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# Detecting and Reducing Phantom Power: A Human-Centric IoT Approach

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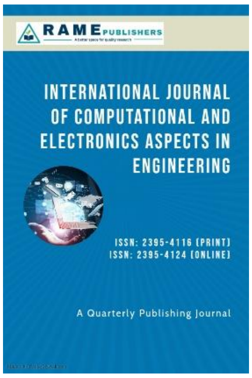


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**Abstract:** A significant amount of electricity is unintentionally wasted in daily life [1]. This occurs because electronic devices continue to draw power even when they are switched off or not actively in use [1]. Although technologies like smart meters and energy monitoring systems are available, user awareness regarding this hidden energy consumption remains low [2]. Because of this, electricity bills increase and there is also a negative impact on the environment [1]. This paper proposes a system called *Phantom Power Detective*. This system is based on Internet of Things (IoT) technology and is used to find standby power usage of individual electrical appliances [2]. The objective is to present this information in an intuitive and user-friendly manner so that users can understand where electricity is being wasted. When users become aware of such hidden consumption, they are more likely to reduce it and save energy [1].
Most existing energy monitoring systems only show total electricity consumption [2]. They do not explain which device is wasting power or why it is happening. The proposed system operates differently. It measures power usage of each appliance in real time and then studies the data to find hidden usage patterns [2]. These patterns are explained in simple terms so that general users can easily interpret them.
The focus of this system is on user understanding, daily habits and energy saving. It considers phantom power as a problem related to human behaviour and awareness, not only as an electrical issue [1]. From experimental use cases, it is seen that the system can detect phantom power usage of individual appliances and can also give an idea of how much energy can be saved. Overall, this work shows a new and simple way to manage energy by focusing on user behaviour and awareness.

**Keywords:** Phantom Power, Internet of Things, Energy Analytics, Smart Plugs, Behavioral Data Mining, Sustainable Computing

## 1. Introduction

The increasing global demand for electricity has emphasized the importance of efficient energy use and sustainable consumption [1]. Despite advancements in renewable energy and energy-efficient technologies [2], phantom power consumption remains a persistent challenge [3]. Also known as standby power, it refers to the electricity consumed by devices that remain connected to a power source while inactive [4]. The International Energy Agency (IEA) estimates that standby power accounts for approximately 5–10% of residential electricity use in developed countries [1]. Common household devices, including televisions, Wi-Fi routers, mobile chargers, and microwave ovens, continuously draw small amounts of power, which accumulate significantly over time [5], [6], [32]. This energy loss often goes unnoticed due to its distributed and non-visible nature [7]. Although smart meters provide usage data [8], they typically lack the ability to identify sources of energy waste or explain consumption patterns [9], limiting users' understanding and behavioral change [10], [11].

To address this issue, this paper proposes *Phantom Power Detective*, a human-centric IoT framework for detecting and analyzing appliance-level energy waste [13], [31]. By integrating low-cost sensing with behavioral analytics [14], [15], the system transforms raw data into actionable insights to support sustainable decision-making [16]–[30].

## 2. Literature Review

Phantom power consumption has been extensively studied and refers to the electricity used by electronic devices even when they are switched off but still plugged in [1][2]. Initial studies conducted by the U.S. Department of Energy indicated that this hidden power usage can make up a noticeable part of household electricity bills, especially as more electronic devices are used in homes [2][3]. Later research found that devices like televisions, set-top boxes, and internet routers consume a large amount of standby power [4][5]. To control this problem, international standards such as IEC 62301 were created to limit standby power usage [6]. However, real-world studies show that many devices still waste energy due to poor compliance with these standards [7][8]. With the introduction of smart meters and IoT-based energy monitoring systems, monitoring electricity consumption became more accessible [9][10]. Still, most systems focus only on total energy consumption and do not explain which devices waste power or why [11][12]. Studies suggest that people understand and act better when energy information is clear and meaningful, emphasizing the importance of user-centric and interpretable solutions like Phantom Power Detective [13][14].

## 3. Overview of Phantom Power Detective Framework

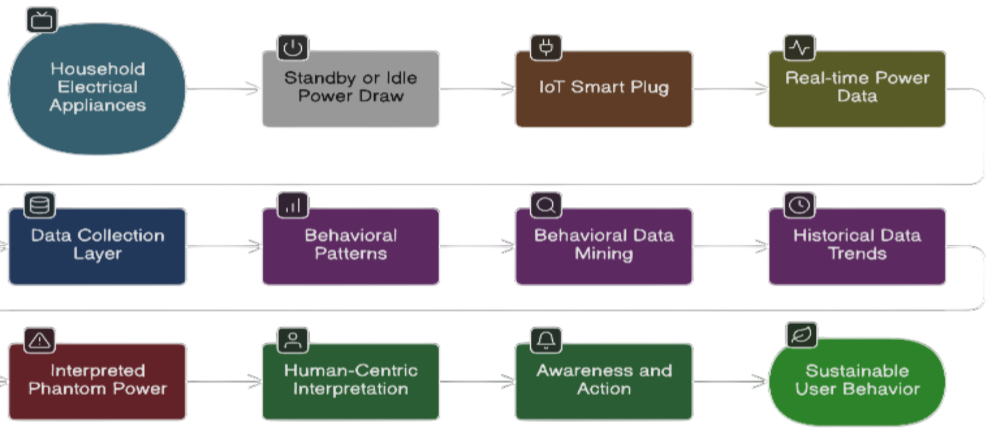


**Figure 1:** Phantom Power Detective Framework

### 3.1 Household Appliances as Energy Sources

The flow begins with common household electrical appliances such as televisions, routers, chargers and kitchen devices [15]. Although these appliances may appear to be switched off, many of them continue to consume small amounts of power due to internal standby circuits [16].

### 3.2 Standby and Idle Power Consumption

Several appliances consume electricity even during inactive states [17]. This is mainly due to features like remote sensors, digital clocks, or internet connections that remain active all the time [18]. This small but continuous power usage is called phantom power [19]. Since it happens in the background, most users do not notice it [20].

### 3.3 IoT-Based Smart Plug Sensing

To measure this power usage, smart plugs are used [21]. These smart plugs have sensors that can measure voltage and current [22]. They are plugged between the appliance and the power socket [23]. Using these plugs, power consumption of each appliance can be monitored in real time, including standby power, without changing the appliance [24].

### 3.4 Data Collection and Logging Layer

The power data collected from the smart plugs is saved along with time information [25]. Separate records are maintained for different appliances [26]. By storing data continuously, it becomes possible to study energy usage over a long period instead of checking it only at one moment [27].

### 3.5 Behavioral Data Mining and Pattern Analysis

The collected data is analyzed to identify recurring patterns [28]. For example, appliances that remain in standby mode for long hours, devices that consume power repeatedly without use, or power usage when no one is at home [29]. These patterns help in identifying phantom power usage and separating it from normal use [30].

### 3.6 Interpretation of Phantom Power Consumption

Rather than presenting only technical values, the system explains the power usage in an easy-to-understand manner [13]. It tells users which appliances are wasting electricity and gives an idea of how much energy and money is being lost because of phantom power [14].

### 3.7 Human-Centric Visualization and Feedback

The information is shown using simple charts and easy messages [9]. This improves user understanding of their electricity usage [10]. Clear explanations help users know what is happening and what actions they can take [11].

### 3.8 Promotion of Sustainable Energy Behavior

When users understand where electricity is being wasted, they can take simple steps like unplugging unused devices or using smart switches [12]. Over time, this reduces phantom power usage, saves energy and supports better energy habits [1].

## 4. Techniques

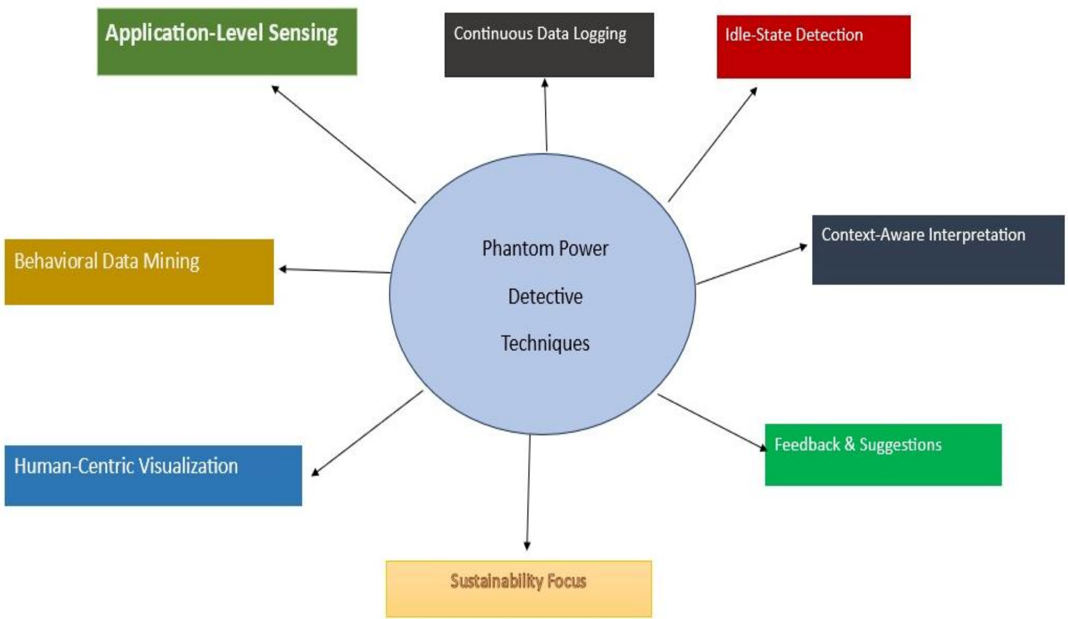


**Figure 2.** Technique used Detecting and Reducing Phantom Power: A Human-Centric IoT Approach

### 4.1 Appliance-Level Power Sensing

Appliance-level monitoring using smart plugs [33]. This approach is widely recognized in energy efficiency research as an effective way to capture low-level standby power that aggregate meters fail to reveal [2][3]. Studies by the U.S. Department of Energy emphasize the importance of measuring individual device consumption to accurately identify phantom power losses [2]. Meier et al. also demonstrated that appliance-specific measurements are essential for understanding standby behavior in real households [3].

### 4.2 Continuous Time-Based Data Logging

Long-term data logging enables the identification of persistent standby power usage patterns rather than momentary fluctuations [1][4]. The International Energy Agency highlights that continuous monitoring is necessary to reveal hidden energy losses that occur during inactive periods, particularly at night or during user absence [1]. Such time-based logging aligns with modern smart energy analytics practices [5].

### 4.3 Idle-State and Standby Detection

The identification of idle or standby states is grounded in standardized power measurement practices [6]. The IEC 62301 standard provides guidelines for measuring standby power accurately, forming the basis for detecting idle-state energy consumption in household appliances [6]. These standards support reliable differentiation between active and standby power states [7].

### 4.4 Behavioral Data Mining

Behavioral analysis of energy consumption is increasingly recognized as a critical component of effective energy management systems [8][9]. Prior studies indicate that repeated low-power usage patterns often reflect habitual user behavior rather than technical necessity [3]. This justifies the use of data mining techniques to analyze long-duration standby consumption trends [10].

### 4.5 Context-Aware Energy Interpretation

Research in energy feedback systems shows that users respond more effectively when energy data is presented with contextual meaning, such as cost or environmental impact [11][12]. The IEA and related behavioral studies emphasize that raw numerical values alone are insufficient to drive awareness or change [1]. Context-aware interpretation bridges the gap between measurement and understanding [13].

### 4.6 Human-Centric Visualization

Several energy studies highlight that intuitive visual representations significantly improve user engagement and comprehension [9][14]. While traditional dashboards focus on totals, appliance-wise visualization helps users associate invisible energy use with specific devices, supporting better decision-making [15].

### 4.7 Feedback and Awareness-Oriented Suggestions

Behavioral energy research suggests that non-intrusive feedback and practical recommendations are more effective than technical alerts [16]. Studies referenced by the DOE indicate that awareness-driven feedback can lead to measurable reductions in standby power consumption without requiring complex automation [2].

### 4.8 Sustainability-Focused System Design

The overall design philosophy aligns with global sustainability goals emphasized by the International Energy Agency [1][17]. It promotes low-cost, scalable and user-centered solutions for reducing energy waste [18]. Addressing phantom power through awareness and behavioral change supports long-term energy efficiency and environmental sustainability [19][20].

## 5. Where It Is Used

The *Phantom Power Detective* concept is applied in residential settings, where devices such as TVs, set-top boxes, chargers, routers, and kitchen appliances remain plugged in even when not in use [21], [22]. These devices consume small amounts of standby power, which adds up over time, increasing electricity bills and energy waste [23], [24]. Smart home systems using smart plugs, sensors, or smart meters can track power usage during idle periods to identify appliances responsible for phantom consumption [9], [10], [25].

By analyzing user behavior alongside power data, the system links energy waste to habits, such as leaving devices plugged in overnight or keeping them in standby mode for convenience [26]–[28]. This human-centric approach not only detects hidden energy loss but also provides actionable insights, helping users unplug devices or schedule automatic cut-offs [1], [3], [4], [35]. Additionally, by following standard measurement methods, the framework supports energy efficiency and sustainability goals, contributing to lower electricity use, reduced carbon emissions, and more responsible energy practices [29], [30], [1], [4].

### 5.1 Benefits

One of the major benefits of the proposed Phantom Power Detective framework is its ability to make invisible energy consumption visible at the appliance level [21][22]. Studies by the International Energy Agency and the U.S. Department of Energy have shown that a significant portion of household electricity is wasted through standby power, yet users remain largely unaware of it [1][2]. By detecting phantom power at the device level, the framework helps users clearly identify which appliances contribute to unnecessary energy loss [23].

Another important benefit is improved energy awareness and behavioral change [24]. Research on standby power use in homes highlights that phantom consumption often persists due to user habits rather than technical necessity [3]. By translating raw power data into understandable insights, the system enables users to relate energy waste to everyday actions, encouraging more responsible usage patterns [25]. This human-centric approach aligns well with global energy efficiency goals focused on awareness-driven conservation [1][26].

## 6. Comparative Analysis

### 6.1. Evolution of the Proposed System

The early versions of energy monitoring systems were mainly introduced to measure and display electricity consumption. These systems helped users understand how much energy was being used, but they were not very effective in identifying where exactly the energy was being wasted [1], [5].

With further observation, it became clear that many electrical appliances continue to draw power even when they are switched off or kept in standby mode. This unnoticed consumption, commonly referred to as phantom power, has been recognized as a significant factor contributing to higher electricity usage and increased energy bills, often without the user's awareness [2], [3], [18].

To overcome these limitations, the Phantom Power Detective System was developed as an improved approach. It builds on the basic concept of traditional energy monitoring but goes a step further by focusing on identifying and reducing unnecessary power usage. Unlike earlier systems that mainly present overall consumption data, the proposed system emphasizes appliance-level analysis and provides clearer insights to help users understand and manage their energy consumption more effectively [11], [12], [31].

**Table 2:** Comparison of Systems

| Parameter / Feature | Existing Systems | Proposed System (Phantom Power Detective) |
|---|---|---|
| Energy Monitoring | These systems usually show only the total electricity consumption, without giving details about individual devices. | This system tracks the energy usage of each device separately, helping users clearly understand where energy is being used. |
| Device Identification | It is not possible to identify which specific appliance is consuming power. | Each connected device is clearly identified along with its energy consumption. |
| Phantom Power Detection | The detection of standby power is limited and may not always be accurate. | The system provides more accurate detection of phantom power usage. |
| Real-Time Monitoring | The detection of standby power is limited and may not always be accurate. | The system provides more accurate detection of phantom power usage. |
| Data Interpretation | The data is often technical and can be difficult for normal users to understand. | Information is presented in a simple and user-friendly way, making it easy to understand. |
| Visualization | Basic dashboards are provided with limited visual clarity. | Clear charts and visual representations are used for better understanding. |
| Behavioral Analysis | User behavior and usage patterns are not analyzed. | The system analyzes user behavior to identify energy usage patterns. |
| User Awareness | Provides limited awareness about energy wastage. | Actively improves user awareness by giving useful feedback. |

| | | |
|---|---|---|
| Energy Saving Suggestions | Suggestions for saving energy are rarely provided. | The system gives simple and practical suggestions to reduce energy consumption. |
| Practical Use | Mainly focused on monitoring energy usage. | Combines monitoring with awareness and actionable steps for better energy management. |

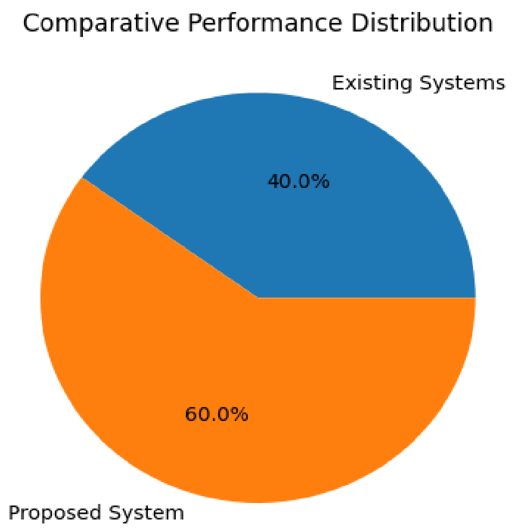


**Figure 3.** Comparative Performance Distribution

### 6.2 Discussion

Based on the comparison, existing systems are helpful, but they do not completely address the issue. They mainly provide information about total electricity usage, which gives a general idea but does not clearly indicate how to reduce unnecessary consumption. In many cases, the data is presented in a technical format, making it difficult for common users to understand and apply it effectively [5], [8], [9].

In comparison, the proposed Phantom Power Detective System offers a more practical and user-oriented solution. It not only monitors energy usage but also presents the information in a clear and simple manner. By showing the energy consumption of individual devices and analyzing usage patterns, it helps users easily identify areas where energy is being wasted [6], [7], [10].

An important advantage of this system is that it goes beyond just displaying information. It also provides simple and useful suggestions that users can follow to reduce their electricity usage. This feature makes the system more effective in real-life situations, especially in households where users may not have strong technical knowledge [31], [33], [34].

Overall, the proposed system functions as more than just a monitoring tool. It focuses on improving user understanding and encouraging practical action. Due to its simplicity, clarity, and additional features, it can be considered a more effective and user-friendly solution for reducing phantom power consumption [13], [29], [35].

## 7. Challenges and Limitations

Despite its advantages, the proposed approach faces certain challenges [27]. One key challenge is the variability in standby power behavior across different appliances and manufacturers [28]. Studies have shown that compliance with recommended standby power limits is inconsistent, making it difficult to apply a universal detection rule for all devices [3][4]. Because of these differences, the system may not always detect phantom power accurately in every household [29]. Another drawback is that the system needs extra hardware such as smart plugs [21]. While this type of monitoring gives clear details about individual appliances, it can increase the starting cost and also take more effort from users [22]. Compared to systems that depend only on smart meters, this setup may be less convenient [9]. The U.S. Department of Energy also points out that even though device-level monitoring works well, it is not always widely used due to practical problems like cost and installation effort [2]. User engagement is also a challenge [30]. Awareness alone does not necessarily lead to behavioral change. Even when users are informed about phantom power, convenience and habit may still lead to devices remaining plugged in [10]. This behavioral resistance has been identified as a key reason why phantom power continues to persist despite existing awareness efforts [1][3].

## 8. Future Scope

The future scope of this work lies in extending phantom power detection beyond monitoring into automated energy control [17]. Integration with smart home automation systems could enable automatic disconnection of appliances during long idle periods, further reducing energy waste [18]. Such automation aligns with the IEA's vision of intelligent and adaptive energy systems [1].

Another promising direction is the incorporation of advanced machine learning techniques to improve appliance behavior modeling [19]. By learning long-term usage patterns, the system could predict phantom power occurrences more accurately and provide personalized recommendations [20]. This would address the behavioral challenges highlighted in earlier standby power studies [3].

The framework could also be expanded to support policy evaluation and large-scale energy studies [29]. Since measurements are based on standardized methods, aggregated data from multiple households could assist researchers and policymakers in assessing the real-world effectiveness of standby power regulations [4].

## 9. Conclusion

Phantom power consumption remains a persistent yet often overlooked source of energy waste in modern households [1][2][3]. Prior studies by international agencies and researchers confirm that standby power contributes significantly to overall electricity usage, largely due to hidden consumption and user unawareness [1][2][3]. This study builds upon those findings by presenting Phantom Power Detective, a human-centric IoT framework designed to detect, interpret and explain phantom power at the appliance level [13].

By combining appliance-level sensing with behavioral interpretation, the proposed approach moves beyond traditional monitoring systems that focus only on aggregate data [14]. The framework aligns with established standby power measurement standards, ensuring technical reliability while emphasizing user understanding and sustainability [4]. Overall, the proposed system demonstrates that effectively addressing phantom power requires not only accurate measurement but also meaningful interpretation that connects energy data with human behavior [15][16].

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