**1. Project Overview**

* **Objective**: The project aims to develop a prototype smart home energy management system using IoT, capable of reducing energy costs and carbon emissions. The system automatically shifts residential loads to an energy storage battery during peak electricity pricing hours and uses sensors to monitor environmental conditions, adjusting appliance usage accordingly.
* **Key Components**:
  + **Microcontroller**: ESP32 Node MCU, selected for its low cost, in-built Wi-Fi, and compatibility with sensors and actuators.
  + **Sensors and Actuators**: Includes temperature (LM35), light intensity (LDR), and motion sensors (PIR). The system controls devices such as fans and lights via relay modules based on real-time sensor data.
  + **Energy Storage**: Gel battery, assumed to be solar-charged, is used to shift loads from the mains supply during peak hours.
  + **Data Communication**: Wi-Fi for transferring sensor data to a web application, where users can monitor energy consumption and make informed adjustments.
* **Scope and Limitations**: Though this setup is designed on a small scale, it provides a model for integration into residential buildings, especially those with renewable energy sources, reducing dependence on non-renewable power sources during high-demand periods.

**2. Problem Definition and Motivation**

* **Problem Statement**: Growing global energy demands, coupled with limited grid flexibility and high carbon emissions, necessitate innovative solutions that can effectively balance electricity supply and demand.
* **Motivation**: This project is driven by an urgency to address the energy crisis by integrating renewable sources in home energy management, ultimately supporting carbon reduction goals. The system aims to help consumers reduce their energy expenses by shifting usage to off-peak hours and optimizing appliance usage.

**3. Literature Review**

* **Demand Side Management (DSM)**:
  + DSM strategies like energy efficiency, demand response, and demand shifting provide frameworks for energy management from the consumer’s perspective.
  + **Energy Efficiency (EE)**: Focuses on reducing energy waste through efficient appliance management, reducing unnecessary consumption.
  + **Demand Response (DR)**: Utilizes a system operator’s signals to adjust energy usage during peak times, often with financial incentives for consumers who participate in load shedding.
  + **Demand Shifting**: Encourages consumers to shift energy usage to off-peak times or low-demand periods, reducing strain on the grid and associated costs.
* **Smart Home Technologies**: Analysis of various technologies for energy management systems, including:
  + **SCADA**: Allows real-time data collection and management but requires a centralized system.
  + **GSM**: Utilizes mobile networks but can have signal reliability issues.
  + **Bluetooth and Zigbee**: Suitable for short-range applications but lack the scalability of Wi-Fi.
  + **IoT-based Systems**: Preferred due to their broad communication range and scalability. Data from sensors is sent to the cloud, providing real-time monitoring without distance constraints.

**4. System Design**

* **Architecture and Design Requirements**:
  + **Main Power Source**: Energy supply from the grid, used during non-peak hours.
  + **Energy Storage Battery**: Used to power devices during peak hours, reducing grid dependency and lowering energy bills.
  + **Microcontroller (ESP32)**: The central processing unit for all sensors and actuators. It supports analog and digital interfaces, controlling appliances based on sensor inputs.
  + **Energy Monitoring**: The ACS712 current sensor measures energy consumption across different devices, enabling load shedding based on pre-set thresholds.
  + **Communication Protocol**: Wi-Fi was chosen over GSM, Zigbee, and Bluetooth for its range, data rate, and low cost.
* **Component Selection**:
  + **Pugh Matrices** were used to compare Wi-Fi, GSM, Bluetooth, and Zigbee, with Wi-Fi scoring the highest due to range and data handling capabilities.
  + ESP32 was selected as the microcontroller for its compatibility with Wi-Fi and wide range of sensor inputs.
* **Sensors and Actuators**:
  + **LDR**: Monitors light intensity, allowing the system to turn off lights if room illumination is sufficient.
  + **PIR Sensor**: Detects occupancy to manage lighting and HVAC only when rooms are in use.
  + **LM35**: Measures room temperature to control fan operation, enhancing comfort and efficiency.

**5. Implementation**

* **Power Source Switching**:
  + The system automatically switches from grid to battery power during peak hours (4:00 pm to 10:00 pm), driven by a scheduler within the ESP32 using the Timer interrupt concept.
* **Sensor Data Collection and Appliance Control**:
  + Sensors are read every three seconds, and averaged readings are used to control the fan and lights.
  + **Temperature Control**: The fan is turned on if the temperature exceeds 26°C, provided motion is detected in the room.
  + **Light Control**: Lights are turned off if the light intensity is adequate and motion is detected, avoiding unnecessary power use.
* **Data Monitoring and Storage**:
  + Sensor readings are averaged hourly and sent to a **MySQL database** via the ESP32’s internal Wi-Fi module.
  + **Database Structure**: Each entry includes readings on temperature, light intensity, occupancy, and energy consumption for analysis.
* **User Interface**:
  + The web application displays hourly and daily energy consumption, providing feedback on usage trends.
  + Visualizations include bar graphs (energy consumption trends for lights and fans) and pie charts (daily consumption breakdown), enabling users to make informed decisions.

**6. Testing and Results**

* **Sensor Accuracy Testing**:
  + **PIR Sensor**: Tested for motion detection sensitivity and range. Results showed increased sensitivity at close range, indicating effectiveness for room occupancy monitoring.
  + **LM35 Temperature Sensor**: Compared against a LabQuest 2 sensor in various environments (hot, cold, and room temperature). Statistical testing confirmed reliable performance but with minor variability.
* **Energy Consumption Testing**:
  + Tested with two hypotheses to determine if automated control of appliances effectively reduced daily energy consumption.
  + Results showed that controlled appliances lowered energy use, but other factors also contributed to energy savings.
* **Statistical Analysis**:
  + Paired t-tests on sensor accuracy confirmed that sensors met project requirements for reliable environmental monitoring.
  + The energy consumption test further validated that automated appliance control (based on environmental data) contributed to reduced daily energy costs.

**7. Conclusion, Limitations, and Future Work**

* **Conclusion**:
  + The project successfully created a prototype smart home energy management system that reduces energy use and costs by managing appliances based on occupancy, light, and temperature, and shifting power sources during peak times.
  + The web application allows users to monitor their energy usage trends and make informed adjustments.
* **Limitations**:
  + Limited knowledge in interfacing the database and web application led to delays in data visualization.
  + Additional testing was restricted due to time constraints, particularly with the automatic power selector’s performance.
* **Future Work**:
  + Expanding analysis of alternative power-switching methods for improved efficiency.
  + Developing a **machine learning model** to predict usage patterns, enabling more proactive and intelligent control of home appliances.