Energy Auditing practices for HVAC Systems: An IoT-based Approaches

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Abstract

Energy consumption in institutional facilities—including universities, hospitals, government buildings and research laboratories—is largely driven by Heating, Ventilation, and Air Conditioning (HVAC) systems alongside a diverse set of distributed mechanical appliances such as pumps, fans, compressors, refrigeration units, and laboratory equipment. Escalating energy costs, increasingly stringent sustainability regulations and global carbon-neutrality commitments necessitate the development of a structured, scalable and technology-enabled energy auditing simple behavior control specifically tailored to these energy-intensive systems. IoT-driven operational behavior practices enhance HVAC system efficiency and reduce overall energy consumption.

The paper provides a comprehensive energy auditing simple behavior control review analysis on the inefficiencies and hidden energy losses in traditional systems visa vis utilizing advancement in control system and use of IoT-based sensing networks, real-time energy monitoring of occupancy related data analytics, and performance benchmarking to make HVAC efficient**.** The article while summarizing application of IoT in optimizing energy uses using simple control techniques and use of real time HVAC system monitoring.

Energy audits have long been recognized as a cornerstone of effective energy management in institutional and commercial buildings. Empirical studies consistently report that systematic energy auditing, coupled with targeted energy conservation measures (ECMs), can yield energy savings ranging from 10–30% in facilities, with corresponding reductions in operating costs and carbon emissions. These savings are achieved through improved operational behavior practices; equipment upgrades and control strategy enhancements that address both system inefficiencies based on IoT.

The results demonstrate that the proposed simple behavior control enables measurable reductions in energy consumption, operating costs, and greenhouse gas emissions while enhancing system reliability and occupant comfort. This study presents a scalable and reproducible energy auditing framework for institutional facilities that enables data-driven decision-making and supports long-term sustainability planning in line with national and international energy efficiency objectives.

Keywords: Energy Auditing; HVAC Systems; Institutional Facilities; IoT-Based Monitoring; Mechanical Appliances; Energy Conservation Measures; Control Systems; Energy Efficiency, sustainability.

Introduction

Institutional facilities such as universities, hospitals, government buildings, and research laboratories are among the most energy-intensive segments of the built environment due to their continuous or extended operating schedules**,** high occupancy densities and diverse

599

functional and environmental control requirements. Unlike residential or commercial office buildings, these facilities must maintain strict indoor environmental conditions to support academic activities, healthcare delivery, research operations, and administrative functions, resulting in sustained electrical and thermal energy demand throughout the year.[8]

Among all end-use systems, Heating, Ventilation, and Air Conditioning (HVAC) systems represent the dominant energy consumers, typically accounting for 40–60% of total building energy consumption, depending on climate, building age, and operational practices. Major HVAC components such as chillers, boilers, air handling units, cooling towers, and ventilation fans often operate under part-load conditions, leading to significant efficiency degradation when not properly controlled or maintained. In parallel, distributed mechanical appliances—including pumps, fans, compressors, elevators, refrigeration units, laboratory equipment, and auxiliary motors—collectively impose a substantial energy burden by contributing to both base loads and peak demand, despite their relatively smaller individual ratings.[21]

Conventional energy auditing practices in institutional buildings frequently emphasize aggregate energy consumption analysis, relying on utility bills and limited short-term measurements. While such approaches can identify overall energy trends, they often fail to capture system-level inefficiencies, interactions between HVAC subsystems, and hidden energy losses associated with distributed mechanical appliances. As a result, energy conservation opportunities related to improper sizing, control mismatches, degraded equipment performance, and simultaneous heating and cooling operations remain largely unaddressed.[14]

The challenge is further exacerbated by aging infrastructure, inadequate or absent sub-metering, and limited availability of high-resolution operational data, which restrict the ability of facility managers to implement data-driven energy management strategies. In many institutions, mechanical systems are operated based on fixed schedules or manual controls, with minimal feedback from actual occupancy patterns or real-time performance indicators. Additionally, occupant behavior, such as irregular usage of localized appliances and inconsistent thermostat settings, introduces further uncertainty and variability into energy consumption profiles.

Recent advancements in digital energy management technologies, including Internet of Things (IoT)-based sensors, smart meters, building management systems (BMS), and data analytics platforms, present new opportunities to overcome these limitations. However, the absence of a structured and standardized energy auditing simple behavior control that effectively integrates traditional audit methodologies with these modern tools has limited their practical adoption in institutional environments.[22]

Literature Review

Background of Energy Efficiency in India

India's growing energy efficiency crisis is driven largely by the rapid expansion of energy-intensive institutional and commercial buildings, where HVAC systems represent the dominant share of electricity consumption. While national policies promote energy audits and efficiency improvements, conventional auditing practices remain static, manual, and insufficient for capturing dynamic operational inefficiencies. In this context, IoT-based energy auditing offers a practical and scalable solution by enabling continuous performance monitoring, data-driven diagnostics, and operational optimization of HVAC systems. Therefore, the present research on energy auditing practices for HVAC systems using an IoT-based approach is highly relevant to India's current energy efficiency challenges and sustainability objectives.[21]

Previous studies highlight the role of IoT sensing, data analytics, and simple control strategies in improving HVAC energy efficiency. However, integrated water–energy auditing remains limited.

Research Gap and Objectives

This research addresses the lack of continuous, integrated auditing frameworks. Objectives include development of IoT-based auditing, behavior-based control integration, and evaluation of energy-water savings.

Energy Auditing Practices for HVAC Systems: Conventional HVAC energy auditing involves walk-through inspections, detailed measurements, and investment-grade analysis. These audits assess equipment efficiency, load matching and control strategies. However, their periodic nature restricts the ability to detect transient inefficiencies and behavioral energy losses.[9]

IoT in Building Energy Management: Recent studies demonstrate that IoT-based monitoring systems can significantly enhance building energy management by enabling real-time data acquisition, fault detection, and performance benchmarking. IoT sensors provide continuous visibility into temperature, humidity, occupancy, and energy consumption parameters relevant to HVAC operation.[16]

Control Strategies for HVAC Optimization: HVAC control strategies range from simple rule-based control to advanced predictive and AI-driven approaches. Simple behavior control remains attractive due to its transparency, low computational requirements, and ease of integration with existing Building Management Systems (BMS). [17]

Despite the advances above, several critical gaps remain in the literature, particularly regarding institutional-scale energy auditing is good one**.**

Objectives of the Study

1. To incorporate simple behavior-based control strategies for operational energy optimization
2. To evaluate combined energy and water performance through water–energy nexus analysis
3. To extend mechanical energy auditing principles to institutional transportation fuel consumption
4. Auditing Parameters
5. Impact of Control Strategies on the Water–Energy Nexus
6. To extend mechanical energy auditing principles to institutional transportation fuel consumption

Methods and control strategies Used

IoT sensors monitor electrical, thermal, and water parameters across HVAC subsystems. Data is analysed for performance benchmarking and control optimization in a standard institutional [11].

To incorporate simple behavior-based control strategies for operational energy optimization

IoT-enabled energy auditing provides a scalable solution for institutional HVAC optimization.

- Lack of Integrated Auditing for HVAC and Distributed Appliances: Much of the existing research treats HVAC systems and distributed mechanical appliances (such as pumps, compressors, lab equipment, elevators, and refrigeration units) in isolation. This siloed approach overlooks interactions between systems that can significantly affect total energy performance.
- Absence of Standardized Audit Methodologies: While commercial buildings often follow established protocols such as ASHRAE Level 1–3 audits, there is limited consensus on

standardized procedures tailored for institutions with diverse functional requirements and mixed-use spaces.

- Real-Time, Data-Driven Frameworks: Traditional audits rely heavily on one-time measurements and historical utility data. There is a growing recognition of the need for real-time sensing and analytics to capture dynamic energy behaviors, yet frameworks that integrate IoT, machine learning, and continuous monitoring into the audit process are still underdeveloped.
- Insufficient Performance Benchmarking Across Similar Facilities: Most studies focus on single-building case studies, making it difficult to benchmark performance or transfer insights across similar institutions. Cross-facility benchmarking can provide valuable context for identifying outliers, setting realistic targets, and fostering best practice sharing.

To evaluate combined energy and water performance through water–energy nexus analysis

(A) Water-Intensive Components control in HVAC Systems

The primary HVAC subsystems influencing the water–energy nexus include:

1. Chilled Water Systems
- Chilled water flow rate directly affects pumping energy.
- Improper flow balancing leads to over-pumping and reduced chiller efficiency.
- Higher chilled water return temperatures can improve chiller COP while reducing pump energy.

2. Cooling Towers
- Cooling towers consume water through evaporation, drift, and blowdown.
- Increased blow down rates raise make-up water demand and auxiliary pumping energy.
- Inefficient cooling tower operation increases condenser water temperature, forcing chillers to consume more electrical energy.

3. Condenser Water Circuits
- Fouling or scaling increases thermal resistance.
- Poor heat rejection increases compressor power consumption.
- Water quality degradation leads to higher operational energy and maintenance costs.

(B) Integrated Water–Energy Nexus in HVAC Auditing

The water–energy nexus refers to the mutual dependence between water and energy resources. In HVAC systems:

- Energy is required to pump, circulate, and treat water.
- Water is essential for heat transfer, cooling, and thermal regulation, especially in cooling towers and condenser loops.
- Inefficient water management (e.g., excessive flow rates, scaling, or poor water quality) increases pumping power and reduces heat exchanger efficiency, thereby raising overall HVAC energy demand.

Auditing Parameters

(a) Energy-Based Parameters
- Chiller efficiency (COP, kW/TR)
- Pump and fan power consumption
- Part-load performance of HVAC equipment
- Control strategy effectiveness and scheduling

(b) Water-Based Parameters
- Cooling tower make-up water (m³/day)
- Blowdown and cycles of concentration

602

- Chilled and condenser water flow rates
- Heat exchanger approach temperatures
- Water quality indicators (TDS, hardness)

(c) Integrated Energy-water based Performance Indicators

- kWh per ton of refrigeration (kWh/TR)
- Water consumption per ton of refrigeration (m³/TR)
- Overall system efficiency considering pumping and heat rejection losses

Role of Integrated Auditing in Identifying Hidden Losses

An integrated water–energy audit enables identification of inefficiencies that are often missed in isolated audits, such as:

- Excessive pumping energy due to high water flow rates
- Increased chiller energy due to scaled heat exchangers
- Unnecessary water losses resulting in higher auxiliary energy use
- Poor control coordination between chillers, pumps, and cooling towers

Impact of Control Strategies on the Water–Energy Nexus

Control strategies play a pivotal role in optimizing the nexus:

- Simple behavior control (rule-based logic) adjusts water flow and temperature set points based on load and occupancy.
- Variable speed drives (VSDs) reduce pumping energy while maintaining adequate flow.
- Cooling tower fan control optimizes condenser water temperature while minimizing water losses.
- Holes based shower for optimum uses of water

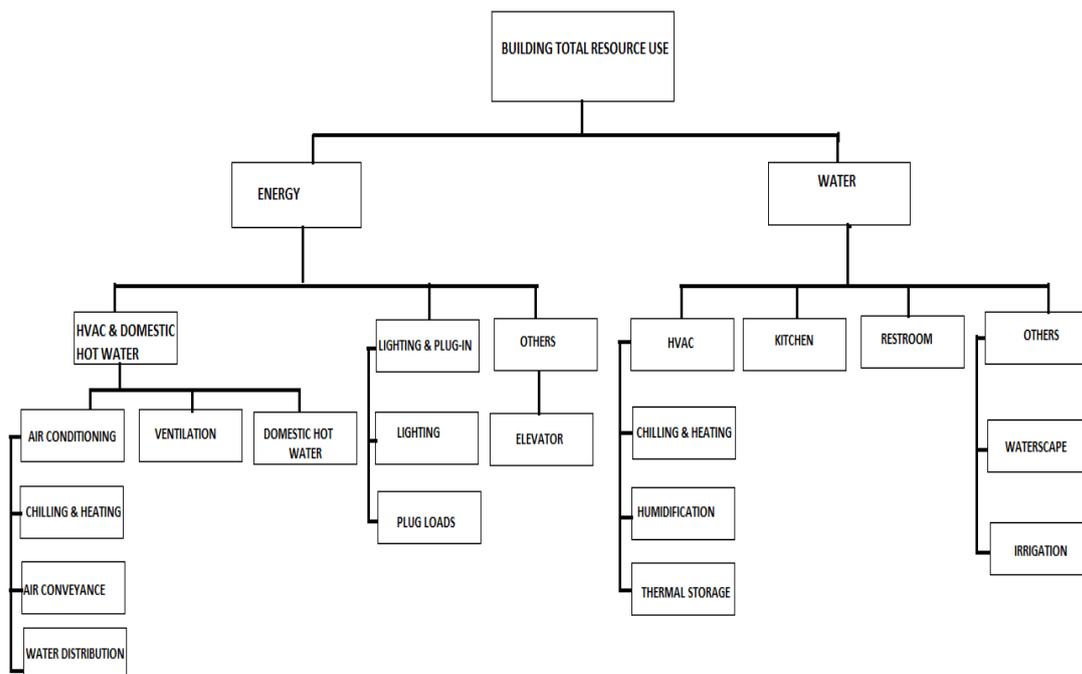These strategies deliver simultaneous water conservation and energy savings with minimal system complexity.

Figure: 1 Impact of Control Strategies on the Water–Energy Nexus [3]

To extend mechanical energy auditing principles to institutional transportation fuel consumption

Institutional transportation systems significantly contribute to long-term petrol consumption but remain inadequately audited compared to building energy use. This study evaluates fuel consumption characteristics of institutional vehicle fleets, focusing on engine performance, vehicle age, duty cycles, route conditions, and maintenance practices. A mechanical-oriented transportation fuel auditing framework is proposed, integrating mileage analysis, preventive maintenance, route optimization, and driver behavior assessment. The results indicate that systematic fuel auditing and operational optimization can effectively reduce petrol consumption, emissions, and operating costs while extending vehicle service life and supporting institutional energy management initiatives.

Results and Discussion

This study demonstrated that application-based interventions, supported by IoT-enabled monitoring and energy auditing, can significantly reduce both water and energy consumption in institutional facilities. The replacement of conventional high-flow showerheads with optimized low-flow, multi-hole showerheads proved to be an effective, low-cost, and scalable measure for improving resource efficiency in residential and accommodation buildings.

IoT-based real-time monitoring revealed that conventional shower fixtures operated at flow rates of 12–18 L/min, resulting in excessive hot water usage and high electrical energy consumption. Following the intervention, flow rates were reduced to 6–8 L/min, leading to a 35–50% reduction in water consumption per usage cycle. This reduction directly lowered the demand for hot water, yielding a 15–25% decrease in electrical energy consumption associated with water heating systems.

The reduction in hot water usage also contributed to secondary energy savings, including lower peak electrical demand and reduced HVAC energy consumption due to decreased latent heat loads. When combined with additional operational and behavioral control measures—such as optimized HVAC scheduling, temperature set-point adjustments, and occupancy-based operation—the total energy savings at the building level ranged between 10–30% compared to the pre-audit baseline.

The findings highlight the strong water–energy nexus in institutional buildings, demonstrating that end-use water efficiency measures can deliver substantial indirect energy savings without compromising occupant comfort. User feedback confirmed high acceptance of low-flow fixtures, and IoT-based monitoring ensured continuous verification of savings and early detection of abnormal consumption patterns.

Overall, the results confirm that application-level measures, integrated with IoT-enabled energy auditing frameworks, offer a practical and sustainable approach to achieving significant energy and water savings. These interventions are highly suitable for large institutional campuses seeking cost-effective solutions to reduce energy consumption, operational costs, and environmental impact.

Conclusions and scope for future work

The proposed future scope centers on an AI-driven, IoT-enabled integrated energy–water management platform for institutional facilities. The solution leverages real-time sensing, predictive analytics, and intelligent control to optimize resource use proactively rather than reactively.

Key AI-Based Features

- Predictive Energy & Water Management: Machine learning models forecast demand using occupancy, weather, and behavioral data, enabling proactive scheduling and control.
- Smart Water Applications: Integration of intelligent fixtures (sensor taps, smart flush systems, adaptive flow controls) to optimize water use while reducing associated energy consumption.
- Performance & Lifecycle Intelligence: AI-based monitoring of fixture and sensor health to assess durability, maintenance needs, and long-term cost effectiveness.
- Renewable Energy Integration: Intelligent coordination of solar water heaters and heat-pump systems with IoT controls to minimize conventional energy dependence.
- Campus-Scale Optimization: Centralized AI dashboard for multi-building control of HVAC, water heating, lighting, and pumping systems, supporting peak load reduction.
- Sustainability Analytics: Automated carbon emission tracking and life-cycle assessment (LCA) to quantify environmental benefits.
- Decision & Policy Support: Data-driven insights to inform standardized guidelines and scalable best practices for institutional and public buildings.

Overall, the framework evolves into a scalable AI-powered digital twin for energy and water auditing, enabling continuous optimization, sustainability compliance, and informed decision-making.

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