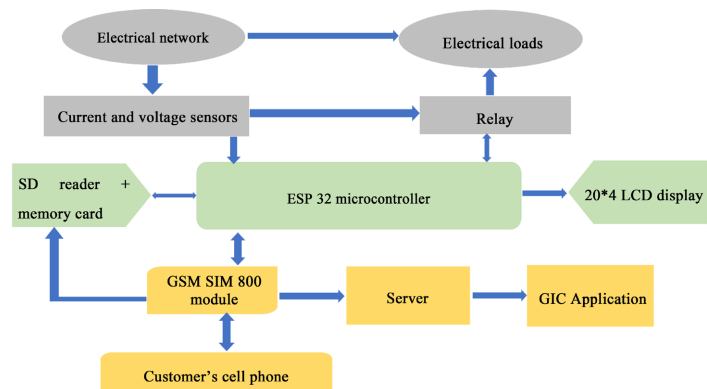


Figure 3. System block diagram.

2.2.4. Electrical Connections

The type for electrical connections was made using the Proteus software (Figure 4).

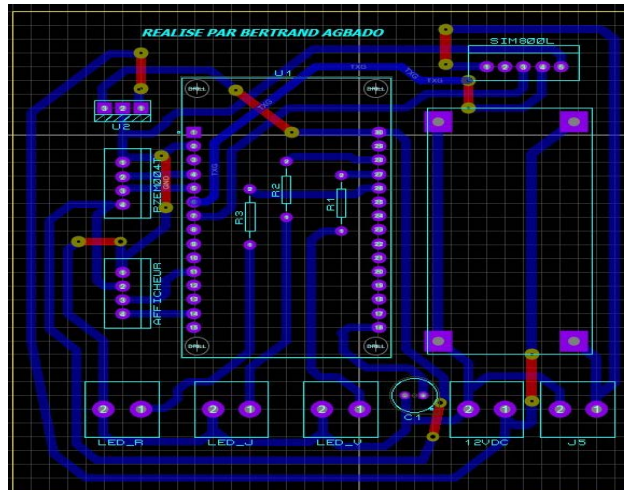


Figure 4. Typon made.

2.2.5. Operating Diagram

Figure 5 represents the operating diagram with actions per step.

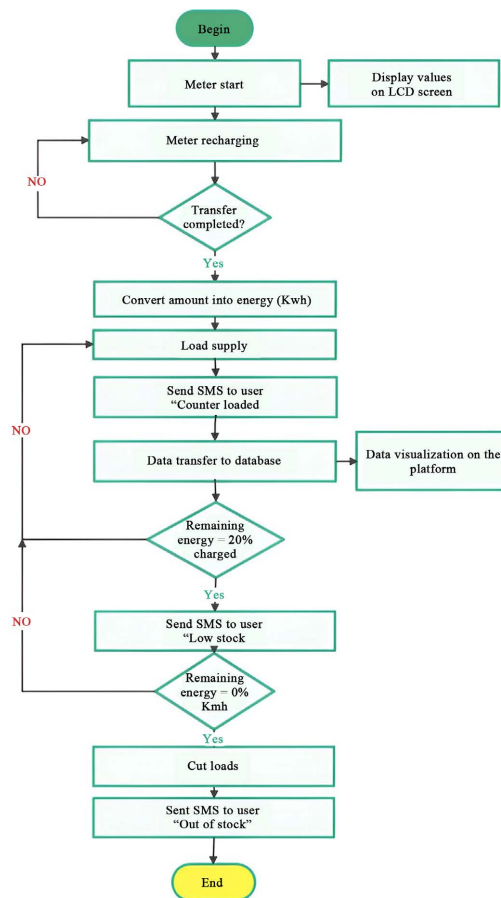


Figure 5. Operating diagram.

2.2.6. Electrical Parameters

A number of electrical parameters come into play to ensure that the system operates correctly. While some are measured directly by sensors, others are calculated using theoretical formulae.

1) Measured parameters

Here, the sensors provide us via the processing unit with electrical parameters such as the instantaneous voltage $\mathcal{V}(t)$ and current $i(t)$.

2) Determined parameters

Some parameters are not directly supplied by the sensors. Theoretical formulas taking into account the measured parameters are therefore used to determine these parameters. They are updated at each period T , where T is the period of the alternating current signal (in seconds).

- **RMS voltage and current:**

$$\mathbf{V}_{eff} = \sqrt{\frac{1}{T} \int_0^T \mathcal{V}^2(t) dt} \quad (1)$$

$$\mathbf{I}_{eff} = \sqrt{\frac{1}{T} \int_0^T i^2(t) dt} \quad (2)$$

with \mathbf{V}_{eff} and \mathbf{I}_{eff} the rms voltage and current respectively.

- **Instantaneous power:**

This power $p(t)$ is obtained by the product of the instantaneous values of voltage $\mathcal{V}(t)$ and current $i(t)$:

$$p(t) = \mathcal{V}(t) \times i(t) \quad (3)$$

- **Real power:**

Real power P , also known as active power, is the average of the instantaneous power over a complete cycle of the waveform. It is measured in watts (W):

$$P = \frac{1}{T} \int_0^T p(t) dt \quad (4)$$

It is also determined by:

$$P = \mathbf{V}_{eff} \times \mathbf{I}_{eff} \times \cos(\phi) \quad (5)$$

$\cos(\phi)$ is the power factor, which is the cosine of the phase angle ϕ between the voltage and the current.

- **Apparent power (S)**

Apparent power is measured in volt-amperes (VA) and is calculated as follows:

$$S = \mathbf{V}_{eff} \times \mathbf{I}_{eff} \quad (6)$$

- **Power factor (PF)**

The power factor is the ratio of real power to apparent power:

$$FP = \frac{P}{S} \quad (7)$$

- **Instantaneous energy**

The instantaneous energy $e(t)$ is obtained by the product of the instantaneous values of the voltage $\mathcal{V}(t)$, the current $i(t)$ and the time t or by the product of the instantaneous power and the time t :

$$e(t) = \mathcal{V}(t) \times i(t) \times t \tag{8}$$

• **Average energy**

$$E = \frac{1}{T} \int_0^T e(t) dt \tag{9}$$

3. Results and Discussions

Figure 6 and Figure 7 show the system’s electrical circuit and the completed prototype respectively.

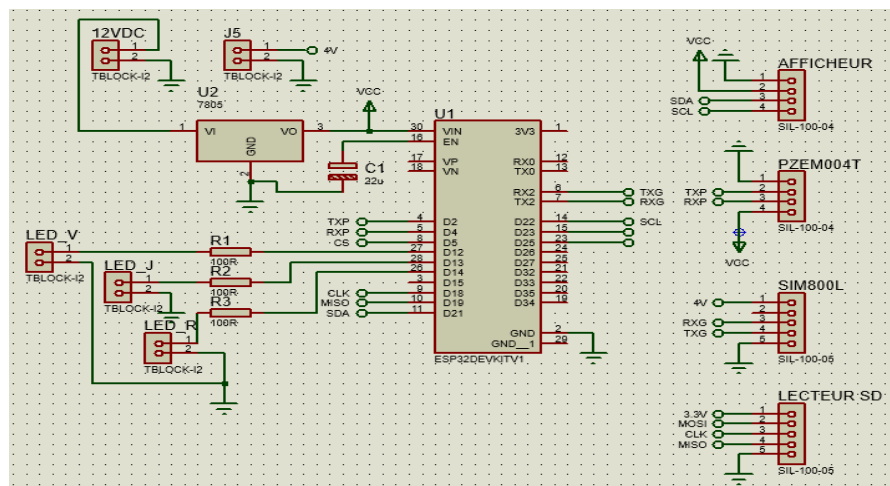


Figure 6. Electrical circuit of the system.



Figure 7. Physical image of the prototype.

3.1. Desktop GIC Application

GIC is a desktop application developed to enable electricity network providers to view their customers’ electricity consumption in real time. When the GIC application is opened, the interface that appears allows the manager to self-identify for

the first time by entering their email address and a password (**Figure 8**). The manager then logs on to access the interface providing information on the status of subscribers' meters, as shown in **Figure 9**.

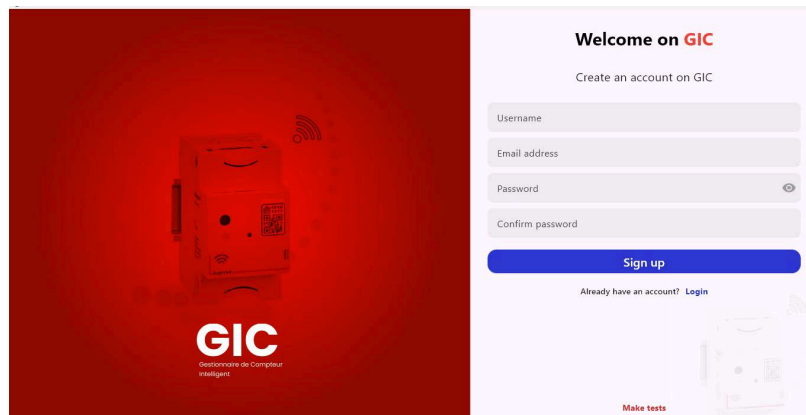


Figure 8. GIC App home interface.

# ID	Full Name	Email	Phone Number	Status
00df61e15cnd41w	Edou Romaric	edouromaric52@gmail.com	90219990	Off
canmxxkuhmn26sx	Akpeli Regis	akpolir@gmail.com	0022961942231	Off
cp1c1o4jn3m91i	Agbado Bertrand	agbadobertrand@gmail.com	96118288	Off
fmwp06zdvb60sqk	Ahui Othniel	ahui@gmail.com	96187168	Off
7naz412dvw6eoqal	Lanmayikpohoué Sédofi Hope	sedofhope@duck.com	0123456789	Off
clientID_2	Smith Jane	jane.smith@example.com	0987654322	Off
clientID_1	Toto John	john.doe@example.com	1234567890	On

Figure 9. Status of customer meters.

Click on “Add” to display the following interface. This is used to register a new subscriber who wants to buy a meter from the supplier. The subscriber provides a few personal details, which the administrator in charge of the application will enter to register them (**Figure 10**).

Figure 10. Subscriber registration.

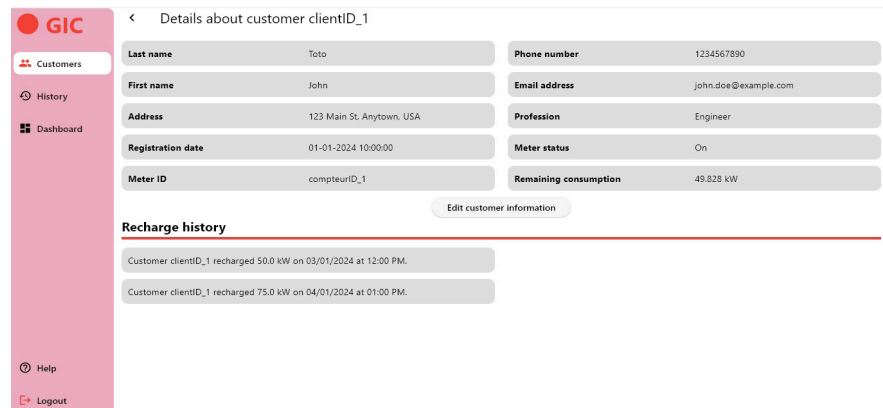


Figure 11. Details about customer.

The “*History*” section traces the various top-ups made by each subscriber from the first top-up when the meter was requisitioned to the last top-up. The following interface is displayed when you click on “Dashbord”. It shows the total power curve of subscribers by day. This will enable suppliers to see the demand from subscribers on a daily basis, so they know whether they need to increase the power of their plants (**Figure 11**).

3.2. Real-Life Tests

The system is tested under real conditions to assess the accuracy of the values of the electrical parameters it displays. To do this, when the meter is switched on, we first connect an electric lamp to its output and then a PC computer. The loads are then each connected to the wattmeter to validate the measurements. The results obtained are shown in **Table 2**.

Table 2. Values displayed by wattmeter and meter for each load.

Electrical parameters	Values displayed by wattmeter			Values displayed by meter			Relatives incertitude (%)		
	Lamp	Computer	Other loads*	Lamp	Computer	Other loads	Lamp	Computer	Other loads
Voltage (U)	227 V	227 V	219.8 V	232.60 V	221.20 V	220 V	2.46	2.55	0.090
Current (I)	0.086 A	0.334 A	1.129 A	0.084 A	0.340 A	1.130 A	2.32	1.79	0.088
Power (P)	13.8 W	44.8 W	61.2 W	13.6 W	44.7 W	60.00 W	1.45	0.22	2.000
Power factor (PF)	0.71	0.59	0.89	0.70	0.59	0.89	1.41	0.00	0.000
Frequency (N)	50 Hz	50 Hz	50 Hz	50 Hz	50.30 Hz	50.1 Hz	0.00	0.4	0.199

*fan, lamp and refrigerator used together.

First of all, we can see that the current demand has increased because the power of the computer is much greater than that of the electric lamp. The uncertainty values are all less than 3%, which complies with ISO/IEC 17025: 2017, which specifies a value of less than 5% [26]. So, when we take a look at existing work, we see that even if the uncertainty values comply with the standard, most

of these works have values in excess of 3%. These results show that our smart meter accurately measures electrical parameters. In addition, characters are pre-defined to allow subscribers to interact with the meter using their mobile phones (**Table 3**).

Table 3. Interaction with the meter.

Characters	Functions	Return to customer
“0”	Turn off the meter	Meter disabled
“1”	Turn on the meter	Meter abled
“3”	Value of energy consumed since meter acquisition	Your total energy is: ...
“4”	Value of remaining kWh	Your remaining kWh is: ...
“5”	Value of the last reload carried out	Your last recharge is: ...

For example, when a customer wants to switch off their meter, they simply send “0” as a character. In return, they will receive the confirmation message “meter disabled” and all their loads will be switched off.

The GIC application dashboard shows us the curve observed in **Figure 12** after the various tests carried out on the electricity meter.

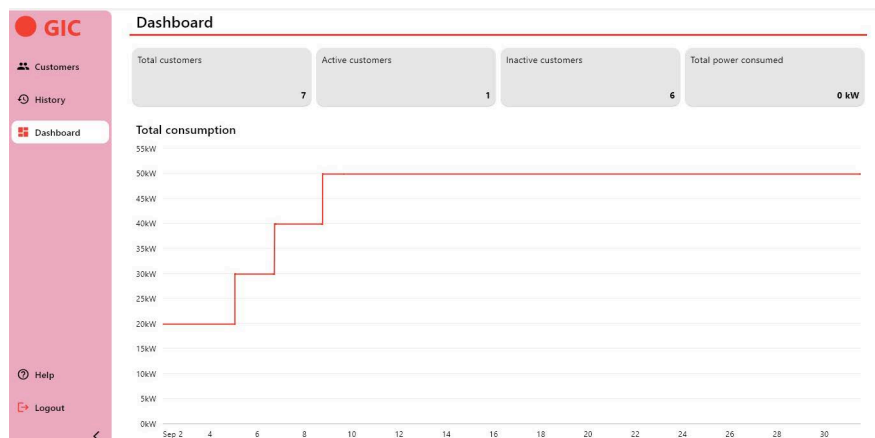


Figure 12. Dashboard showing lamp and computer consumption.

The electric lamp and the computer each remained connected to the counting device that we developed for an approximate period of one hour. The analysis of the energy consumption curve associated with these two loads reveals a virtual absence of variation, with the consumption remaining practically zero, which is reflected in zero-sloped segments (horizontal asymptotes) on the graph. On the other hand, sudden increases in the level of credit (vertical asymptotes) correspond to recharging operations: each injection of credit induces an instantaneous increase in the value of the available kilowatt-hour. The result is a “stepped” representation of consumption, as displayed in the GIC application dashboard, that is both consistent and self-explanatory (**Figure 13**).

3.3. System Security Analysis

The current design of the smart electricity metering system, while effective for measuring and transmitting consumption data, has some potential vulnerabilities that are worth investigating to enhance the robustness and reliability of the device in a real-world environment (Table 4).

Table 4. System security analysis.

Potential vulnerabilities identified	Descriptions	Recommendations
Interception of GSM data	Data sent from the meter to the GIC app via GSM can be intercepted by man-in-the-middle attacks if not encrypted, compromising the privacy of consumption information.	Implementation of secure communication protocols such as MQTT-SN secure for future GPRS/4G versions of the meter.
Risk of local data tampering	SD card storage without a protection mechanism can allow physical tampering with consumption data when directly accessing the device.	<ul style="list-style-type: none"> ✓ Using a simple but effective encryption method (such as the 128-bit AES built into the ESP32) to encode data before it is transmitted via GSM, ensuring its confidentiality and integrity. ✓ Automatic detection of behavioral anomalies (e.g. overcharging, untimely stops) by on-board lightweight machine learning.
Data loss in the event of a prolonged outage	In the absence of regular automatic synchronization with the GIC app, a prolonged GSM communication failure could result in a loss of history between two transmissions.	Provide for automatic synchronization of local data with the server as soon as GSM communication is restored after an interruption.

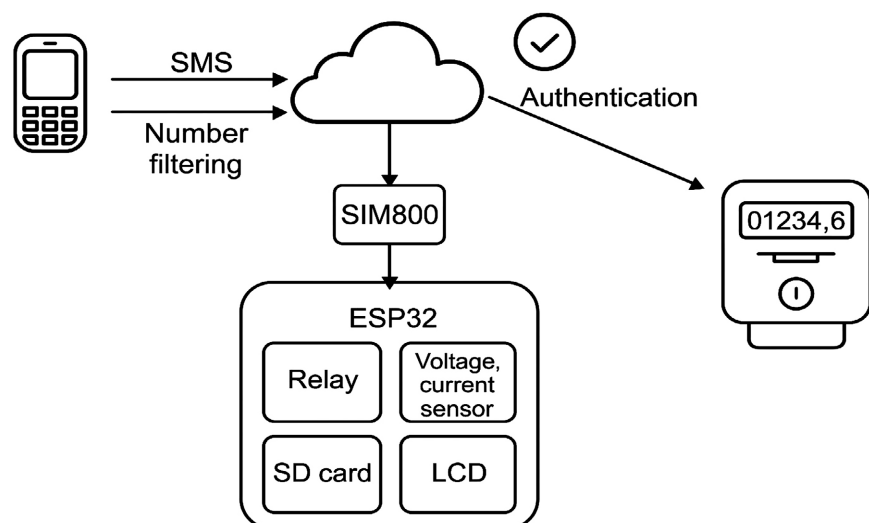


Figure 13. Secure communication.

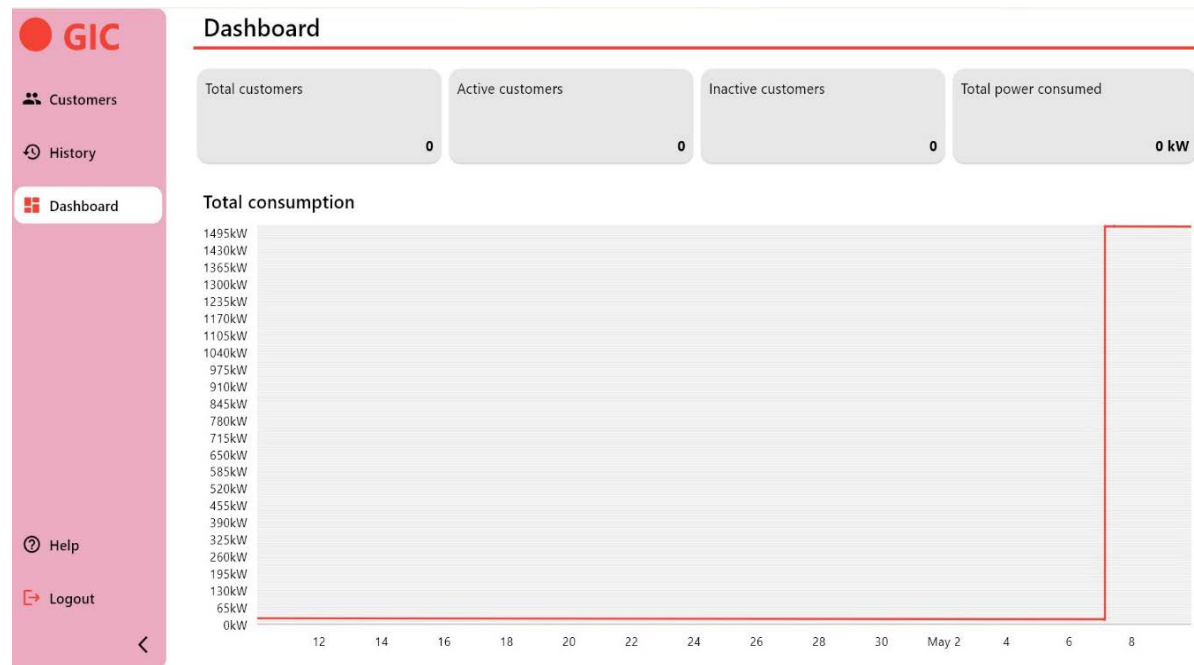


Figure 14. Dashboard showing other loads consumption.

A few months later, after recharging the 1500 kWh meter—bringing the remaining credit from about 19 kWh to 1519 kWh—we left a refrigerator with an electric lamp running continuously for about three hours. Observation of the remaining credit curve shows a marginal decrease (from 1519 kWh to 1518 kWh), reflecting limited electricity demand and therefore low energy consumption (**Figure 14**).

4. Conclusion

In this article, we have proposed a smart electricity meter for electricity suppliers to enable them to better manage their electricity networks in isolated locations. Our approach followed a methodology that included design, production and testing in real-life conditions. The system developed fulfils all the essential functions, such as remote recharging of the meter and transmission of consumption data to the GIC platform. Test results show that the device accurately measures electrical parameters, making the system promising in terms of customer satisfaction and the supplier's autonomy in managing its network. Overall, the device is a modern and effective solution for monitoring energy consumption. Although the system is already effective, there is still room for improvement over time because disturbances may occur if the area where the meter is installed does not have a good telephone and/or internet network. Future work could therefore focus on improvements such as making the system more secure, by incorporating an anti-fraud system for example, not forgetting its extension to three-phase networks. These improvements could make the system even more attractive and facilitate its wider commercialization.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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