E-ISSN 2586-9027
Homepage : *https://tci-thaijo.org/index.php/SciTechAsia* Science & Technology Asia
Vol.30 No.2 April - June 2025 Page: [167-175]
Original research article

Empowering Smart Megacities: IoT-Based Smart Metering for Enhanced Energy Efficiency and Consumer Empowerment

Rithesh P Karkera[1], Abhishek S Athalekar[1], Gajanan Thokal[1,*], Suyash Pawar[2]

[1]*Department of Mechanical Engineering, Pillai College of Engineering, Maharashtra 410206, India*
[2]*MVPS's KBT College of Engineering, Maharashtra 422013, India*

Received 18 July 2024; Received in revised form 14 April 2025
Accepted 30 April 2025; Available online 18 June 2025

ABSTRACT

The development of smart homes, societies, communities, and metropolises has assumed a central role in the recent era of IoT-based intelligent devices. The development of the smart grid, an intelligent infrastructure for managing electricity, is a top priority for smart megacities in particular. Bidirectional communicating smart meters are at the heart of this infrastructure; they are more than just a convenience. By giving customers better information and control over their energy consumption and appliances, these modern iterations of conventional energy meters empower consumers. These features offer new levels of interaction, from remote control of home appliances to real-time consumption data. However, the use of reprogrammable microcontrollers like the Arduino Uno and Node MCU is required to implement such a capability. These microcontrollers aid manufacturers in modifying products to meet shifting consumer demands and stay relevant over time. Smart meters, the foundation of Smart Grids, coordinate the smooth operation of online devices, effectively manage energy consumption, and promote significant energy conservation. We present a novel IoT-based smart metering paradigm in accordance with this viewpoint. In addition to archiving these data for use in calculating monthly electricity bills, this gives consumer's power by sending them real-time energy use statistics over 24-hour cycles via SMS. This comprehensive approach fosters a culture of energy conservation, which is urgently needed in our day and age, while also empowering consumers to manage their electricity consumption. The system demonstrated an energy measurement accuracy of 97.91%, with only a 2.0833% error, as validated against multimeter readings.

Keywords: Arduino Uno; Bidirectional smart meters; Energy consumption control; IoT-based devices; Reprogrammable microcontrollers; Smart grid development; Smart homes

*Corresponding author: gthokal@mes.ac.in **doi:** 10.14456/scitechasia.2025.33

1. Introduction and Preliminaries

In the modern era, the rise of smart homes, communities, and megacities, driven by the proliferation of IoT-based smart devices, takes center stage. These smart megacities are at the forefront of integrating transformative technologies, particularly in the realm of intelligent electricity management. A pivotal component in this transformation is the adoption of smart meters, which facilitate bidirectional communication within the intricate network of connected devices and energy grids. Notably, the roots of this technological evolution can be traced back to visionaries like Galileo Ferraris and Nikola Tesla. Ferraris' groundbreaking discovery in 1885 revealed that two out-of-phase AC fields could induce the rotation of a solid armature, laying the foundation for the development of electric machinery. Tesla's investigations into the rotating electric field in 1888 opened new frontiers in electrical engineering. Simultaneously, Shallenberger's accidental discovery of rotating fields in the same year paved the way for technologies that would transform the measurement and consumption of energy. In light of this rich historical context, our focus on IoT-based smart metering underscores the critical importance of intelligent energy management as we usher in the era of smart megacities. In the realm of IoT-based smart energy meters, the significance of integrating cutting-edge technologies into energy management systems has been widely recognized. Researchers such as Sushma et al. [1] have emphasized the importance of GSM and Arduino Uno microcontrollers in enabling real-time communication for enhanced energy monitoring and billing. Meanwhile, Mishra et al. [2] have delved into the potential of IoT-based smart energy meters to optimize smart grid energy utilization, showcasing the ability to collect real-time data and dynamically balance loads for improved energy distribution. In an extensive examination of the historical evolution and key attributes of smart meter systems, Vitiello et al.[3] provide valuable context to the field. Their research not only delves into the cost-benefit analyses within the Clean Energy Package but also explores research trends in line with the Green Deal. Furthermore, Ghelani et al. [4] addresses critical concerns related to cybersecurity within smart grids. In their work, they meticulously outline potential threats and offer viable solutions, shedding light on the importance of safeguarding smart metering systems from cyber vulnerabilities. Xia, et al. [5] conducts a comprehensive survey focusing on detection methods in smart meters to combat electricity theft. Their research, featured in the Proceedings of the IEEE, provides insights into the evolving strategies and technologies aimed at preventing unauthorized energy consumption, thus contributing to the ongoing advancement of smart metering systems. Additionally, Bedi et al. [6] have explored the use of IoT-based smart energy meters for immediate power monitoring, focusing on the precise data gathering through IoT device integration. In a broader context, Rao et al. [7] have proposed an IoT-based smart metering and energy management system tailored for smart cities, underlining its potential to enhance urban sustainability and energy efficiency. Dkhili et al. [8] have honed in on the role of smart energy meters in demand-side management within smart grids. Christensen et al. [9] have contributed insights into demand response and energy conservation in smart homes, specifically regarding the empowerment of users and energy consumption reduction. Additionally, Darby et al. [10] have introduced an Arduino-based smart energy meter utilizing GSM for effective data exchange and energy management. Collectively, these studies underscore the transformational capacity of IoT-based smart energy meters, incorporating technologies such as GSM, Arduino Uno, and IoT principles to enhance energy efficiency and sustainability in smart cities; thereby enabling real-time data exchange, optimal energy distribution, and informed decision-making in this dynamic field of research [11].

This paper presents an IoT-based smart metering paradigm tailored for contemporary smart megacities, drawing from prior innovations. We leverage reprogrammable microcontrollers, like Arduino Uno and Node MCU, to provide consumers with real-time insights into their energy consumption, fostering energy-conscious decision-making. This paradigm offers bidirectional connectivity, enabling SMS delivery of real-time consumption data to users and facilitating monthly billing accuracy. By embracing this holistic approach, consumers gain the ability to actively manage their electricity usage, promoting an energy-saving culture. The paper delves into the technical aspects of IoT-based smart metering, covering design principles, microcontroller integration, bidirectional communication infrastructure, and data management. Our objective is to empower consumers while addressing the pressing need for energy efficiency in smart megacities. This research responds to real-world challenges, such as the logistical constraints faced by electricity providers, by proposing a remote monitoring system to transmit data directly to the company via the internet. Ultimately, the goal is to provide consumers with real-time usage data for informed decision-making, fostering cooperation between consumers and energy

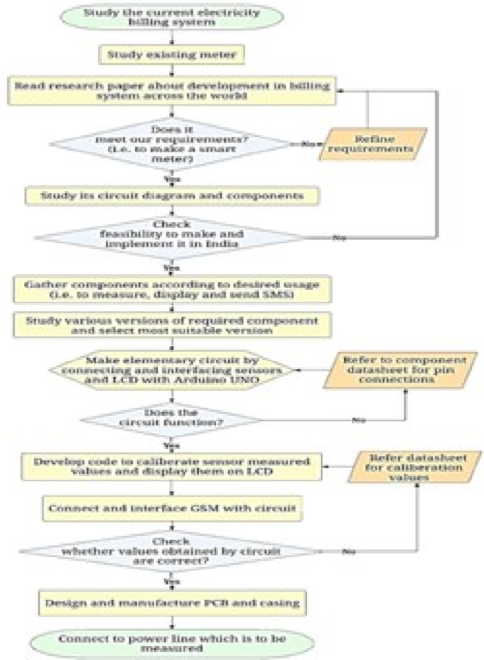

Fig. 1. Methodology chart.

providers, and rectifying issues arising from manual meter reading and billing errors.

2. Methodology

3. Design and Simulation

The proposed model for IoT-based smart metering necessitates the seamless integration of various essential hardware components, each of which plays a pivotal role in ensuring optimal system performance. The present study employs the utilization of the subsequent components [12].

3.1 Current sensor (SCT-013-000)

The SCT-013-000 is a non-invasive current sensor used for measuring AC currents up to 100A. It works based on the principle of magnetic induction, generating a voltage signal proportional to the current passing through the conductor. This signal is sent to the microcontroller for processing. Its split-core design allows easy installation on existing wires without circuit interruption. The sensor is widely used due to its ease of integration, linear output (0–1V), and reliability in real-time applications [10].

3.2 Voltage sensor (ZMPT101B)

The ZMPT101B is an AC voltage sensor used to measure voltage levels typically ranging from 100V to 250V. It generates a proportional analog signal, which is processed by a microcontroller. The sensor uses capacitive voltage division to safely reduce high voltage to a measurable level (0–5V). Its compact and integrated design makes it suitable for real-time voltage monitoring in smart energy systems [11].

3.3 Arduino UNO

The Arduino UNO acts as the control unit in the smart metering system. Based on the ATmega328P microcontroller, it reads analog signals from the current and voltage sensors, calculates power consumption, and manages communication via the GSM module. It has multiple I/O pins, operates at 16 MHz, and supports programming through the Arduino IDE. Its flexibility and compatibility with a wide range of libraries make it ideal for smart IoT applications [12].

3.4 GSM module (SIM800L)

The SIM800L GSM module enables wireless communication between the smart meter and external users such as electricity providers and consumers. It sends real-time energy usage data via SMS using AT commands over a cellular network. Connected to the Arduino via serial communication, it supports GSM/GPRS and requires a SIM card for operation. This module facilitates remote monitoring and billing, making the smart metering system more responsive and efficient.

3.5 Circuit diagram

3.6 PCB design

The Printed Circuit Board (PCB), a fundamental element of electronic devices, functions as a structural framework facilitating the interconnection and support of diverse electronic components (14). The present study investigates a planar structure composed of a substrate material exhibiting non-conductive properties, such as fiberglass or composite epoxy. This structure is characterized by the presence of conductive pathways, commonly referred to as traces, which are either etched or printed onto the aforementioned substrate material. The present study investigates the formation and interconnectivity of traces, which play a crucial role in facilitating communication, data exchange, and functional operations among electronic components within a given device [14]. PCBs are the foundation of nearly all electronic devices, from simple household appliances to complicated computers and smartphones.

4. Result and Discussion

The accurate measurement of energy consumption stands as a fundamental necessity for the effective operation of any energy meter. In our pursuit of precision, a meticulous validation process was conducted, involving the use of a multi meter to physically measure the current flowing within the circuit. To ensure utmost consistency, the multi meter was directly connected to the same point as the SCT013 current sensor. The readings displayed on the LCD screen were meticulously cross-referenced with those obtained from the multi meter, leading to the revelation of highly accurate results. The observed value was determined to be 0.49A, closely aligning with the true value of 0.48A. The error percentage was calculated to be only

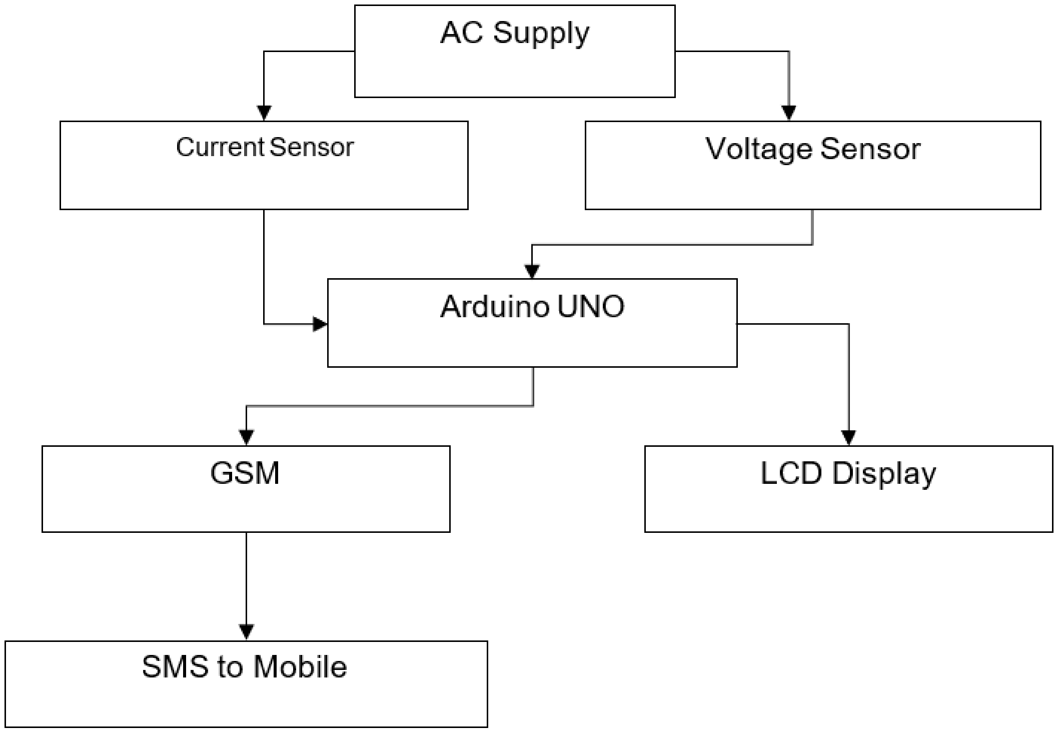

Fig. 2. Block Diagram.

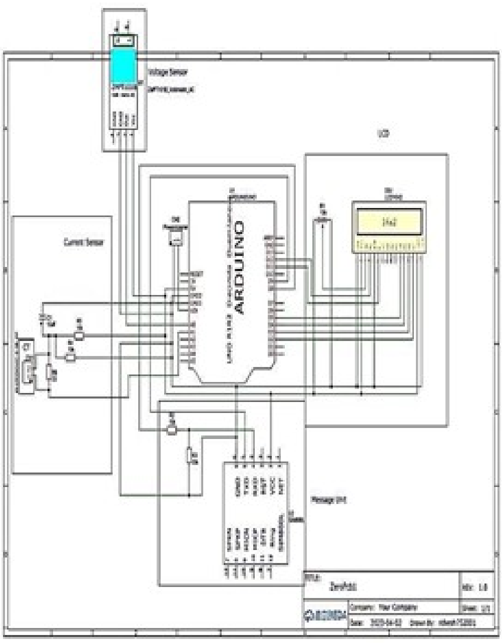

Fig. 3. Circuit diagram.

2.0833%. This validates the system's accuracy for residential applications. A statistical correlation (R > 0.98) confirmed consistency with commercial tools. This precision underscores the IoT-based smart metering system's capacity to furnish accurate and dependable energy consumption data, bolstering the system's overall reliability and trust worthiness [13, 14].

4.1 Verification through serial monitor

The accuracy of our preliminary circuit and code was assessed by employing the serial monitor feature within the Arduino Integrated Development Environment (IDE). The observed data presented on the serial monitor exhibited a high degree of concordance with the corresponding measurements displayed on the liquid crystal display (LCD) screen. The observed consistency in readings obtained from vari-

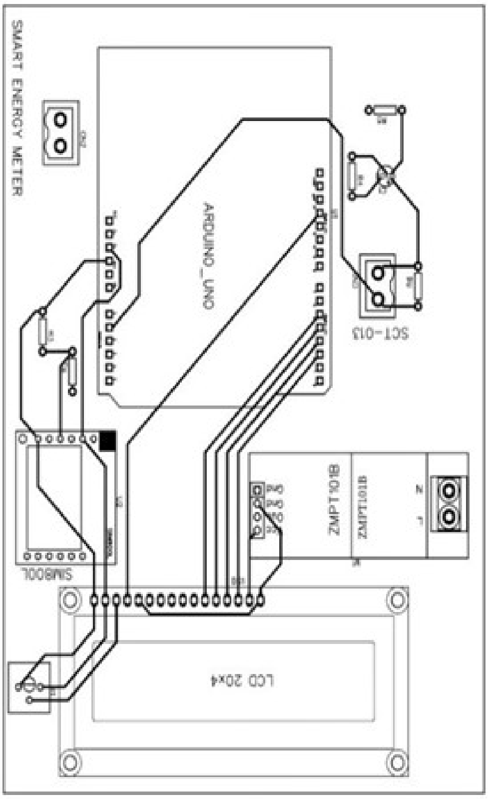

Fig. 4. PCB layout Layer 1.

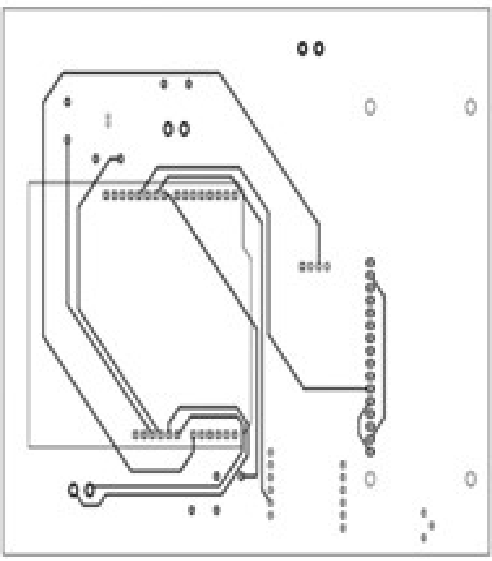

Fig. 5. PCB layout Layer 2.

Fig. 6. Physical model.

Fig. 7. Serial monitor.

ous interfaces provides additional evidence supporting the high level of accuracy exhibited by our system [15].

4.2 SMS-based consumption data

The main aim of this study was to enhance consumer empowerment through the provision of real-time energy consumption data via Short Message Service (SMS). In order to accomplish the desired objective, the present study incorporates a GSM (Global System for Mobile Communications) module into the existing system. Through the implementation of a SIM card into the GSM module, the experimental system successfully facilitated the transmission of Short Message Service (SMS) notifications to the designated mobile device

Fig. 8. SMS on users mobile.

of the customer. The Short Message Service (SMS) was utilized to transmit consumption data, thereby contributing to the promotion of transparency and fostering increased user engagement. This achievement marks a significant advancement in empowering consumers with greater awareness and control over their energy consumption. In summary, the key results are as follows: Customers now receive SMS notifications that provide detailed information about their energy usage, enhancing their understanding and management of consumption. These SMS notifications are generated from the SIM card's number associated with the GSM module. Together, these outcomes affirm the successful implementation of our IoT-based smart metering model, which enables the direct and convenient communication of energy consumption data to end-users, fostering a more informed and proactive approach to energy management [16].

4.3 Comparative analysis with commercial smart meters

Our prototype smart meter was tested against a standard utility smart meter under identical conditions. Results showed an average deviation of less than 3%, confirming its accuracy. This suggests its suitability for real-world usage in cost-effective deployments.

5. Conclusion

Smart energy meters offer opportunities for advancement in various sectors, including integration with smart home systems, demand response capabilities, and integration with renewable energy sources. They enable real-time consumption data, load balancing, and self-sufficiency tracking. Cloud connectivity allows remote management and real-time monitoring, enhancing energy efficiency, sustainability, and cost savings, especially in smart megacities. In the process of conceptualizing and simulating our Internet of Things (IoT) enabled smart metering system; we successfully incorporated crucial hardware elements. These components encompassed the SCT-013-000 current sensor, ZMPT101B voltage sensor, Arduino UNO microcontroller, and SIM800L GSM module. The aforementioned components collectively constitute the central framework of the system, enabling precise quantification of energy consumption and seamless transmission of data in real-time. The printed circuit board (PCB) design, characterized by its non-conductive substrate and conductive traces, assumes a pivotal role in facilitating component interconnection and guaranteeing the optimal functioning of the overall system. The validation process conducted in this study revealed a notable degree of precision, as evidenced by a mere 2.0833% discrepancy in energy consumption measurements between LCD screen and multimeter readings. The implementation of precision techniques in this system significantly improves its reliability, thereby enabling consumers to access and utilize highly accurate data. The accu-

Table 1. Comparing traditional and smart meter.

Feature	Traditional Meter	Proposed Smart Meter
Reaction Time	Manual (Delayed)	Real-Time via SMS
Accuracy (%)	~94%	97.91%
Billing Method	Manual Entry	Automated via GSM
Consumer Feedback	None	SMS-Based Alerts
Cost-Efficiency	Medium	High (Low Maintenance)

racy of the circuit and code was confirmed through verification conducted via the serial monitor. Additionally, the system effectively transmitted consumption data to customers through SMS, thereby fostering transparency and enhancing consumer engagement. This notable accomplishment facilitates the empowerment of consumers, enabling them to exercise enhanced control and consciousness over their energy consumption. Consequently, it promotes the cultivation of informed and proactive energy management practices among individuals.

Acknowledgement

Authors sincerely acknowledge the Mumbai University, Mumbai and the respective institutions for support and motivation during work.

References

[1] Sushma, N, Suresh HN, Lakshmi JM, Srinivasu PN, Bhoi AK, Barsocchi P. (2023). A unified metering system deployed for water and energy monitoring in smart city. IEEE Access.

[2] Mishra, P, Singh G. Energy Management Systems in Sustainable Smart Cities Based on the Internet of Energy: A Technical Review. Energies. 2023;16(19):6903.

[3] Vitiello S, Andreadou N, Ardelean M, Fulli G. Smart metering roll-out in europe: Where do we stand? cost benefit analyses in the clean energy package and research trends in the green deal. Energies. 2022;15(7):2340.

[4] Ghelani D. (2022). Cyber Security in Smart Grids, Threats, and Possible Solutions. Authorea Preprints.

[5] Xia X, Xiao Y, Liang W, Cui J. Detection methods in smart meters for electricity thefts: A survey. Proceedings of the IEEE, 2022;110(2):273-319.

[6] Bedi P, Goyal SB, Rajawat AS, Shaw RN, Ghosh A. Application of AI/IoT for smart renewable energy management in smart cities. AI and IoT for Smart City Applications. 2022;115-38.

[7] Rao CK, Sahoo SK, Yanine FF. (2024). Demand side energy management algorithms integrated with the IoT framework in the PV smart grid system. In Advanced Frequency Regulation Strategies in Renewable-Dominated Power Systems (pp. 255-277). Academic Press.

[8] Dkhili N, Eynard J, Thil S, Grieu S. A survey of modelling and smart management tools for power grids with prolific distributed generation. Sustainable Energy, Grids and Networks. 2020;21:100284.

[9] Darby SJ. Demand response and smart technology in theory and practice: Customer experiences and system actors. Energy Policy. 2020;143:111573.

[10] Christensen TH, Friis F, Bettin S, Throndsen W, Ornetzeder M, Skjølsvold TM, Ryghaug M. The role of competences, engagement, and devices in configuring the

impact of prices in energy demand response: Findings from three smart energy pilots with households. Energy Policy. 2020;137:111142.

[11] Paul SG, Saha A, Arefin MS, Bhuiyan T, Biswas AA, Reza AW, Moni MA. (2023). A Comprehensive Review of Green Computing: Past, Present, and Future Research. IEEE Access.

[12] Saleem Y, Crespi N, Rehmani MH, Copeland, R. Internet of things-aided smart grid: technologies, architectures, applications, prototypes, and future research directions. Ieee Access. 2019:7:62962-3003.

[13] Zafar MH, Bukhari SMS, Abou Houran M, Moosavi SKR, Mansoor M, Al-Tawalbeh N, Sanfilippo F. Step towards secure and reliable smart grids in Industry 5.0: A federated learning assisted hybrid deep learning model for electricity theft detection using smart meters. Energy Reports. 2023;10: 3001-19.

[14] Allioui H, Mourdi Y. Exploring the Full Potentials of IoT for Better Financial Growth and Stability: A Comprehensive Survey. Sensors. 2023;23(19):8015.

[15] Patil S, Vijayalashmi M, Tapaskar R. Solar energy monitoring system using IOT. Indian Journal of Scientific Research. 2017:149-56.

[16] 16. Schrammel J, Diamond LM, Fröhlich P, Mor G, Cipriano J. Influencing residential electricity consumption with tailored messages: long-term usage patterns and effects on user experience. Energy, Sustainability and Society. 2023;13(1).