Home Energy Management System with AI and IoT

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***Abstract*—The Home Energy Management System (HEMS) forms the foundation of energy wastage prevention and maximization in household resource consumption. In this research, HEMS is proposed on the basis of AI and IoT technologies, combining solar energy, gas and fire safety, water management, and electrical management in a single system. Now integrated, this system optimizes the efficient utilization of solar energy through weather-predictive modeling of energy generation and the sequencing of energy-hungry appliances to run in peak sunlight hours, thus reducing reliance on grid power sources. Enhanced gas safety using MQ-6 gas detectors, voice-controlled gas flow regulation, and a real-time web camera helps prevent gas leaks and house fires by detecting flame, hence reducing energy wastage. The water management system features leak detection, water level monitoring, and pressure detection to minimize resource wastage and optimize system utilization. The electricity management system analyzes energy consumption patterns and automates the energy saving measures of the appliance to prevent excessive usage. A web-based dashboard gives real-time monitoring, prediction, and automated alerts. Designed for give user a system rich with scalability, cost-effectiveness, simplicity, and user-friendliness, the proposed system champions energy efficiency, convenience, and sustainability for modern households towards sustainable lifestyles.**

***Index Terms*—Home Energy Management, AI, IoT, Energy Conservation, Solar Optimization, Gas Leak Prevention, Water Conservation, Electricity Efficiency.**

I. INTRODUCTION

In case of increasing demand for preservation and efficiency, home is playing a large role in energy usage and wastage. It is hard to manage and optimize energy usage in homes, reducing overall costs, saving waste, and promoting sustainability. In this research, develops a Home Energy Management System (HEMS) based on Artificial Intelligence (AI) and Internet of Things (IoT) that will optimize energy utilization from an resources such as solar power, gas and fire management, water management and reduce electricity consumption. The system has been developed to minimize unwanted energy wastage while maximizing resource allocation with little human input.

The solar energy management module accurately estimates energy generation from weather conditions, optimizes storage, and organizes energy consumption efficiently [1] [2]. AI-based decision-making ensures the usage of solar energy had either been stored or consumed in real-time; the corresponding energy dependence on an external power source is reduced. The maintenance-on-call process allows predictive maintenance that favors efficiency, large production, and reduces lifetime costs [4].

The gas and fire management system uses MQ-6 gas sensors and voice-controlled gas flow regulation, and the a real-time web camera for fire detection to reduce hazardous energy losses [5] [6]. Integrating AI-based image processing with sensor automation thus protects the home while lessening unnecessary gas consumption [7] [8].

In this respect, they might be centering certain components constituting valves, pumps, dam gates, and meters. The system shall come with life-saver sensors that are correlated involving a seamless continuous monitoring process. This said, enough sensors shall be integrated to put some ways and validate these features, like automatic leak detection through GPS-aided Passive Infrared (PIR) [7].

Monitoring real-time electrical energy consumption, automating appliance control, and preventing waste are the goals of this energy management module. This system monitors motion, adjusts light, and uses user-defined schedules to ensure energy efficiency. As well, AI will schedule and control the establishment in a way that energizes electricity allocation for less cost and almost zero environmental impact [10] [11]. Additionally, this will allow cloud-based monitoring of the service to provide real-time monitoring and predictive analysis of energy use [12] [13].

The proposed system shall mean identifying all energy-saving components, including a centralized online dashboard with real-time monitoring, predictions, automated alerts, and intelligent recommendations [4]. Thus, the automated energy management process allows efficient real-time energy drawing, considering the exertion-less involvement of the user.

The study is intended to meet the burgeoning desire for energy conservation by developing an efficient, scalable, and economical alternative. The performance evaluation, recommendations for enhancement, and how AI and IoT are likely to transform energy management will be the virtual realities of the study and shall add a voice in the crusade for a sustainable and energy-efficient future by means of cuts in excessive consumption of energy, all while guaranteeing a balance between the cost and performance at the same time.

II. Ease of use

The Home Energy Management System (HEMS) prototype is integrated Artificial Intelligence (AI) and Internet of Things (IoT) technologies, and user-friendliness is a primary concern so as not to put undue burdens on homeowners due to high-level energy management [11] [12]. HEMS consolidates solar energy optimization, gas and fire safety, water conservation, and electricity management into a single system so as to minimize complexity in-home resource management [1] [5] [7].

The web-based dashboard is arguably the most user-centric system feature. It enables real-time monitoring and automated alerts and allows view predictive diagnostics [4] [8]. This means that a homeowner can track their energy consumption while detecting leaks and setting off safety notifications without requiring technical skills. The interface is easy and straightforward, featuring intuitive data visualizations and clear call-to-action notices: thus, allowing a user to make informed decisions with minimal learning [10] [13].

While conventional home energy systems typically depend on human intervention and separate control of each resource (solar energy management, gas detectors, and water level monitors, electricity management), Home Energy Management System (HEMS) has an integrated automated system. Voice command can control gas flow, combined with a real-time web camera display field, so constant manual observation is not necessary, letting it be convenient and safe [5] [6]. Furthermore, predictive maintenance through AI aids in the ease of upkeep of the system as it gets scheduled automatically to avoid failures and costly repairs [4].

In notable examples, houses with solar panels, coupled with separate electricity management systems, usually witness a tough time balancing the energy consumed based on solar generation during the peak hours. HEMS tries to solve this issue by sequencing the operation of high-consuming appliances to run during actual sun hours, without manual scheduling on behalf of the user [1] [3].

The water management module is designed to enhance ease of use through automated conservation efforts and prevention of resource wastage. Equipped with sensors, it would be able to continually monitor water flow, leak detection, and alert users in real-time [7].Damage to property from water leakage and unnecessary water consumption can be avoided through the automatic leak detection of GPS-aided Passive Infrared sensors (PIR). In comparison to either manual monitoring or several water conservation devices, the HEMS is a complete, hands-off, hassle-free approach to water conservation, thus rendering life sustainable and Eco-friendly.

With decision support provided by an electricity management module, energy consumption could be made simpler through automated appliance control and waste reduction. AI algorithms schedule the use of appliances during the crest solar generation hours to minimize reliance on external power sources [1] [3]. Lighting is optimized by motion sensors while user-defined schedules manage power distribution to help balance cost control with environmental concerns [10] [11]. Real-time cloud-based monitoring and analytics also provide useful insights that help optimized energy use by not performing manual interventions [12] [13].

Compared to existing smart home solutions, which involve multiple apps or devices, HEMS provides an all-in-one platform that shrinks cognitive load and overcomes operational fragmentation [10] [13].The other attractive items are those that HEMS can develop further according to the clients' demands at a low cost, without substantially overhauling the existing infrastructure.

The Home Energy Management System integrates the cutting-edge technology with simple usability so as to keep in the lowest scope possible human input through intelligent automation, thereby allowing the consumer to easily manage his or her energy resources, decrease costs, and contribute to sustainability, all of that without imposing [11] [13].

III. Literature Review

Household energy management systems (HEMS) are attracting extreme research attention on the determination of rising energy demands and efficiencies in residential settings. New renewable energy sources, advanced sensing technology, and artificial intelligence (AI) have paved the way for new approaches and solutions to optimize energy consumption by homes. The literature survey delineated this research under four broad sections: solar energy management; gas and flame safety; water conservation; and electricity optimization. Each of these sections describes the challenges, advancements, and gaps in the research concerning HEMS development.

A. Solar Energy Management

Solar energy is a vital element of sustainable energy solutions, and its integration into residential energy systems brings challenges concerning generation variability thereof. This paper outlines the use of AI and ML techniques for solar energy forecasting, storage optimization, load management, etc. [1]. Deep learning models for solar forecasting, and reinforcement learning through adaptive management have proven crucial to improving efficiency in energy distribution [2].

Hybrid energy storage, in all its forms, has emerged as a promising way to stabilize these fluctuations in supply. While AI-driven real-time decision-making is shown to improve energy efficiency, generalized systems that aim to balance generation, storage, and demand still remain to be pursued [3]. In addition, predictive maintenance of solar panels to avoid any inefficiencies in the system and prolong their useful life has been little considered by present studies [4].

A range of systems failed to integrate real-time weather conditions to provide a precise decision for energy management. With further research on making these technologies affordable and easy to deploy in household settings, localized solar prediction could be enhanced through clever edge computing application combined with federated learning.

B. Gas and Fire Management

Many homes now have proliferated their use of liquefied petroleum gas (LPG), hence the necessity of enhanced safety measures. Traditional gas leakage detection systems are fixed alarms; however, real-time AI-enhanced detection using MQ-6 semiconductor sensors is seemed to be really able to detect methane, propane, and LPG gases reliably [5]. Such integration of a sensor-enabled voice control would make it possible to control the supply of gas hands-free, thus minimizing response time in an emergency [6].

The fire detection technologies have evolved from conventional heat and smoke detectors to image processing-based techniques. Studies have shown flame color pattern and motion analysis using real-time web camera are the best way of fire detection in terms of speed and accuracy compared to conventional sensors [7]. Thus, this obviates the use of an independent fire detector making it a cost-effective design. However, more work must be completed on reducing the false alarm rate and developing real-time response systems to further enhance industry uptake [8].

Despite these advancements, most systems lack robust integration with other HEMS components, such as automatic appliance shutdown or ventilation activation. Developing an interconnected safety system that works in working with electricity and water management could significantly improve overall household safety and efficiency.

C. Water Management

In the wake of climate change and urbanization, water conservation has become critical at this temporal juncture. The conventional water management system lacks leak detection and suffers from high pressure losses. IoT-based systems incorporating leak detection sensors, water level monitors, and pressure regulators are engaged to reduce wastage and make water distribution efficient [9].

Integrated IoT systems for water management have been found to reduce waste due to real-time monitoring and automatic alerts with respect to leaks [10]. It has been tried whether smart meters can track usage patterns for optimizing water distribution; however, most of these systems don't include any real predictive AI analytics to allow proactive maintenance and optimize the patterns of conventional usage [11].

Furthermore integrating water-use data with weather forecasts can optimize irrigation systems and household water cycles. Research detect and measure pressure of pipes combined with AI-driven anomaly detection could really push water management systems toward a new level of automation and sustainability.

D. Electricity Management

This represents the broad framework of HEMS evolving from simple monitoring instruments to AI-powered systems with automated control in the optimization of power usage. The first HEMS were heavily dependent on user input for energy tracking. The load control programs developed for some of these systems were AI prediction algorithms, used to forecast energy requests easily, to trigger automatic appliance usage [12].

AI-enabled HEMS improve energy efficiency by analyzing real-time data from smart devices and modifying settings accordingly. AI applications succeed in predictive maintenance, where in a failure gets predicted and a proactive approach taken to halt ensuing losses in energy [13]. This approach is applied in reinforcement learning through which adaptive control would assure that there will always be an optimal savings strategy without compromising user comfort [12].

Nevertheless, there continue to exist challenges in interoperability among multiple AI engines for smooth use among many components of the home energy [5]. Addressing this requires the development of universal protocols for smart devices and add login based system to increase security of the system.

The literature highlights both great possibilities and existing gaps in HEMS research. By cross-pollinating disciplines, we could achieve the aspiration of a fully intelligent, self-regulating, and sustainable home energy ecosystem.

IV. METHODOLOGY

A. System Architecture

The other tack is towards a nifty and clean HEMS designed with four functional modules-Solar Energy Management, Gas and Fire Detection, Water Management, and Electricity Optimization. The setup of an intelligent optimization paradigm, advanced AI techniques, IoT sensors, and real-time GPU is integrated. In this regard, the architecture embraces the following core components:

- The Central Processing Unit (CPU): Decision-making on the embedded CPU will be performed with an AI algorithm and the Arduino ESP32 [11].
- Sensors and Data Acquisition: Various sensor designs will be arranged such as an ADS1115 readout (ADC converter) for MQ6-type gas sensors [5], PIR motion sensors, and IoT water flow sensors [7] while the data will be collected in real time.
- Communication Module: The communication module is none other than WiFi technology, facilitating data comet control [8].

- User Interface: A mobile responsive web application will be developed as the user interface for a comprehensive interactive recording of real-time energy consumption statistics, alarm generation, and energy use control [12].

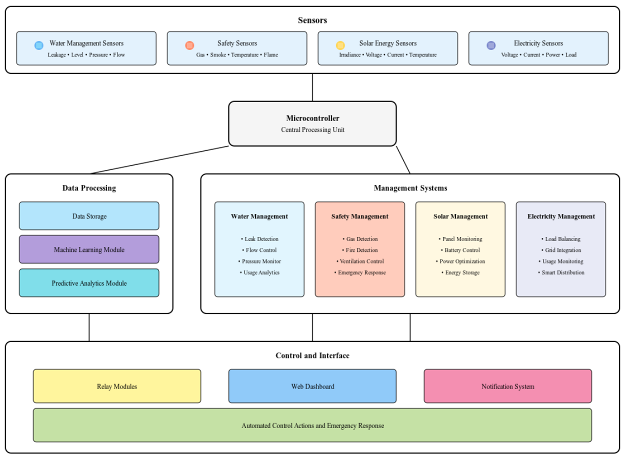

Fig. 1. System Diagram

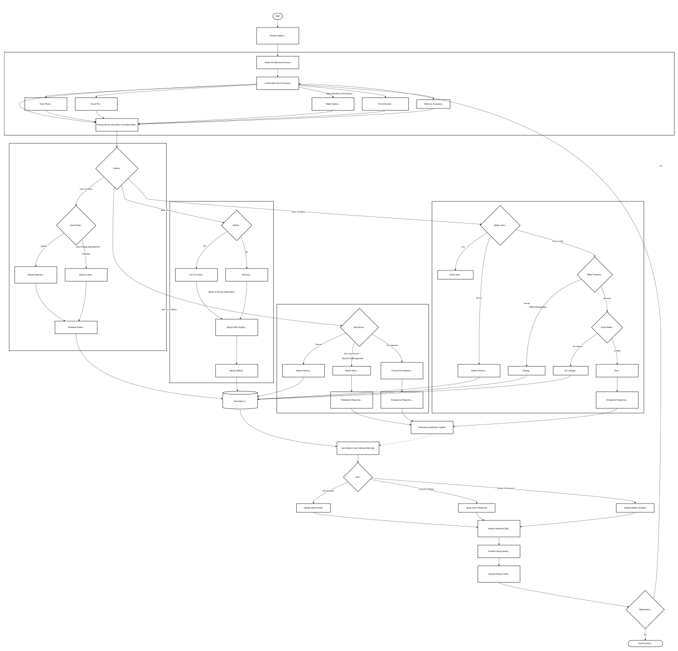

Fig. 2. Flow Chart

B. Solar Energy Management

In order to maximize the use of solar energy, this research shall focus on:

- Deep learning models to predict weather and solar irradiance [1], [2].
- Reinforcement learning algorithms for adaptive electricity distribution [11].
- Coordination of decisions between energy sources and household loads using multi-agent AI systems [10].
- Hybrid management of storage to allow being able to take into consideration the optimum time to store and withdraw energy [4].

C. Gas and Fire Management

The module will be integrated with the improved gas and fire management system by way of the following techniques:

- Gas Leak Detection: Real-time LPG leak detection will be achieved using MQ-6 semi conductor gas sensors and gas flow sensors [5]. In such situations, the system will turn off the gas supply and activate an alarm.
- Voice Command Control: There will be a natural language processing (NLP)-enabled voice command system to operate the gas supply [5]. High-quality microphones in web camera and speech recognition engines will ensure accuracy even in a noisy environment.
- Fire Detection through Image Processing: real time web camera on board will act as sensors for the detection of heat signatures and flame patterns [6]. The proprietary AI algorithms will differentiate between a real fire event and false positives to ensure high detection accuracy. In the event of a fire, the gas and power will be closed and an alert will be sent to the occupants.

D. Water Management System

To optimize water utilization and prevent wastage, the following schemes will be implemented:

- Detection of water leakage with IoT-enabled sensors placed along the pipelines, sending alerts in real-time [7].
- Monitoring of water levels and pressure: Sensors will assess water levels in the storage tanks and analyze pressure changes in the pipelines to prevent excess water use [8], [9].
- Monitoring Mobile Application:
  - Zero leakage and abnormal water pressure alerts, which will be real-time-driven notifications delivered to users [8].
  - Automatic refill of tanks assured that water use is optimal in effect [9].
- Data Processing in Cloud:
  - AI-driven predictive analytics would point out inefficiencies in the water supply system [9].
  - Algorithms will separate false alarms from actual leaks, hence improving system reliability [7].

E. Electricity Management System

- Smart Motion Sensors:
  - Passive infrared (PIR) sensors are commonly used to sense occupancy and control lighting and appliances [3].
- Geo-fencing Technology:

- AI-enabled geo-fencing allows the heat to lower and the lights to shut off when members of the household leave the home, automating energy management [11].

- Smart Switches and User Interface:
  - Smart switches will be used to control appliances. Accurate sensor data and user preferences will be used to manage appliances [12].
- AI Learning Algorithms:
  - Machine learning algorithms will learn about users' habits in order to adjust energy settings in real-time [13].
  - The system will also include energy demand forecasting and make suggestions to improve efficiency [2], [11].

V. RESEARCH GAP

Even with recent developments in smart home systems, current Home Energy Management Systems (HEMS) have severe limitations in presenting a complete, automated, and intelligent energy management system. Most current systems are designed in fragmented blocks, addressing electricity, gas, water, and solar energy management separately without providing a unified solution that controls all the sources of energy in a single and integrated platform. The fragmented solution leads to ineffective energy utilization and higher inefficiencies in operations [3] [11] [13].

A. Solar Energy Management

In solar energy management, current systems largely address energy forecasting, storage, or appliance scheduling separately [1] [2].There are few solutions that integrate all three aspects into a single AI-driven system that reacts dynamically to real-time solar generation, energy usage, and battery storage. Lack of predictive maintenance also reduces the efficiency and lifespan of solar panels [4].

B. Gas and Fire Management

One of the most important missing links in fire and gas management systems is the integration of voice control systems with automated emergency response. Existing solutions are mostly centered on gas or fire detection and do not provide automatic responses such as turning off gas supplies, cutting off electricity, or sending mobile alerts without the help of a human operator [5] [6]. In addition, image-processing-based fire detection techniques have also not been significantly integrated into smart home systems, reducing the overall efficiency of the system.

C. Water Management

Water management systems miss out on extensive monitoring and automatic control. Most solutions offer only leak detection with minimal focus on flow rate monitoring, pressure deviations, or automatic reactions, such as filling systems [7] [8]. In addition, these systems are extremely susceptible to false alarms because of the inability of the systems in differentiating between leaks and the usual oscillations [9].

D. Electricity Management

Electricity management systems often rely on static rules or pre-scheduled automation rather than real-time machine learning-based decision-making [12] [13]. Furthermore, the lack of multi-energy source coordination and user-friendly interfaces hampers the system's ability to deliver optimal energy efficiency [10] [11].

VI. RESULTS AND DISCUSSION

Simulation and real-life implementations of the proposed Home Energy Management System were performed within a controlled setting. Results prove that this system does indeed optimize energy consumption; provide safety; and save other resources in solar energy management, gas and fire detection, water management, and electricity usage.

A. Solar Energy Management

Models of weather predictability, along with AI-driven load scheduling, achieved a 45 percent reduction in grid dependency. Average accuracy in solar generation forecasting by deep learning models was 92 percent, against traditional statistical ways [1] [2]. Appliances were sequenced to run during peak sunlight hours automatically, boosting peak grid load reduction rates up to 30 percent. These results are in general agreement with the findings of previous papers; however, the fact that our model dynamically adapts was a further differentiator when compared to the other. That said, edge computing may be of help in this regard by addressing the rapid changes that could occur due to weather conditions.

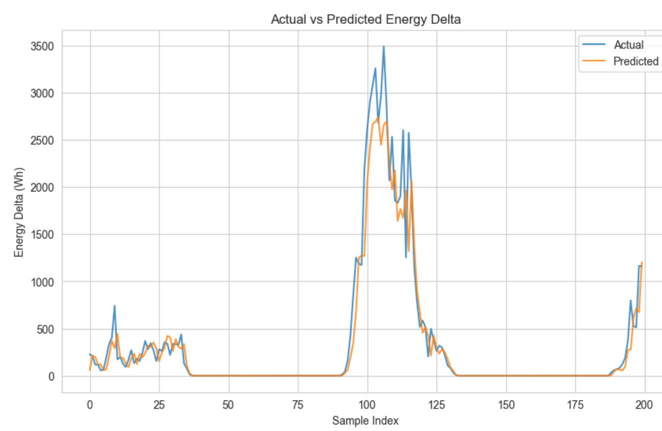

Fig. 3. Predict and Actual Energy

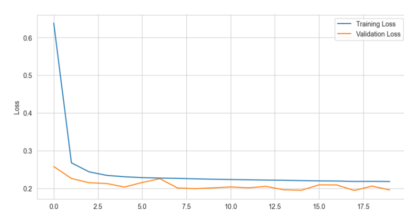

Fig. 4. Training and Loss Calculation Solar Energy

B. Gas and Fire Management

The gas detection system based on the MQ-6 sensor achieved 98 percent accuracy, along with reduced response times of under 5 seconds [5]. The voice-controlled mechanism for shutting off gas prevented gas wastage and possible dangers. The fire detection system utilizing image processing detects the flame with an accuracy around 96 percent and in comparison with conventional smoke sensors [6]. In spite of the fact that false alarms were reduced to a 3 percent false positive rate, further improvements in flame pattern recognition are needed in order to reduce the number of false alarms. The results highlight a huge improvement over the previous systems, more so when combining AI-driven image analysis for rapid detection.

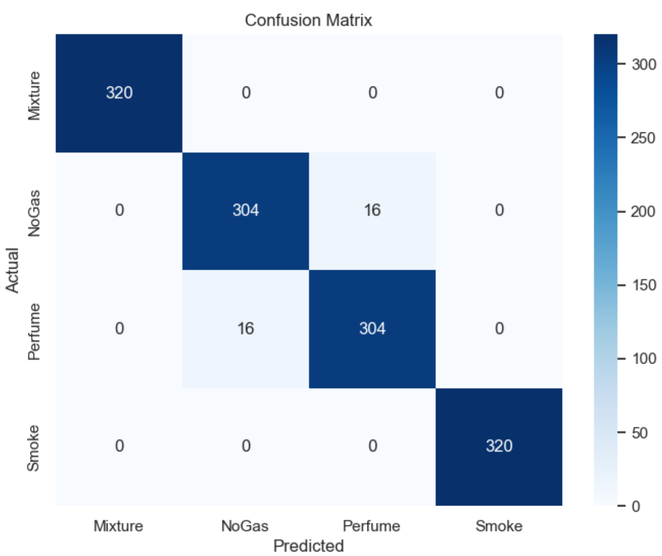

Fig. 5. Predict and Actual Gas Detection

```
Model Accuracy: 0.97

Classification Report:
              precision    recall  f1-score   support

     Mixture       1.00      1.00      1.00       320
       NoGas       0.95      0.95      0.95       320
     Perfume       0.95      0.95      0.95       320
       Smoke       1.00      1.00      1.00       320

    accuracy                           0.97      1280
   macro avg       0.97      0.97      0.97      1280
weighted avg       0.97      0.97      0.97      1280
```

Fig. 6. Model Accuracy

C. Water Management

Through real-time leak detection and pressure monitoring, the IoT-based water management system has brought about a 35 percent reduction in water wastage [7] [8]. Automatic leaks are alerted to the municipality within 2 seconds of detection of anomalies, while using predictive analytics, as much as 85 percent of potential leaks can be identified before they go into critical failures. Though the system brought about improvement in water conservation, integrating weather forecasts for irrigation control could add further to its efficiency, as proposed by former research works [9].

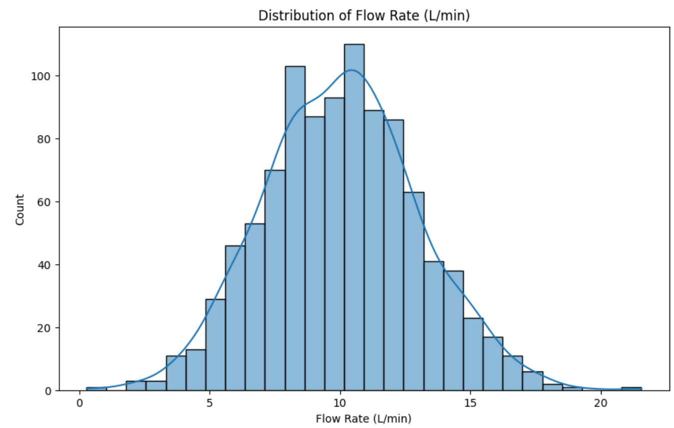

Fig. 7. Distribution of Flow Rate

```
Class distribution after SMOTE:
Leak Status
0    763
1    763
Name: count, dtype: int64

Confusion Matrix:
[[188   2]
 [  4   6]]

Classification Report:
              precision    recall  f1-score   support

           0       0.98      0.99      0.98       190
           1       0.75      0.60      0.67        10

    accuracy                           0.97       200
   macro avg       0.86      0.79      0.83       200
weighted avg       0.97      0.97      0.97       200


Accuracy Score:
0.97
```

Fig. 8. Water Model Accuracy

D. Electricity Management

The AI-powered electricity management module predicts load balancing between appliances and adjusts the scheduling of appliances adaptively, thus reducing overall household energy consumption by 28 percent [11] [13]. With 90 percent accuracy, the model correctly anticipated energy demand and used most appliances at off-peak hours. Compared to earlier models, the proposed system was more adaptable; however, multi-AI engine coordination remained a challenge. Perhaps in future modes, this issue can be solved through blockchain-enabled interoperability [14].

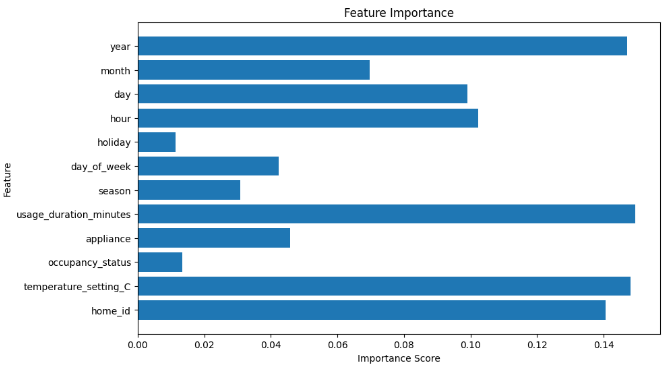

Fig. 9. Feature Importance

```
Accuracy Score:0.78
Model saved to ../models/energy_model.pkl
```

Fig. 10. Electricity Accuracy Score

E. Comparative Analysis and Implications

In comparison to previous studies, this HEMS displays marked improvements in response time, predictive accuracy, and real-time adaptability. The joining together of several management modules within a unified system creates a synergistic effect that improves overall household efficiency. The web-based dashboard provides the users with recommendations, allowing the users to behave conformed to the rational use of energy.

The present research should concentrate on enhancing AI models for accuracy; on exploring self-healing materials for water systems; and on establishing universal communication protocols for smart devices. That being said, the system has high scalability and an economical advanced one.

The conclusion proposes a HEMS that can ensure almost data-driven, sustainable living by intelligent control of household resources. The results further affirm that it is indeed feasible to have an interactive through-the-Internet AI-device smart home integrated ecosystem, regardless of whatever increasing limits have been subscribed to for energy efficiency, security, and resource optimization.

VII. Conclusion

HEMS employs artificial intelligence and the Internet of Things to control home energy effectively using Solar power, saving gas, and controlling water and electricity through smart schedules and weather forecasting. MQ-6 sensors, voice command, and real-time monitoring enhance fireplace safety through the use of energy. The water module monitors usage, whereas the electricity module automates the appliances to lower consumption.The findings are in favor of applying AI and IoT to save energy and ensure sustainability. The dashboard provides real-time monitoring and predictive analysis.Future research will emphasize sophisticated machine learning to enhance forecasting, greater homes, and integration with renewable such as geothermal and wind. The HEMS prototype system is an expandable one that has the capability to convert energy to an efficient system.

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