Design and Application of an in Situ IoT-Based Energy Monitoring System for Use in Real Time Building Modeling

Aaron Farha
Student Member ASHRAE

Jonathan Ore, Ph.D.
Member ASHRAE

Elias N. Pergantis
Student Member ASHRAE

Lokesh Sriram
Student Member ASHRAE

Davide Ziviani, Ph.D.
Member ASHRAE

Eckhard A. Groll, Dr. Eng.
Fellow ASHRAE

ABSTRACT

The residential building end-use sector represents one of the world's most significant CO_2 producers and energy consumers. As principal endpoints of an aging power system within the US, these consumers are faced with compounding reliability concerns and necessitate innovative solutions to address ever-increasing power demands. To mitigate these issues, novel systems need to be developed to minimize buildings' overall impact on the grid in a real-time approach. One such improvement is to retrofit existing buildings with an energy monitoring system which can support such a strategy. In this paper, a design for an IoT based smart monitoring system is developed to achieve reduced overall energy consumption. Economical, low-power current transformer (CT) sensing units are implemented inside an AC load panel within a residential home to monitor the heaviest electrical loads, focusing efforts on the HVAC system and the heat-pump driven water heater. Data from these sensors are collected via IoT microcontroller units (MCUs) and maintained within a real-time database on an in-situ server. This could then be used for "faster than real-time" modeling of the electrical loads of a residential building.

INTRODUCTION

Energy consumption of residential and commercial buildings has been increasing steadily over the last several decades and as a sector is often noted as one of the largest global producers of CO_2 (Allouhi et al, 2015). These issues only become more prevalent due to aging power grid systems, such as in the United States which was only recently rated as a C- by the

Aaron Farha is a PhD candidate at Purdue University, West Lafayette, IN. **Jonathan Ore** is a research engineer at Emerson, PA. **Elias N. Pergantis** is a PhD candidate at Purdue University, West Lafayette, IN. **Lokesh Sriram** is an undergraduate student in the school of Mechanical Engineering at Purdue University, West Lafayette, IN. **Davide Ziviani** is an Assistant Professor at Purdue University, West Lafayette, IN. Dr. **Eckhard A. Groll** is the William E. and Florence E. Perry Head of Mechanical Engineering, and the Reilly Professor of Mechanical Engineering at Purdue University, West Lafayette, IN.

American Society of Civil Engineers (ASCE, 2017). A monitoring system distributed across many buildings can provide a solution towards better predicting the load on the power system thus aiding in reducing potential shutdowns and improving overall system reliability.

Currently, most buildings across the United States have energy monitoring systems that only their local energy supplier can access. End users can solely see their monthly energy consumption when service providers send a bill for usage. A distributed system which allows consumers to view their usage in real time can have a significant impact on their overall energy consumption (Barsocchi et al, 2014) since it enables them to understand how their daily habits can impact the building's energy profile. Currently, many systems exist on the market which enables users to view their power usage in real time, but these systems are often expensive and require monthly subscriptions to view the data. Implementing a low-cost internet of things (IoT) system with existing sensors and an inexpensive micro-controller will thus be the focus of this paper.

There are several IoT system solutions which can be implemented within an existing building, such as with a renewable energy system grid (Kabalci et al, 2013), a distributed network of ZigBee sensors (Kim et al, 2011), and even with an ESP8266 and multiple CT sensors (Chooruang et al, 2018). Additionally, these papers also provide various web services such that an end user can quickly access their energy consumption data at a moment's notice (Barsocchi et al, 2014), (Kabalci et al, 2013), and (Kim et al, 2011). Non-invasive systems also exist with wireless capabilities such that a user can very simply install sensors to monitor their building energy usage (Hashizume et al, 2012). The design presented in the current study will take advantage of an ESP32 microcontroller monitoring data from the PZEM-004T power sensing modules and can wirelessly communicate this data to an in-situ server.

The instrumentation can allow for a multitude of different control strategies as well. The power correction factor was controlled using a digital microcontroller driving a capacitor bank in (Kabir et al, 2017) to reduce the impact of inductive load responses which can occur very frequently for larger appliances such as an HVAC system's compressor. A real-time monitoring system can also be used to control an HVAC system as in (Yoon et al, 2014) where the dynamic response of retail energy pricing was used to reduce the peak demand of the power grid, Yoon et. al. also provide a simulation of the home under their case study in Simulink to test their controllers. A simpler control strategy is to shut off certain parts of a building which are not using any power to reduce standby power loss (Al-Arif et al, 2011) and (Devadhanishini et al, 2019). The goal of the present study is to develop the infrastructure by which these control strategies could be implemented as a retrofit to an existing home.

The DC Nanogrid House is a 2-story, 1920's era home situated on the West Lafayette campus of Purdue University. It houses 3 graduate students who live and work within the building, thus providing accurate loading for study and can be designated as a *living laboratory.* Several renovations have been incorporated to increase the overall performance of the DC Nanogrid House, including but not limited to the following: improved insulation, waterproofing of the basement, and triple pane window replacement. The key focus of the project is the retrofitted DC Nanogrid architecture which serves to convert AC power from the electric grid to DC power at a singular point for more efficient distribution to key appliances that can run on DC power (Ore, 2021).

Another key aspect of the DC Nanogrid House is the clever implementation of low-cost IoT capable sensors for precise monitoring of the building, named the “Eco-IoT DAQ” (Ore et al, 2020). This includes the measurement of temperature, pressure, humidity, etc. across each room controlled by a Raspberry Pi and sent to an in-situ server. This allows for several unique controls-based applications within the house related to both the thermal and electrical management of the DC Nanogrid House. For instance, precise temperature and humidity measurements in each room could be used to maintain human comfort at optimal energy consumption levels.

The present work seeks to add another data source: power consumption of the AC load panels. Obtaining precise measurements across the different appliances and rooms of the house allows for a more accurate model of the building to be obtained, thus allowing for faster than real-time simulations of the DC Nanogrid House for predictive loading. Presented here is a prototype IoT based system utilizing the PZEM-004T power monitoring sensor and will be compared to a similar IoT based device, the IoTaWatt home power monitoring system.

Motivation of pzem modules

The present investigation seeks to continue the theme of low-cost sensor applications within a residential home and the relevant design necessary to implement these solutions. To this effect, the use of PZEM-004T AC power modules combined with current transforming (CT) sensors allows for an effective method of data collection and evaluation. Table 1 provides the details of the sensing capability of these modules for a multitude of power measurements. With nearly all measurement abilities, the modules have an accuracy rating of 0.5% error which is well within acceptable bounds considering per unit costs are as low as $4.59 USD through some vendors. This is often coupled with a clamp-style CT ring which then provides a non-invasive method for power sensing applications.

Table 1. Full list of measurement capabilities of the PZEM004T 100A module

Measurement	Range	Resolution ±	Accuracy
Voltage [V]	80 – 260	0.1	0.5%
Current [A]	0 – 100	0.02	0.5%
Power [kW]	0 – 23	0.0001	0.5%
Power Factor	0.00 – 1.00	0.01	1%
Frequency [Hz]	45 – 65	0.01	0.5%
Energy [kWh]	0 – 9999.9	0.001	0.5%

While there does exist power sensing equipment that boasts accuracies ranging from 0.02% to 0.1%, it should be noted that these systems are not nearly as flexible nor cost-effective as the measurement system of the present study. A quick survey revealed that typical systems present on the market for advanced power monitoring of a home are within the range of $300 - $1500 (USD) for a single sensor. Thus, for monitoring the power consumption of the loads present within a residential building, the cost of reduced accuracy in the PZEM-004T modules is more than made up for with the advent of a cheap, reliable, and flexible system that has hot-swappable components which can quickly be reconfigured to the desired needs of the project at hand. The modular architecture currently presented has an additional benefit of robustness since the event of a failure is localized to a single component and would not disrupt the entire system. Easy maintenance is afforded since a multitude of the modules can be kept in inventory on hand to quickly repair any subsystem that fails. The goal of the present study is to therefore prototype several key parts towards an encompassing system: 1) verifying PZEM-004T sensor accuracies, 2) developing robust communication protocols to monitor multiple sensors with a single microcontroller, 3) comparing real-time measurements of the PZEM-004T to a more expensive counterpart.

DESIGN OF IOT-BASED SYSTEM

Experimental methodologies

Due to the ground-up approach of using these low-cost sensors, a preliminary evaluation was conducted to verify the reliability and consistency of the PZEM-004T modules. This was done on a static test bench which makes use of a variable AC transformer attached to a resistor load which can be adjusted to investigate the sensing capabilities of the PZEM-004T sensors. The static testing consists of five 20 Watt resistors wired in series to simulate a basic and constant load. This test was chosen to represent the simplest possible load a power monitoring system could measure and allowed the authors to verify the accuracy reported on the PZEM-004T sensor. The microcontroller used was an Elegoo Arduino Mega in this experiment and measurements were verified using a Fluke 325 multimeter. A calibration curve was generated from these static tests by plotting the Fluke 325 multimeter measurements against the measurements of the PZEM-004T. A sample curve can be seen in Figure 1 which reports an R^2 value of 1. This test was repeated for all individual PZEM-004T sensors that were then used to further prototype the IoT system discussed in subsequent sections.

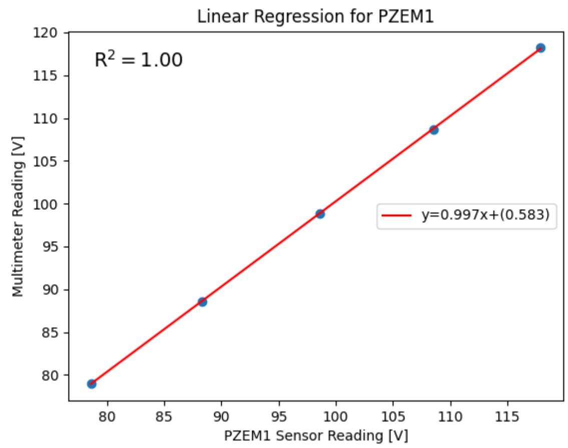


Figure 1 Example calibration curve for the PZEM-004T.

A prototype system to monitor multiple devices on the AC load panel of a home was developed at the DC Nanogrid House. The system includes the use of an Espressif ESP32 microcontroller continuously monitoring 4 different PZEM-004T sensors at once. The following loads are monitored: 1) AHU Main (AHU-MAIN), 2) AHU auxiliary heating (AHU-AUX), 3) Outdoor Unit (OU), 4) Heat Pump Water Heater (HPWH). These loads were chosen as they typically constitute the largest energy consuming appliances in a residential setting, and each has a unique energy profile for modeling. To monitor these 4 loads, the PZEM-004T sensors were mounted as can be seen in Figure 2. Since the PZEM-004T and the ESP32 communicate on 5V and 3.3V logic levels respectively, a logic shifter circuit was needed as a bridge for the serial communication between the microcontroller and the 4 sensors. This will be discussed in more detail in the section on communication protocols used for this project. Once communication is established between the devices, the PZEM sensor module is wired as shown in Figure 3 with the voltage from the Line and Neutral wires of each load wired to the sensor, and a current transforming sensor attached to the Neutral pole of the device monitored. For two-pole appliances such as the AHU of a residential HVAC system, the CT ring should be clamped to both poles to capture the 240VAC load input.

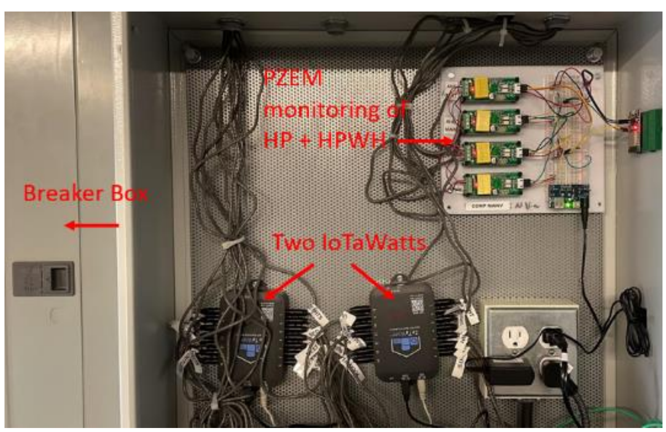


Figure 2 Prototype PZEM system shown on the right which is monitored by a single ESP32. The IoTaWatt power monitoring system is also shown on the left.

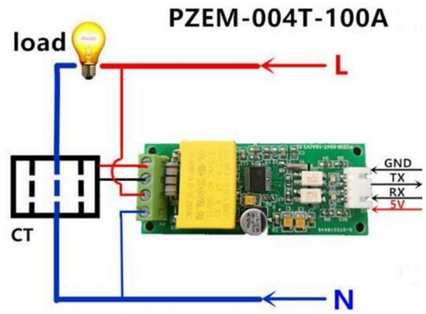
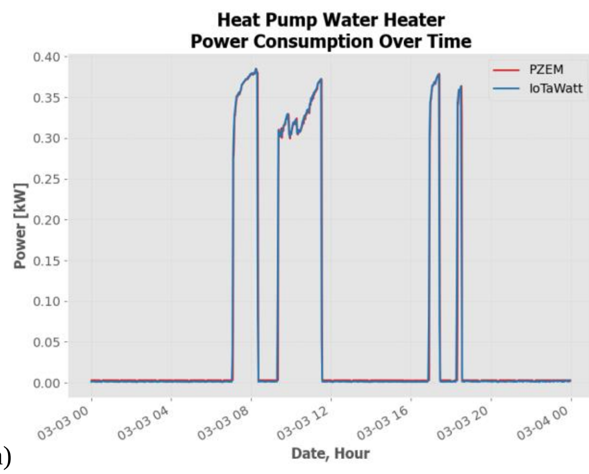


Figure 3 Wiring diagram to attach a load to the PZEM-004T sensor.

Comparison to the IoTaWatt system

As a point of comparison, the data read from the PZEM-004T sensors during 24-hour time periods was also compared to a similar power monitoring device: the IoTaWatt. The IoTaWatt is an IoT-based electrical monitoring system (IoTaWatt, 2020). It is powered by a USB power supply, and it monitors the AC line frequency using a 9V AC voltage reference transformer (TDC DA-10-09-E6) with an ESP8266. Power is monitored across individual circuits using clamp on current transformers (CT). Each current CT transformer is sized based on the maximum load it is expected to measure. The off-the-shelf CTs that come with an IoTaWatt kit were used, which are AcuCT -H040-50:50mA for the low loads (fridge, sockets, etc.) and AcuCT -H063-100:50mA for high loads (HP, HPWH, AUX) and AcuCT -H100-200 to monitor the mains. These units have an accuracy 0.5% of the measured current down to 10% of their rating and are linear down to 0.5% of their rated current (0.25,0.5,1 A) with an error of 1%. The current price of the unit (with full monitoring equipment) is at $363.3. Data was collected from both sensors and are compared in Figure 6 which shows the heat pump water heater's power consumption over a 24-hour period on March 3rd, 2023.



a)

Figure 4 a) Real-time power consumption of the heat pump water heater on March 3rd, 2023, showcasing the comparison between the PZEM-004T and the IoTaWatt sensor systems.

As can be seen, both the IoTaWatt and the PZEM-004T report nearly identical values and trends in data. Figure 4 is used to visualize an encompassing data stream: real-time power draw. Similarly for the outdoor and air-handling units, the PZEM-004T and the IoTaWatt produce nearly identical data sets. Table 2 outlines the general performance of the PZEM-004T using the IoTaWatt as a reference sensor by comparing the average error and the total cost savings. In the 4 time-series data sets generated (AHU-Main, AHU-AUX, HPWH, and OU), the error between each sensor was calculated as the absolute value of the difference between the PZEM-004T and the IoTaWatt. This was averaged for each data set and is shown in Table 2. The cost savings is shown as well and is meant to demonstrate that the PZEM-004T power sensing system provides significant cost savings as a home-grown solution. The comparison to the IoTaWatt is used as a reference mid-cost sensing system, but the comparison holds true for other power monitoring systems.

Table 2. Error and cost comparison between the IoTaWatt and PZEM-004T

Sensor System	Error [kW]	Total Cost Saving
IoTaWatt	-	-
PZEM-004T	0.001	x2.9

3.2 Communication Protocols

The PZEM-004T sensors leverage an RS485 communication interface using differential signaling over a two-wire connection to transmit and receive information. An application layer is defined over the interface supporting the Modbus Remote Terminal Unit (RTU) protocol, with a default baud rate of 9600 bps. Modbus RTU messages are constructed of 16 bits with an accompanying Cyclic-Redundant Checksum (CRC) to ensure message quality and reliability. Measurements provided by the PZEM-004T sensor with the corresponding resolutions are defined in Table 1.

Electrical load readings are obtained through the PZEM-004T's internal measurement system, and then provided to a dedicated Transistor-Transistor Logic (TTL) interface through an optocoupler. The optocoupler employs an LED to transfer information from one circuit to another, with a dielectric barrier in between to provide isolation between each circuit. This mechanism ensures that the potentially high voltage and current readings of the electrical load under observation do not create a hazard to downstream IoT devices connected to the much lower voltage TTL communication interfaces. A functional block diagram of these interactions is depicted in Figure 5.

Modbus RTU messages can be processed over a Serial Universal Asynchronous Receiver-Transmitter (UART) channel, common on many IoT devices used in data acquisition systems (DAQs). In this study, an ESP32 IoT module was selected for use in performing these DAQ responsibilities, but an initial modification was necessary to establish compatibility with the PZEM-004T sensor. The ESP32 operates on a primary operating voltage of approximately 2.2 V to 3.6 V, and requires the same of receiver (RX) and transmitter (TX) connections attached to it. The PZEM-004T sensor utilizes the 5 V TTL logic interface, resulting in an impediment to processing the messages.

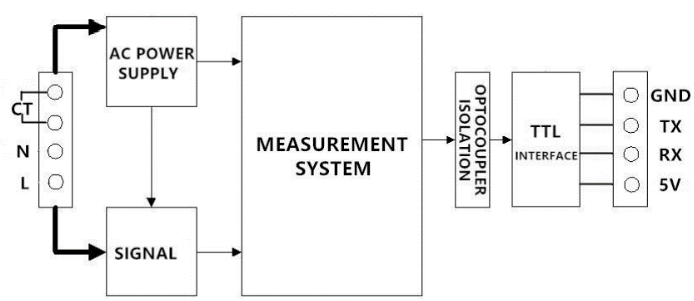


Figure 7 PZEM-004T Communication Interface Functional Diagram

To mitigate this discrepancy, the 5 V reference signals from the PZEM-004T sensors need to be converted to a 3.3 V reference compatible with the ESP32 I/O channels. This transformation is achieved with a bi-directional logic level shifter leveraging n-channel MOSFETs and pull-up resistors to appropriately shift the signals. A schematic and functional diagram of the logic level shifter are illustrated in Figures 6 and 7, with “L” indicating the low-side (3.3 V) and “H” indicating the high side (5 V).

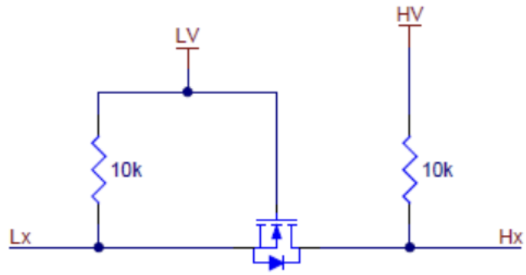


Figure 6 Bidirectional logic level shifter circuit schematic

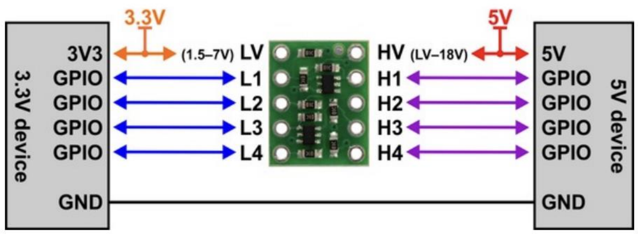


Figure 7 PZEM-004T to ESP32 Communication Functional Diagram

To ensure that communications are properly referenced, the ESP32 IoT device and any corresponding PZEM-004T sensors are grounded together. A maximum of four PZEM-004T sensors can be simultaneously managed by one ESP32; this ensures that the electrical demands of the logic level shifters are satisfied, and the communication channels are not overwhelmed. Each PZEM-004T sensor has a default Modbus communication ID of 0xF8, which is used to uniquely identify it to receive and broadcast data. Since multiple PZEM-004T sensors are used on the same ESP32 UART channels, this will result in conflicts and other issues processing data. Before instrumenting the PZEM-004T sensor in a desired measurement location, it is first modified over its Modbus RTU interface to assign it a unique communication ID (e.g., 0x10). As long as each of the four PZEM-004T sensors connected to the ESP32 have non-matching communication IDs, individual readings can be properly processed and recorded.

3.3 Evaluation of Results

Several repeatable test methods are presented to properly assess the validity of the PZEM-004T modules for use in monitoring the energy usage of appliances instrumented at the DC Nanogrid House. Static testing was done to ensure that each of the sensors were linear and verify their recordings, and a prototype system was successfully developed and demonstrated in this paper. The static testing was done successfully and demonstrated that the PZEM-004T modules require little to no calibration upon purchasing them. However, it should be noted that several of the sensors arrived faulty and thus it is strongly encouraged to check the performance of each sensor in a controlled manner as proposed by the static test stand. A prototype system was developed to compare the PZEM-004T to the IoTaWatt by collecting data on four separate appliances over a 24 hour period of study. From this, an error analysis was conducted to see if there was any discrepancy between the two sensors. The PZEM-004T sensor was well within range of error, and its prototype system was developed at a fraction of the cost of the IoTaWatt system. This demonstrates that a home system can be cheaply and easily developed.

CONCLUSION

In the present study, a novel design of a home power monitoring system is presented which incorporates low-cost Internet of Things (IoT) devices capable of providing accurate power monitoring of the AC loads in a residential building.

This design has successfully and rigorously been tested in a multitude of test beds to verify not only the accuracy of said power sensing modules but also their performance in a realistic study for use in the DC Nanogrid House. RS485 communication protocols have been tested and implemented such that multiple modules can all be simultaneously monitored by a single microcontroller device and sent to an in-situ data server localized at the DC Nanogrid House. The modular architecture presented is also robust and allows for ease-of-maintenance with the use of hot-swappable components. Real-time measurements were accomplished on a low-cost infrastructure which can easily be replicated. This will provide a bottom-up approach to monitoring all appliances and devices connected to the home and create a sufficient level of granularity for the creation of a variable-horizon optimization schedule to manage the energy consumption of the house effectively and efficiently. The use of real-time power measurements in a house could provide a novel infrastructure for this control schema and will be the focus of future studies.

REFERENCES

Al-Arif, S.M.M.R., Kadir, K.M., Morshed, Md.A., Ferdous, A.H.M.I., Alam, Md.M., Haque, Md.S., 2011. Energy Saving by Limiting Standby Power Loss and Using Smart Power Control (2011), *International Conference on Information Management, Innovation Management and Industrial Engineering*. 496–499. https://doi.org/10.1109/ICIII.2011.265

Allouhi, A., Fouih, Y.E., Kousksou, T., Jamil, A., Zeraouli, Y., Mourad, Y., (2015). Energy consumption and efficiency in buildings: current status and future trends. *Journal of Cleaner Production* 109, 118–130. https://doi.org/10.1016/j.jclepro.2015.05.139

ASCE's 2021 American Infrastructure Report Card | GPA: C-, (2017) *ASCE's 2021 Infrastructure Report Card* https://infrastructurereportcard.org/

Barsocchi, P., Ferro, E., Fortunati, L., Mavilia, F., Palumbo, F., 2014. EMS@CNR: An Energy monitoring sensor network infrastructure for in-building location-based services (2014), *International Conference on High Performance Computing & Simulation (HPCS)*, 857–862. https://doi.org/10.1109/HPCSim.2014.6903779

Chooruang, K., Meekul, K., (2018). Design of an IoT Energy Monitoring System, *16th International Conference on ICT and Knowledge Engineering (ICT&KE)*. 1–4. https://doi.org/10.1109/ICTKE.2018.8612412

Devadhanishini, A.Y., Malasri, R.K., Nandinipriya, N., Subashini, V., Padma Gowri, P.G., (2019), Smart Power Monitoring System Using Iot, *5th International Conference on Advanced Computing & Communication Systems (ICACCS)* 813–816. https://doi.org/10.1109/ICACCS.2019.8728311

Hashizume, A., Mizuno, T., Mineno, H., (2012). Energy Monitoring System Using Sensor Networks in Residential Houses, *26th International Conference on Advanced Information Networking and Applications Workshops*. 595–600. https://doi.org/10.1109/WAINA.2012.187

Kabalci, E., Gorgun, A., Kabalci, Y., (2013). Design and implementation of a renewable energy monitoring system, *4th International Conference on Power Engineering, Energy and Electrical Drives* 1071–1075. https://doi.org/10.1109/PowerEng.2013.6635759

Kabir, Y., Mohsin, Y.M., Khan, M.M., (2017). Automated power factor correction and energy monitoring system, *Second International Conference on Electrical, Computer and Communication Technologies (ICECCT)* 1–5. https://doi.org/10.1109/ICECCT.2017.8117969

Kim, W.H., Lee, S., Hwang, J., (2011). Real-time Energy Monitoring and Controlling System based on ZigBee Sensor Networks. *Procedia Computer Science, The 2nd International Conference on Ambient Systems, Networks and Technologies (ANT-2011)*, 794–797. https://doi.org/10.1016/j.procs.2011.07.108

Yoon, J.H., Baldick, R., Novoselac, A., (2014). Dynamic Demand Response Controller Based on Real-Time Retail Price for Residential Buildings. *IEEE Trans. Smart Grid* 5, 121–129. https://doi.org/10.1109/TSG.2013.2264970