Design and implementation of smart meter for optimizing and managing electrical energy in Morocco

Alhussein Bagayogo[1], Omar Kabouri[1], Aboubakr El Makrini[1], Mohamed Azeroual[2], Hassane El Markhi[1]
[1]Science and Engineering Research Laboratory, Faculty of Sciences and Technology, Sidi Mohamed Ben Abdellah University, Fez, Morocco
[2]SEIMC Research Group, LASMAR Laboratory, Higher School of Technology, Meknes, Moulay Ismail University, Meknes, Morocco

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ABSTRACT

The growth of renewable energy sources necessitates the use of accurate and fast smart meter solutions. This article presents a low-cost internet of things (IoT) based smart meter adapted to the Moroccan electricity grid, supporting bidirectional energy measurement, DLMS/COSEM-based communication and control relays for automated energy flow management. The experimental validation shows a maximum measurement error of less than ±0.5%, satisfying the IEC-oriented accuracy requirements. The measured end-to-end latency is approximately 700 ms, including data acquisition (≈450 ms), signal processing (≈60 ms), data serialization (≈75 ms), network transmission (≈90 ms), and server-side processing (≈25 ms). These results demonstrate that the proposed system allows an almost real-time monitoring and control of imported and exported energy, which makes it suitable for the integration of residential renewable energies and the application of smart grids.

Corresponding Author:

Alhussein Bagayogo
Department of Electrical Engineering, Science and Engineering Research Laboratory, Faculty of Sciences and Technology, Sidi Mohamed Ben Abdellah University
Fez 30000, Morocco
Email: alhussein.bagayogo@usmba.ac.ma

1. INTRODUCTION

The global energy transition seeks to reduce dependence on fossil fuels by promoting renewable sources such as solar and wind energy. Benefiting from abundant renewable resources, Morocco has set an ambitious goal of reaching 52% renewable energies in its energy mix by 2030 [1], [2]. However, the effective integration of these resources requires advanced energy management solutions capable of handling the dynamic and bidirectional energy exchanges inherent in renewable energy systems [3]–[5]. Smart metering and internet of things (IoT) based energy monitoring systems have become a popular research topic for improving power quality, energy efficiency, and demand-side management. Morales, Morales-Velazquez *et al.* [6] introduced a distributed smart sensor network for power quality monitoring, which is mainly about harmonic analysis and multi-node architectures. Although this method works well for the monitoring of electrical installations, it is not especially aimed at low-cost smart energy metering. There have also been studies into low-cost microcontroller-based solutions. Abed and Naser [7] revealed an ESP32-based smart power meter with wireless connectivity, yet there was almost no consideration of measurement accuracy and latency. In the same way, Viciana *et al.* [8] came up with an open, hardware IoT platform capable of power quality and energy-saving applications, where the emphasis was on modularity rather than metrological performance. In the most recent works, IoT-based smart meters have been combined with energy management and monitoring services at a higher level. Ahammed and Khan [9] concentrated on demand-side-side management and power quality issues in developing countries, whereas Garcés *et al.* [10] targeted real-time monitoring and cloud integration. Nevertheless, both papers only show limited quantitative evaluation of accuracy and response time. Further studies deal with different facets like data analytics [11] and privacy, preserving communication protocols [12], the authors having in mind reliable metering hardware.

Finally, current smart meters. also have problems with communication and real-time data security, which negatively affects the transparency and reliability of the electricity. In responding to these problems, this research proposes to design a smart meter that is particularly adapted to both renewable energy and non-renewable energy management in Morocco [12], [13]. This new device will have two important innovations: i) an import-export feature so that the user can track precisely all incoming and outgoing flows and thereby optimize management and valorization of produced energy locally; ii) a communications protocol such as device language message specification (DLMS) that also can ensure safe, timely transfer of energy data while helping to bolster accountability and trust in the energy system; and iii) A feature with control relays to manage loads and detect fraud.

The smart energy management system in Figure 1 has a smart meter, a battery storage system, and a renewable energy source utilizing a direct current (DC) bus to efficiently distribute energy before conversion to alternating current (AC) via a DC/AC inverter. At the center of the architecture, the smart meter is positioned to monitor energy transactions between loads, the power grid, and also the units that produce power from renewable energy sources. In addition, the smart meter provides data communications to manage energy so that it can be done without overload or fraud. While on the DC bus, it has alternative sources and battery storage, so it has energy autonomy, even if the production is erratic. The AC bus handles all the distributed energy to domestic and industrial loads with a grid supply, so there is a supply at all times.

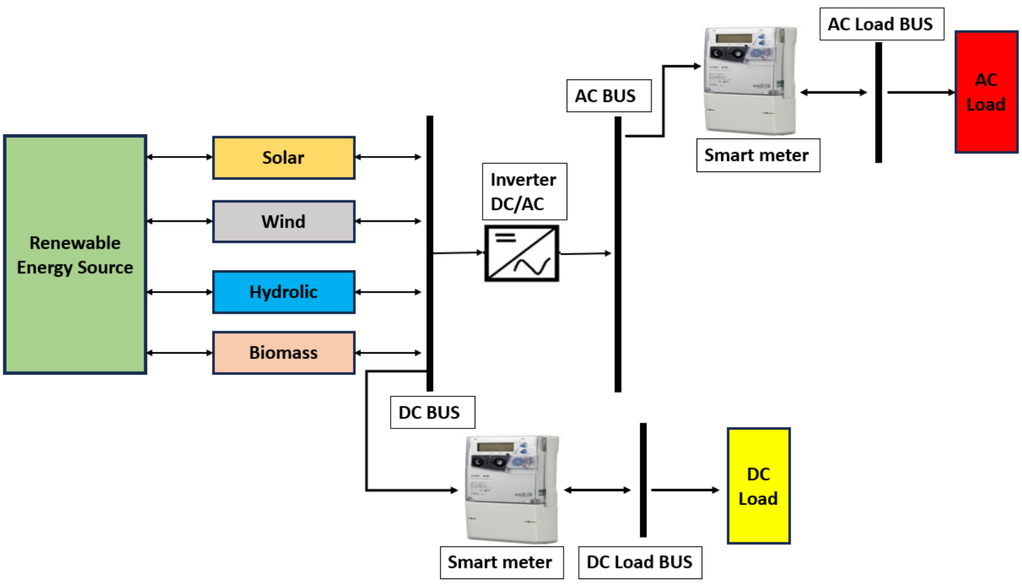


Figure 1. The network schematic includes a new smart meter

The document consists of five main sections, which the section 2 describing how the research has been carried out. Section 3 reveals the design and features of the newly developed smart meter. Section 4 illustrates a case study that shows the practical usage of the results. Then, section 5 provides a thorough discussion of the research together with the results from the case study. Finally, section 6 concludes with final notes and recommendations for future research.

2. METHOD

The three-phase smart meter developed in this paper aims to optimize energy management in real-time by accurately measuring the import and export of electricity. Procedure in Figure 2 is begun with energy supply data recording, which makes tracing both energy production as well as energy consumption feasible. A validation of energy sources is also made in order to establish operational energy flows. The data are utilized in order to measure in real time a range of electric parameters regarding energy import as well as energy export, which are voltage (V), current (A), apparent power (S), active power (P), reactive power (Q), energy utilized (kWh), as well as power factor (PF). The system also incorporates advanced functionalities that entail frequency as well as power factor measurement as well as establishing overall harmonic distortion voltage as well as current [14], [15]. All these measures enable us to measure correctly energy exchange dynamics in the network. The gathered data are transferred into a relay control module, which is essential in fraud detection as well as in detecting nonconformities.

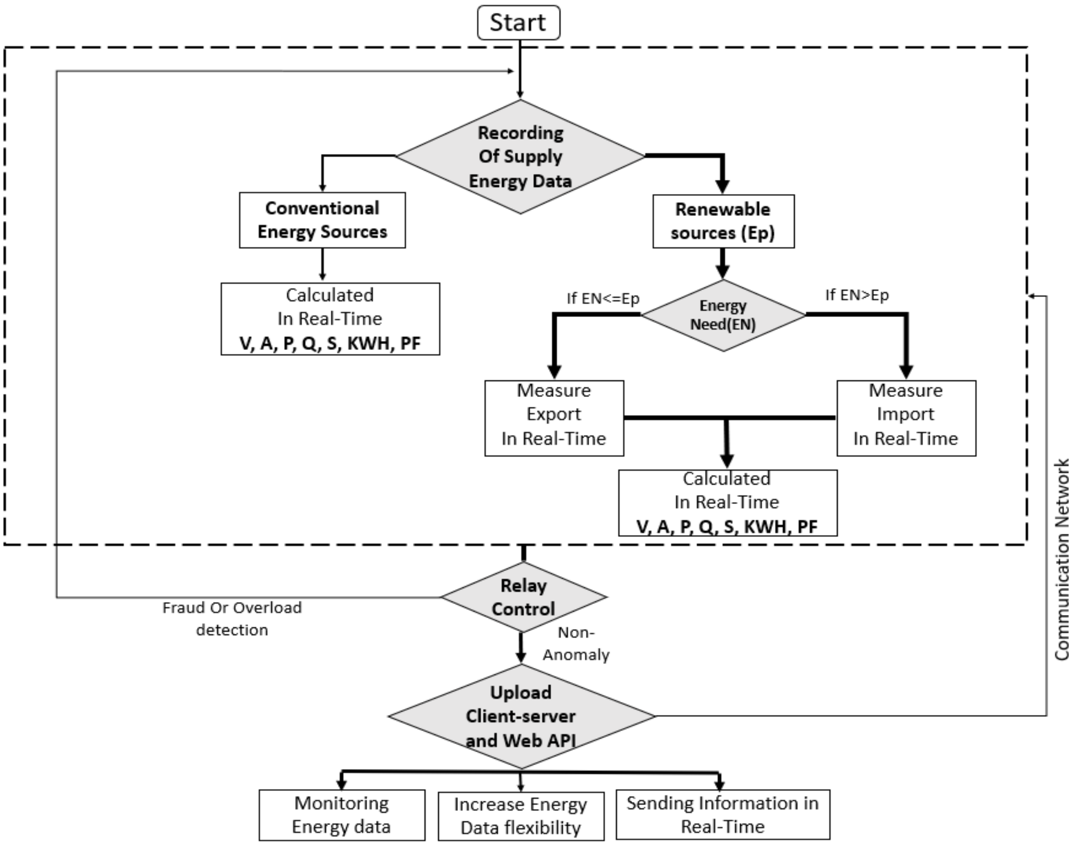


Figure 2. The process flowchart

A communications module then facilitates information transfer via a web interface as also a client-server. This allows energy data to be monitored in a remote form as well as promote energy flexibility by dynamically modulating energy flows according to demands. In addition, live data transfer supports anticipatory power grid management, which allows users as well as power grid owners to coordinate consumption with production variability.

3. DESIGN AND FUNCTION OF A SMART METER

The design of this scalable smart meter has been made using several key components to optimize electricity management, import, and export. These include a microcontroller HT5023 that ensures intelligent energy measurement management, a Voltage transformer EE19-005101, a Current transformer JD01 80A-400VAC-18VDV, an HTZ810V1.3 Bluetooth module, resistive attenuators for voltage input regulation, an SD card storage module, a real-time clock (RTC) ER14250, and an integrated power supply module. Figure 3 illustrates the architecture of this advanced system.

The smart meter (SM) measures and analyzes electrical data by sampling current and voltage via dedicated circuits connected to a microcontroller (MCU). The power calculation is shown in (1):

$$P = \frac{1}{T}\int_0^T v(t)i(t)\,dt * \cos(\varphi) \quad (1)$$

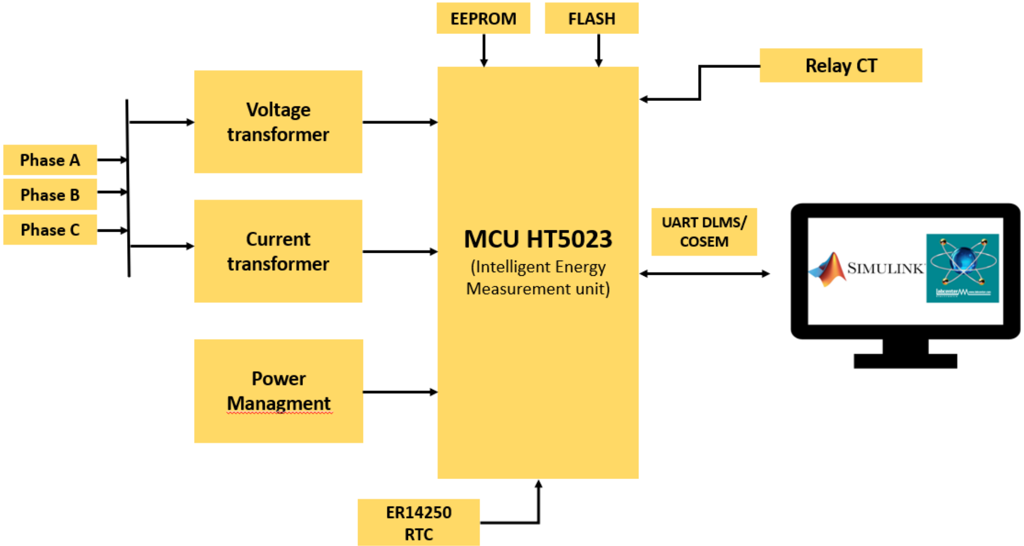


Figure 3. Smart meter architecture

These analogy signals are converted into digital, making it possible to calculate the active and reactive energy, the instantaneous power, and the energy quality parameters. The system manages its power supply through a combination of sources: a main power supply, a backup battery for minimal operation in case of failure, and a public switched telephone network (PSTN) battery to maintain the clock in real-time. A management module optimizes the transitions between these sources to guarantee service continuity. Finally, the microcontroller controls light emitting diodes (LEDs) to indicate the state of the system, an liquid crystal display (LCD) screen to display essential information (voltage, current, energy), and relays to activate or deactivate the electrical circuits according to the detected commands or events.

3.1. Voltage measuring instrument

The diagram in Figure 4 shows a voltage measurement circuit designed for the input of the HT5023 microcontroller. It makes it possible to convert the high voltages of a three-phase electrical network into signals compatible with the microcontroller. At the input, the phase (L) and the neutral (N) of the network first go through a set of protective resistors that form a voltage divider which lowers the network voltage to a safe and suitable level for the microcontroller. The resistors R1, R2, and R3, associated with the capacitors C1, C2, and C3, play a filtering and stabilizing role, eliminating rapid variations and unwanted noise on the signal. The output voltages thus obtained, VxP and VxN, are proportional to the voltages of the electrical network and are transmitted to the input of the HT5023 microcontroller for their analysis. Equation (2) ensures both the protection of the microcontroller against over voltages and the provision of a stable and accurate measurement signal.

$$v(t) = [V_m \sin(wt + \varphi_i)]$$
$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v(t)^2\, dt} \qquad (2)$$

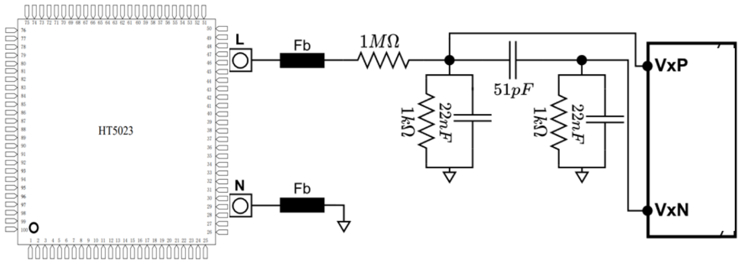


Figure 4. Voltage block diagram

3.2. Current measuring instrument

Figure 5 illustrates a current measurement circuit designed for the input of the HT5023 microcontroller. It makes it possible to convert the input currents (IA, IB, and IC) into voltage signals compatible with the capabilities of the microcontroller. For the IA phase, the IxP+ and IxPA- signals pass through the resistors R1, R2, R3 and R4, which act as protection and attenuation elements. Capacitors C2 and C3, connected in parallel with these resistors, provide signal filtering to eliminate unwanted noise and stabilize the output. The corresponding output voltages, VxP and VxN, are then transmitted to the microcontroller. This circuit thus makes it possible to condition the current signals coming from phases IA, IB, and IC into voltages adapted for the HT5023 microcontroller. Equation (3) guarantees an accurate measurement while protecting the microcontroller against sudden variations or noises in the input signal.

$$i(t) = [I_m \sin(wt + \varphi_i)]$$
$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i(t)^2\, dt} \quad (3)$$

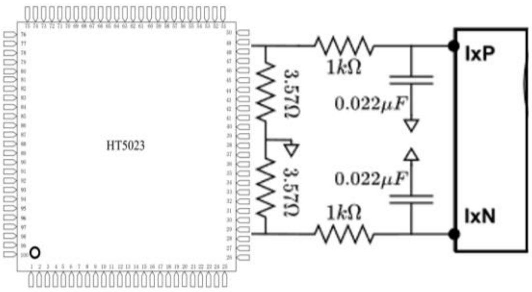


Figure 5. Current block diagram

3.3. Communication model

The exchange of data between data collection systems and measurement equipment using the companion specification for energy metering (COSEM) protocol is based on an interface model structured around the client/server paradigm. The measurement equipment, such as smart meters, play the role of servers. The tools that gather and sometimes count data are represented by one or more application processes (AP) in the model. As shown in Figure 6, communication is always between a client access point and a server access point: the client starts service requests, and the server converses by giving the required data. Here, a client access point may connect to one or more server access points at the same time, thus enabling the handling of multiple measuring devices together [16]. Similarly, a server access point can provide a reply to several client access points at once, thus assuring efficient two-way communication [17], [18].

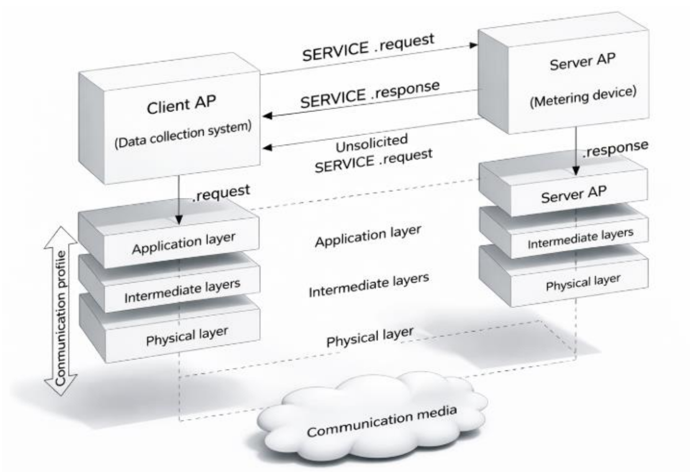


Figure 6. Infrastructure of the communication mechanism

The DLMS/COSEM communication protocol has a number of different standard security features that allow smart meters and communication systems to exchange data securely. There are two levels of authentication: the first involves very basic security (LLS) which is password, based, and the second involves high, level security (HLS) that offers challenge, response mechanisms. DLMS/COSEM uses AES-based encryption for the confidentiality of data [19]. Meanwhile, message integrity and security against replay attacks are ensured by cryptographic counters and security control fields, which are in accordance with the IEC 62056 standards [20], [21].

This service can be connection-oriented (connection established before the data exchange) or without connection (direct exchange without prior establishment). A smart meter can support several communication profiles, which allows it to adapt to various media and communication technologies (such as GPRS, LTE, or even LoRaWAN) [22], [23]. This flexibility ensures increased compatibility with the various infrastructures of the electrical networks and allows the exchange of data on different channels [24], [25].

3.4. Relay control and fraud detection mechanism

A proposed smart meter integrates management with three main states (Disconnected, Connected, and Ready for reconnection), offering a smooth and secure transition between these states thanks to manual, local, and remote commands to optimize the control, protection, and reliability of the energy network, especially in the context of the integration of renewable energies. The suggested fraud detection system in Figure 7 is built around sensor monitoring and real-time algorithmic analysis. In particular, it consists of:

- Current transformer (CT) sensors that detect abnormal current or bypassing,
- Hall effect sensors that check for magnetic tampering,
- Optical sensors that register unauthorized meter cover openings.

The sensor data obtained is subjected to a rule-based algorithm to pinpoint disordered usage patterns or signs of tampering. When it detects a possibility of fraud, the system sets an alarm, and the event is registered for verification.

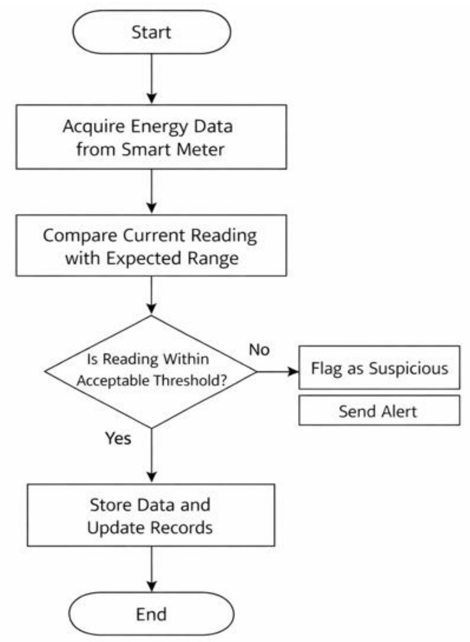


Figure 7. Fraud detection flowchart

4. CASE STUDY

This case study, illustrated in Figure 8, promotes smart metering in a grid-connected solar photovoltaic (PV) system consisting of panels with an on-grid inverter, a residential load (house), and a smart meter connecting to the public electricity grid. Any energy excess is exported to the grid, and any energy deficit (if the house load demand is greater than what is supplied from solar production) will be imported from the grid. In the experimental case study, the simultaneous import and export of energy at a single connection point is presented for illustrative purposes only. In a real net metering scenario, the energy flows are calculated as the net difference between import and export, which guarantees physical consistency. The diagram indicates that at some points in time, the system is exporting 4.71 kW to the grid and importing 2.35 kW, both of which are dynamic energy flows. The proposed three-phase measurement system uses an 80 A current transformer for experimental validation. The 80 A current transformer used in this work is selected specifically for the experimental prototype and laboratory validation of the proposed three-phase measurement system. This configuration targets low to medium current applications and does not represent a universal utility-wide deployment. For industrial or high-current distribution network applications, current transformers rated at hundreds of amperes can be used without changing the overall system architecture.

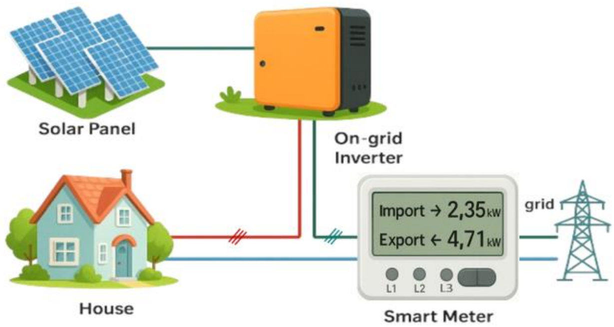


Figure 8. Framework

5. RESULTS AND DISCUSSION

In this investigation, we utilized two simulation environments, ISIS Proteus and MATLAB Simulink, to model and gather data from a grid-connected PV system. ISIS Proteus was employed to simulate the electronic portion of the system, including the connections between solar panels, the on-grid inverter, smart meter, house, and the electrical grid. This platform provided opportunities to test components' behaviors and confirm that the circuit operated as intended. MATLAB Simulink was used to model the overall performance of the energy system.

5.1. Error analysis and response time

The proposed smart meter has been tested in accordance with IEC 62053-21, demonstrating a maximum measurement error of ±0.5% over the rated current range, confirming compliance with international accuracy standards. Specifically, the error acceptance limits defined by the reference standard (NM06.4.001) for different phase and power factor conditions are summarized in Table 1.

Table 1. The percentage error acceptance limit is determined by the Moroccan Standard, NM06. 4. 001

Current	Phases	Power Factor	Basic Errors limit
5% Ib	A-B-C	1	-0.0088
10% Ib	A-B-C	1	-0.0099
10% Ib	A-B-C	0.5	+0.0650
Ib	A-B-C	1	-0.0222
Ib	A-B-C	0.5	-0.0388
Imax	A-B-C	1	-0.0589
Imax	A-B-C	0.5	-0.0104

In Figure 9, it is evident that the end-to-end latency results primarily correspond to the data acquisition and transmission sequence, where each step depends on the previous one. Specifically, the whole process time is made up of the identification and measurement phases (about 450 ms), the digital signal processing operations (around 60 ms), the encoding and serialization of the data at the 9600 baud communication rate (75 ms), the transmission through the gateway and the communication network (approximately 90 ms), and finally the processing operations performed on the server side (about 25 ms). The entire system latency is simply the sum of the time that each of these steps takes.

$$\boldsymbol{L_{tot} = \frac{1}{f_s} + + L_{DSP} + \frac{N_b}{R_b} + L_{net} + L_{Server}} \quad (1)$$

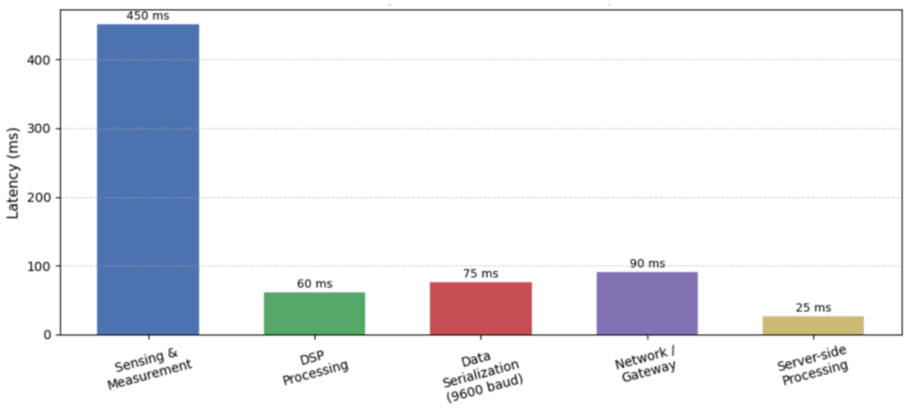
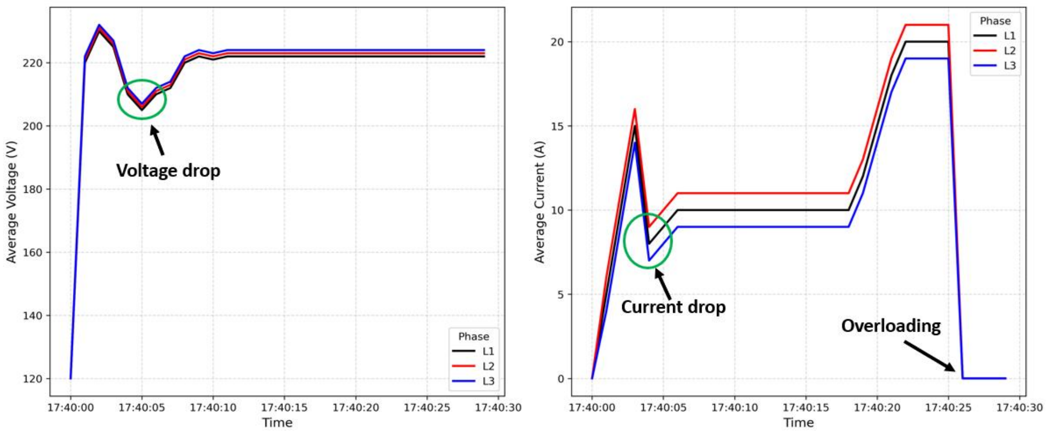


Figure 9. Latency breakdown of the data acquisition chain

5.2. Voltage and current data performance

In Figure 10(a) we observed that the voltage starts around 120 V, then rises quickly to about 230 V, where it remains stable with some small variations. This indicates that the power is working normally. In Figure 10(b) current It is noted that the current begins at 0 A, then gradually increases up to 10 A, before varying and reaching a peak at 20 A. However, at the end, the current drops abruptly to 0 A. The cutoff relay integrated into the meter accounts for this sudden drop. It enables the disconnection of power if the maximum allowed power is exceeded, thereby facilitating an automatic cutoff to prevent overloading. In summary, the voltage remains stable, but the current varies according to demand and ends up being cut when the power exceeds the authorized limit. This shows that a protection mechanism is in place to avoid overloads and ensure the proper functioning of the network.



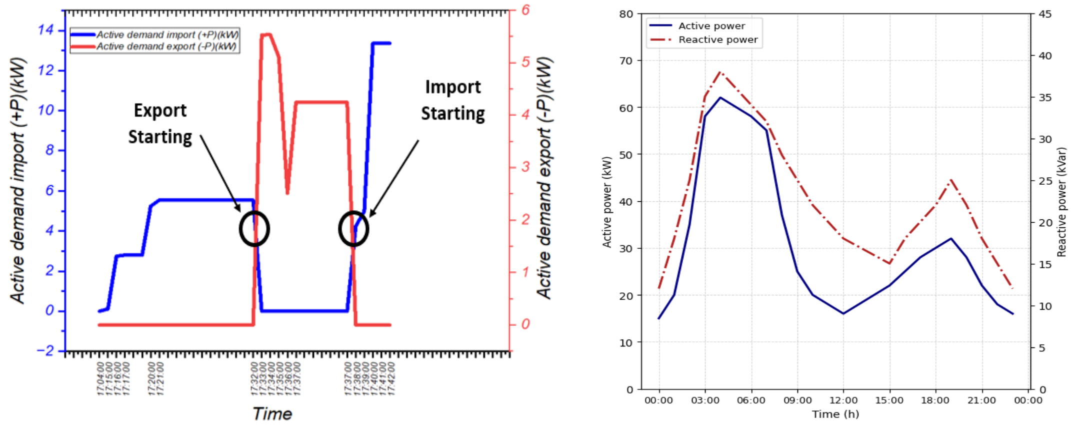
(a) (b)

Figure 10. Variation of (a) voltage and (b) current depending on the time

5.3. Hours profile import and export

In Figure 11(a), we can follow the dynamics of energy flows measured in real-time by the smart meter and highlight the variation of imported and exported energy at different periods, thus illustrating the interactions between a production system and an energy consumption system with the electrical network. The import curve, located to the left of the ordinate axis, indicates the amount of energy taken from the grid by the system to satisfy the demand, and to the right, we have the export curve, which indicates the energy injected into the grid due to the availability of a surplus of production in particular in the presence of a generator or renewable sources.

Figure 11(b) shows the evolution of the import and export of active and reactive energy over time. The horizontal axis represents time, while the vertical axes indicate the amount of energy measured in kilowatt-hours. It is observed that the import of active energy (blue curve) gradually increases, which means that the system consumes more energy over time. At the same time, the active energy export (red curve) starts at a low level, and then increases towards the end, indicating a return of energy to the grid. Regarding reactive energy, the blue curve shows a relatively stable import, while export (curve not visible or very low) remains negligible.



(a) (b)

Figure 11. Hours profile import and export (a) active power demand and (b) active and reactive energy demand

5.4. Comparative analysis with other studies

In contrast to most studies, this paper takes three aspects of a low-cost IoT-based smart meter: measurement accuracy, system latency, and standards-based performance evaluation. Unlike [16], [18], and [20], this paper not only provides a quantitative error analysis but also thoroughly links it to the IEC accuracy requirements. The proposed solution differs from the ones that are focused on energy quality, like [15], in that it aims at the real-time energy metering of the end user with low latency; the comparison is summarized in Table 2.

Table 2. Comparative analysis

Authors	Latency Evaluation	3-Phase	PQ Monitoring	DLMS/COSEM	Bidirectional Energy	Control Relay
[1]	No	No	No	No	No	No
[2]	No	Yes	Yes	No	No	No
[3]	No	No	No	No	No	No
[4]	Yes	Yes	Yes	No	No	No
[5]	Yes	No	Yes	No	No	No
[6]	Yes	No	No	No	No	No
[7]	Yes	No	No	No	No	No
This Work	Yes	Yes	Yes	Yes	Yes	Yes

6. CONCLUSION

This article presented a low-cost IoT-based smart meter adapted to the Moroccan electricity grid, capable of measuring bidirectional energy, DLMS/COSEM communication, and controlling the operation of relays for automated energy management. The experimental results demonstrate a maximum measurement error of less than ±0.5% and an end-to-end latency of approximately 700 ms, confirming the relevance of the system for the monitoring and control in near real time of imported and exported energy. A comparative analysis with existing smart meters and the literature shows that, unlike many commercial or academic solutions, the proposed system combines inexpensive hardware, IEC-oriented accuracy, low latency, and integrated fraud detection, while supporting flexible integration with residential renewable sources. These characteristics highlight its potential as a practical solution to improve network observability and energy efficiency.

Future work will address the actual field deployment of smart meters under real operating conditions, which include different environmental and load scenarios, to the performance, reliability, and adaptability of the smart meters in practical grid and renewable energy environments.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Alhussein Bagayogo	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	
Omar Kabouri	✓		✓	✓			✓			✓	✓			✓
Aboubakr El Makrini		✓				✓		✓	✓	✓	✓	✓		
Mohamed Azeroual														
Hassane El Markhi					✓		✓			✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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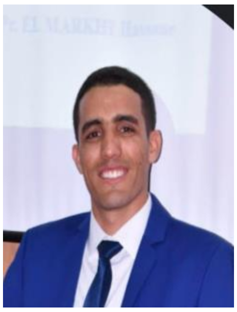
BIOGRAPHIES OF AUTHORS

Alhussein Bagayogo obtained an engineering degree in intelligent systems and energy at the Faculty of Science and Technology in Fez, Sidi Mohamed Ben Abdellah University, in 2023. He is currently a doctoral student in electrical engineering (intelligent systems, Laboratory of Geosources and Renewable Energies) at the Faculty of Science and Technology of Sidi Mohamed Ben Abdellah University. His research interests include power systems, renewable energy, and artificial intelligence. He can be contacted by e-mail at alhussein.bagayogo@usmba.ac.ma.

Omar Kabouri obtained an engineering degree in intelligent systems and energy at the Faculty of Science and Technology in Fez, Sidi Mohamed Ben Abdellah University, in 2023. He is currently a doctoral student in electrical engineering (intelligent systems, Laboratory of Geosources and Renewable Energies) at the Faculty of Science and Technology of Sidi Mohamed Ben Abdellah University. His research interests include power systems, renewable energy, and artificial intelligence. He can be contacted by e-mail at omar.kabouri@usmba.ac.ma.

Aboubakr El Makrini received his engineering degree in electrical engineering from Hassan II University, Casablanca, in 2002. In 2018, he obtained his Ph.D. degree in electrical engineering at the Faculty of Science and Technology, Sidi Mohamed Ben Abdellah University. His primary research areas include electrical grids, power systems, and renewable energy systems. He may be reached by e-mail at aboubakr.elmakrini@usmba.ac.ma.



Mohamed Azeroual received his engineering degree in embedded systems and telecommunications in 2016 from the National School of Applied Sciences, Tangier, Morocco. In 2016, he joined the Faculty of Science and Technology, Sidi Mohamed Ben Abdellah University, Fez, to pursue his Ph.D.. His fields of interest include renewable energy, power electronics, fault location, and smart grids. Dr. Azeroual is an assistant professor at the High School of Technology, University of Moulay Ismail, Meknes, and has been a reviewer for various international journals and conferences. He can be reached by e-mail at mohamed.azerouall@usmba.ac.ma.

Hassane El Markhi received the engineering degree in electrical engineering from Hassan II University, Casablanca, in 1995. He was awarded a Ph.D. degree on fault location in electrical power distribution systems and enhancement of a grid-connected DFIG-based wind turbine system at Sidi Mohamed Ben Abdellah University, Fez, in 2015. He is currently a professor in the Department of Electrical Engineering at the Faculty of Science and Technology, Fez, Morocco. His core research areas are smart grids, fault location, and renewable energy systems. He may be reached by e-mail at hassane.elmarkhi@usmba.ac.ma.