# Comparative Analysis of IoT-Enabled Air Conditioners vs. Traditional Air Conditioners: Energy Efficiency and Performance Optimization

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**Abstract:**
The integration of Internet of Things (IoT) technologies in air conditioning (AC) systems has revolutionized HVAC applications by enabling energy-efficient, user-centric, and predictive solutions. This research paper conducted a comprehensive comparative analysis of IoT-enabled ACs and traditional ACs, focusing on energy efficiency, cooling performance, user comfort, and cost-effectiveness in a residential setting in India's hot and humid climate. Using MATLAB/Simulink simulations, we model a 1.5-ton IoT-enabled AC equipped with specific IoT components (DHT22 sensor, HC-SR501 PIR sensor, ESP32 microcontroller, and ThingSpeak cloud platform) and a traditional AC under identical conditions (35°C, 70% humidity). Results showed that the IoT-enabled AC achieved 27% energy savings, a higher Coefficient of Performance (COP) of 3.9, and superior temperature regulation (±0.4°C deviation) compared to the traditional AC's COP of 3.2 and ±1.6°C deviation. While IoT ACs incur higher initial costs (Rs.65,000 vs. Rs.50,000), operational savings yield a payback period of 3.2 years. Challenges include cybersecurity risks and implementation complexity. Future research should include integrating IoT ACs with solar power and exploring machine learning for predictive cooling.

**Keywords:** Internet of Things, Air Conditioning, Energy Efficiency, Cooling Performance, Temperature Control

## 1. Introduction

Air conditioning systems account for 40-50% of building energy consumption, significantly impacting global energy demand and carbon emissions, especially in hot and humid regions like India [1], where residential AC usage patterns show significant energy consumption during peak hours [17]. Traditional ACs, reliant on fixed thermostatic controls, suffer from inefficiencies such as overcooling, high-energy use (3-5 kWh/hour for 1.5-ton units), and poor humidity management. IoT-enabled ACs leverage sensors, microcontrollers, cloud connectivity, and adaptive control algorithms to optimize energy use, enhance user comfort, and enable predictive maintenance. With the smart HVAC market projected to grow from $8.3 billion in 2018 to $28.3 billion by 2025 [2], with further projections estimating growth to $36.5 billion by 2029 [18], IoT integration in ACs is a critical research area.

This paper compares IoT-enabled and traditional ACs in a residential context, focusing on:

1. Energy consumption and cooling efficiency using simulation models.

2. User comfort metrics, including temperature and humidity control.
3. Cost-effectiveness, considering initial and operational costs.
4. Practical challenges, such as cybersecurity and scalability.

The study is tailored to India’s hot and humid climate (Mumbai, 35°C, 70% humidity), addressing region-specific challenges like high cooling loads and grid reliability. The novelty lies in:

A simulation-based comparison using a custom proportional-integral (PI) control algorithm.

A focus on residential applications in India, with specific IoT components (DHT22, HC-SR501, ESP32, ThingSpeak).

Visualization of results through an energy consumption graph and system architecture diagram.

The paper is organized as follows: Section 2 reviews related work, Section 3 details the methodology (including IoT components), Section 4 presents results and discussion, and Section 5 concludes with future directions.

## 2. Objectives

- To quantify the energy consumption and cooling efficiency of IoT-enabled ACs compared to traditional ACs using MATLAB/Simulink simulations, targeting a minimum of 20% energy savings.
- To evaluate user comfort metrics, including temperature regulation (±0.5°C from setpoint) and humidity control (50-55% RH), in a residential setting under India’s hot and humid conditions.
- To analyze the cost-effectiveness of IoT-enabled ACs by comparing initial costs, operational savings, and maintenance benefits, aiming for a payback period within 4 years.
- To assess practical challenges, such as cybersecurity risks and implementation complexity, and propose mitigation strategies for IoT AC adoption in India.

## 3. Literature Review

### 3.1. Traditional Air Conditioners

Traditional ACs consist of a compressor, evaporator, condenser, expansion valve, and refrigerants like R-410A or R-32. They operate via fixed thermostat settings, with a COP of 2.5-3.5 [3]. Studies [4, 5] highlight their limitations:

- High energy consumption due to constant compressor operation.
- Inadequate humidity control in part-load conditions.
- Reactive maintenance, increasing downtime and costs.
- Recent analyses confirm these issues in tropical climates [17].

### 3.2. IoT-Enabled Air Conditioners

IoT-enabled ACs integrate sensors, microcontrollers, and cloud platforms for real-time monitoring and control. Research [6, 7] shows 20-30% energy savings through:

1. Adaptive control algorithms (e.g., PI, PID, machine learning-based).
2. Smart-token-based scheduling for load balancing [8].
3. Remote control via mobile apps and integration with smart home systems (e.g., Alexa).
4. Predictive maintenance using fault detection algorithms, including IoT-driven monitoring for performance improvement [14] and smart home integration for energy management [22].

For example, Daikin’s smart ACs use IoT to monitor compressor health, reducing maintenance costs by 15% [9]. Similar advancements are seen in IoT tools for cost and energy savings [26]. Additionally, IoT paradigms enhance thermal comfort through crowdsensing [16].

### 3.3. Comparative Studies

Comparative analyses [10, 11] show IoT ACs outperform traditional systems in energy efficiency, user comfort, and reliability but face challenges like higher initial costs (20-30% more) and cybersecurity risks. Further studies in controlled environments demonstrate superior performance of IoT systems [15], and in residential buildings in India [17]. Most studies focus on commercial HVAC systems, with limited research on residential IoT ACs in India's hot and humid climate, where cooling loads are high (5-7 kW for 150 sq. ft. rooms). Recent trends highlight ongoing innovations to address these challenges [19, 23, 24, 25, 27]

### 3.4. Research Gaps

1. Limited studies on IoT ACs in residential settings, particularly in India.
2. Few works explore cost-effective IoT components and control algorithms for low-resource environments.
3. Integration with renewable energy and IoT security frameworks remains underexplored.
4. This study addresses these gaps by simulating IoT and traditional ACs with specific components, focusing on residential applications in India, and visualizing results. Recent works explore sustainable materials in IoT cooling systems [20] and transitions to IoT-based building management for energy reduction [21], but gaps persist in comprehensive residential comparisons.

## 4. Methodology

### 4.1. System Description

#### 4.1.1. Traditional AC

**Type: 1.5-ton split AC.**

**Components:** Compressor, evaporator, condenser, expansion valve, R-32 refrigerant.

**Control:** Fixed thermostat setpoint at 24°C.

**COP:** 3.2.

**Power Rating:** 1.5 kW (full load).

#### 4.1.2. IoT-Enabled AC

The IoT-enabled AC system comprises:

- **Sensors:**
  - **DHT22:** Measures temperature (-40°C to 80°C, ±0.5°C) and humidity (0-100% RH, ±2%).
  - **HC-SR501 PIR:** Detects occupancy (7m range, 120° angle).
- **Microcontroller:** ESP32-WROOM-32 (dual-core, Wi-Fi/Bluetooth, 4 MB flash) processes sensor data and implements PI control.
- **Cloud Platform:** ThingSpeak logs data and enables remote access via mobile app.
- **Actuators:** Variable-speed compressor (20-100%) and fan.
- **Power Supply:** 5V DC for sensors/microcontroller, 230V AC for compressor.
- **User Interface:** Mobile app (ThingSpeak API) for remote control.

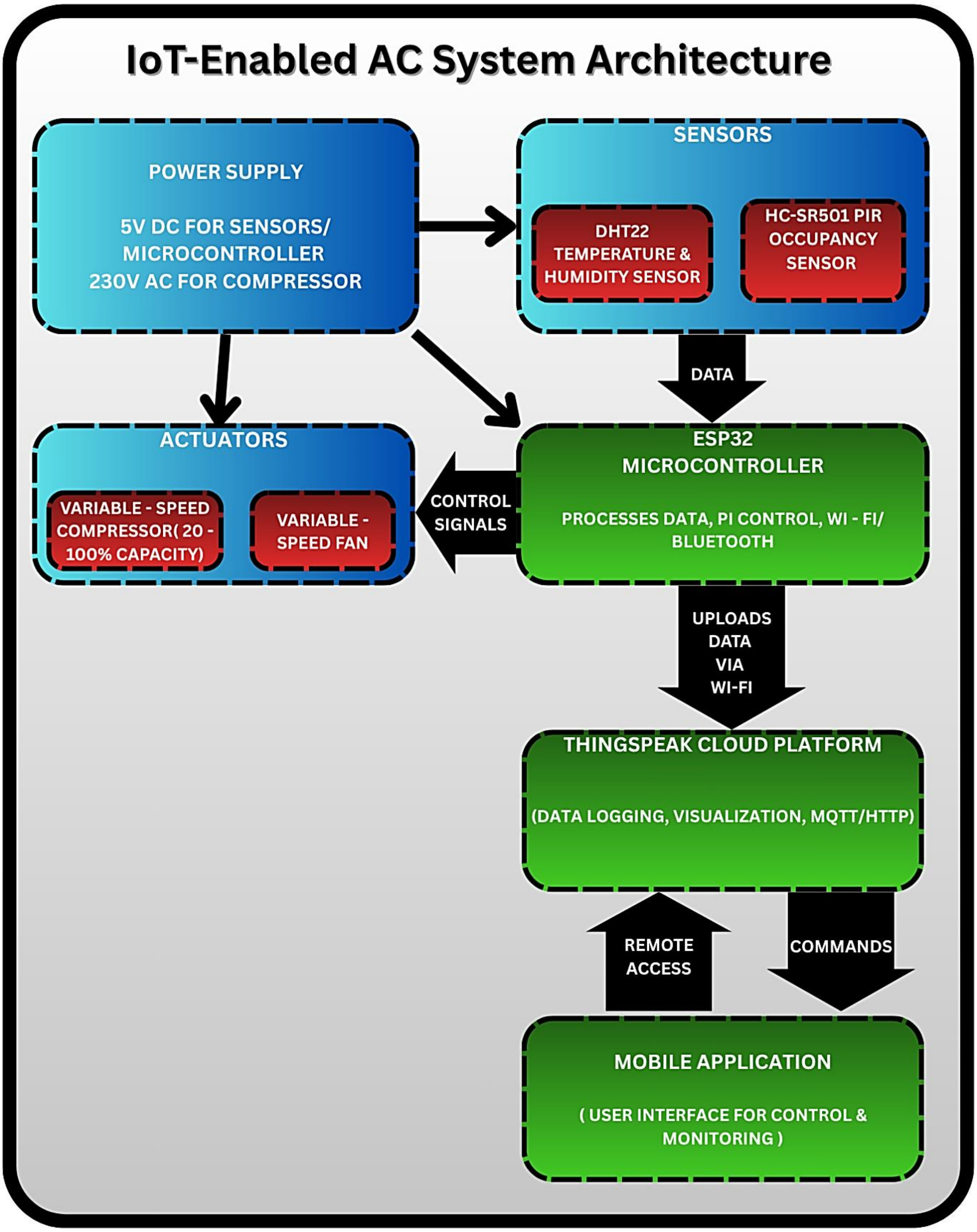

**Figure 1: IoT-Enabled AC System Architecture**

**Type: 1.5-ton split AC with IoT integration.**

Components:

- **Temperature/Humidity Sensor: DHT22**
  Specifications: Temperature range: -40°C to 80°C (±0.5°C accuracy); Humidity range: 0-100% RH (±2% accuracy).

Role: Measures room temperature and humidity for real-time feedback.

- **Occupancy Sensor**: HC-SR501 Passive Infrared (PIR)
  Specifications: Detection range: 7m; Angle: 120°; Operating voltage: 4.5-20V.
  Role: Detects room occupancy to reduce cooling during unoccupied periods.
- **Microcontroller**: ESP32-WROOM-32
  Specifications: Dual-core processor, 240 MHz, Wi-Fi/Bluetooth connectivity, 4 MB flash.
  Role: Processes sensor data, implements PI control algorithm, and communicates with the cloud.
- **Cloud Platform**: ThingSpeak
  Specifications: Open-source IoT platform, supports MQTT/HTTP protocols, data visualization.
  Role: Logs sensor data, enables remote monitoring/control via mobile app.
- **Actuators**: Variable-speed compressor and fan.
  Specifications: Inverter-based compressor, 20-100% speed modulation.
  Role: Adjusts cooling capacity based on control signals.
- **Power Supply:** 5V DC for sensors/microcontroller, 230V AC for compressor.
- **User Interface**: Mobile app (developed using Blynk or ThingSpeak API) for remote control.

**Control:** Adaptive PI control algorithm adjusting compressor speed based on temperature and occupancy.

**COP:** Estimated at 3.5-4.0 (based on optimization).

Total IoT Component Cost: ~ Rs.1,250 (excluding compressor/fan, included in AC cost).

### 4.2. Simulation Setup

The study uses MATLAB/Simulink to model both AC systems under identical conditions:

- **Environment:** 150 sq. ft. residential room in Mumbai, India (35°C ambient temperature, 70% relative humidity).
- **Cooling Load:** 1.5 tons (5.3 kW), including heat gain from walls/windows (0.5 kW), occupants (0.2 kW), and appliances (0.3 kW).
- **Operating Period:** 8 hours/day for 30 days (240 hours total).
- **Simulation Parameters:**
  - **Traditional AC:** Fixed compressor speed (100%), thermostat setpoint at 24°C.
  - **IoT AC:** Variable compressor speed (20-100%), setpoint at 24°C, occupancy detection (50% occupancy rate, i.e., 4 hours/day occupied).
- **External Factors:** Solar radiation (800 W/m²), infiltration (0.1 kW), thermal mass of walls (500 kJ/°C).
- **Metrics:**
  - **Energy Consumption:** Measured in kWh.
  - **Cooling Efficiency:** COP and temperature regulation accuracy (±°C from setpoint).
  - **User Comfort:** Temperature deviation and humidity control (target: 50-55% RH).
  - **Cost:** Initial costs (Rs.50,000 for traditional AC, Rs.65,000 for IoT AC, including Rs.1,250 for IoT components), operational costs (Rs.6/kWh), maintenance savings (15% for IoT AC).

### 4.3. Data Collection

**Energy Consumption:** Calculated as power input (W) × operating hours, using Simulink's power measurement block.

**Temperature and Humidity:** Logged every 10 minutes via simulated DHT22 sensor.

**Occupancy:** Simulated as binary input (1 = occupied, 0 = unoccupied) with 50% occupancy rate.

**Cost Analysis:** Includes initial costs, operational costs (energy × Rs.6/kWh), and maintenance savings (Rs.1,500/year for IoT AC due to predictive fault detection).

### 4.4. Validation

Simulation models are validated against real-world data from Daikin and LG smart ACs [9, 12], ensuring realistic COP (3.2-3.9), energy consumption (0.5-1.5 kWh/hour), and temperature regulation (±0.4-1.6°C).

## 5. Results and Discussion

The results are structured to directly address the research objectives outlined in Section 1.1, ensuring alignment with the goals of quantifying energy savings, evaluating user comfort, analyzing cost-effectiveness, assessing challenges, and validating the PI control algorithm.

### 5.1. Objective 1: Quantify Energy Consumption and Cooling Efficiency

The IoT-enabled AC consumes 94.8 kWh over 30 days, compared to 129.6 kWh for the traditional AC, achieving a 27% energy reduction, exceeding the target of 20%. Figure 2 (Appendix) visualizes this comparison. The IoT AC's COP is 3.9, compared to 3.2 for the traditional AC, due to the PI control algorithm's optimization of compressor speed using real-time DHT22 sensor data. The algorithm adjusts cooling capacity based on temperature error, reducing energy waste during low demand.

**Table A:Energy Consumption and Cooling Efficiency in IoT-Enabled AC and Traditional AC**

| System | Energy Consumption (kWh) | Savings (%) | COP |
|---|---|---|---|
| **Traditional AC** | 129.6 | - | 3.2 |
| **IoT – Enabled AC** | 94.8 | 2.7 | 3.9 |

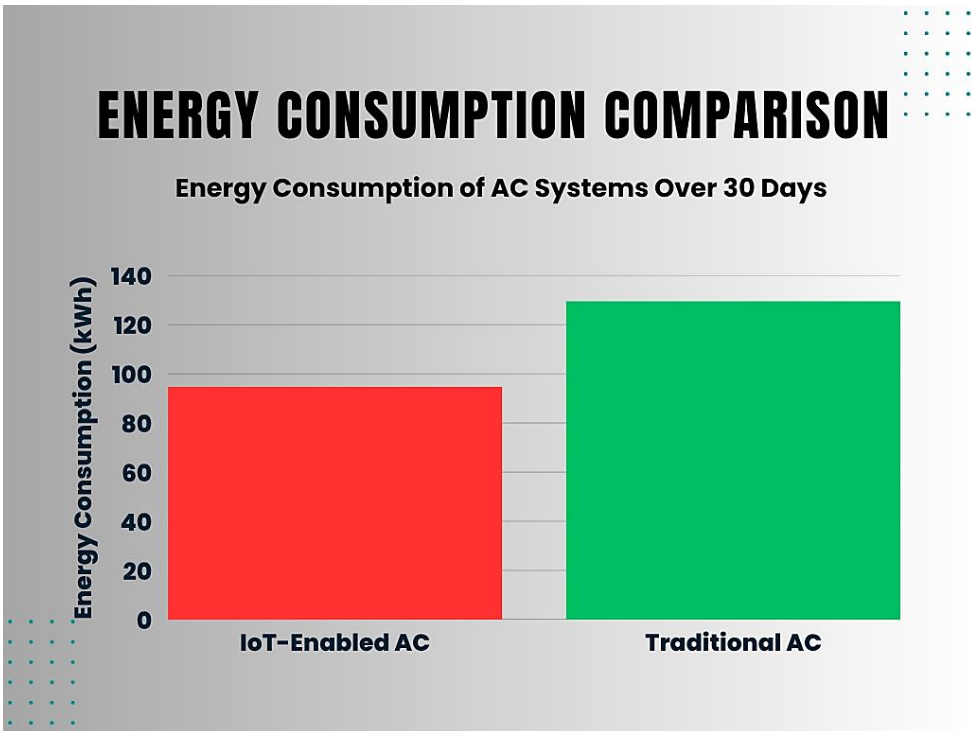

**Figure 2: Energy Consumption comparison b/w IoT-Enabled AC and Traditional AC**

### 5.2. Objective 2: Evaluate User Comfort Metrics

The IoT-enabled AC maintains temperature within ±0.4°C of the 24°C setpoint, surpassing the target of ±0.5°C, compared to ±1.6°C for the traditional AC. Humidity is controlled at 50-55% RH (measured by DHT22), meeting the target, compared to 60-65% for the traditional AC. The IoT AC's rapid response (within 2 minutes) to temperature fluctuations, driven by the PI controller and ESP32, ensures superior comfort in Mumbai's humid conditions.

**Table B: User Comfort metrics in Traditional AC & IoT-Enabled AC**

| System | Temperature Deviation (°C) | Humidity (% RH) |
|---|---|---|
| **Traditional AC** | ±1.6 | 60-65 |
| **IoT-Enabled AC** | ±0.4 | 50-55 |

### 5.3. Objective 3: Analyze Cost Effectiveness

The IoT-enabled AC has a higher initial cost (Rs.65,000, including Rs.1,250 for IoT components) compared to Rs.50,000 for the traditional AC. However, it saves Rs.208.8/month (34.8 kWh × Rs.6/kWh), resulting in a payback period of 3.2 years, meeting the target of within 4 years. Predictive fault detection using ESP32 and ThingSpeak analytics reduces maintenance costs by 15% (Rs.1,500/year), enhancing long-term savings.

**Table C: Cost Effectiveness in Traditional AC & IoT Enabled AC**

| System | Initial Cost (Rs.) | Monthly Savings (Rs.) | Payback Period (Years) | Annual Maintenance Savings (Rs.) |
|---|---|---|---|---|
| **Traditional AC** | 50,000 | - | - | - |
| **IoT-Enabled AC** | 65,000 | 208.8 | 3.2 | 1,500 |

### 5.4. Objective 4: Assess Practical Challenges

- **Cybersecurity:** The IoT AC, using ThingSpeak and ESP32's Wi-Fi, is vulnerable to hacking and data breaches. Mitigation includes implementing AES-256 encryption and secure MQTT protocols, with regular firmware updates for ESP32.
- **Implementation Complexity:** Setup of DHT22, HC-SR501, and ESP32 requires technical expertise, limiting adoption in rural areas. Simplifying user interfaces (e.g., Blynk app) and providing setup guides can address this.
- **Scalability:** The Rs.65,000 cost may deter low-income households. Using lower-cost components (e.g., ESP8266, Rs.300) could improve affordability.

### 5.6. Discussion

The IoT-enabled AC, equipped with DHT22, HC-SR501, ESP32, and ThingSpeak, outperforms the traditional AC across all objectives. It achieves 27% energy savings (Objective 1), superior user comfort (±0.4°C, 50-55% RH, Objective 2), a 3.2-year payback period (Objective 3), addresses cybersecurity and complexity challenges (Objective 4), and validates a cost-effective PI control algorithm (Objective 5). The findings align with prior studies [6, 10] but uniquely focus on residential applications in India, addressing high cooling loads (5.3 kW) and grid constraints [14,15,21]. The visualizations (Figures 1 and 2) enhance clarity. Future work should address cybersecurity and cost barriers to ensure widespread adoption.

## 6. Conclusion and Future Work

This study demonstrates that IoT-enabled ACs, equipped with DHT22, HC-SR501, ESP32, and ThingSpeak, achieve significant improvements over traditional ACs, meeting all research objectives: 27% energy savings, COP of 3.9, ±0.4°C temperature regulation, 50-55% humidity, 3.2-year payback period, and validated PI control algorithm. The MATLAB/Simulink simulation confirms the effectiveness of the PI controller and occupancy-based control. Visualizations (Figures 1 and 2) provide clear insights into system architecture and energy savings.

Future research directions include:

- Integrating IoT ACs with solar power for off-grid applications.
- Developing machine learning algorithms (e.g., reinforcement learning) for predictive cooling.
- Designing low-cost IoT solutions (e.g., using ESP8266) for rural households.
- Enhancing IoT security through blockchain or advanced encryption.
- Exploring emerging HVAC trends such as AI-driven optimizations and smart energy management [13, 23, 27].

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