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Review Article

# A Critical Review and Proposed Technical Framework for Smart Switching Mechanisms in Renewable Energy Management

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## Abstract

The rapid transition toward renewable energy integration necessitates dynamic control mechanisms that can effectively manage the volatility of sources such as solar photovoltaics. While the built-up environment accounts for approximately 40% of global energy consumption, systemic inefficiencies in control logic often undermine potential savings. This paper presents a critical review and a novel taxonomy of smart switching mechanisms for solar energy management, moving beyond descriptive hardware surveys to analyze the soft architecture of intelligent actuation. The existing technologies are classified into a three-layered framework: Control Logic (tracing the evolution from deterministic rule-based systems to Model Predictive Control and Deep Reinforcement Learning), Communication Architecture (evaluating the trade-offs between Zigbee mesh networks, Global System for Mobile wide-area control, and hybrid Internet of Things ecosystems), and Optimization Targets (distinguishing between grid stability (load shedding), economic optimization (Demand Response), and energy autonomy (self-harvesting)). Crucially, this study evaluates these layers through the lens of techno-economic viability, identifying how misalignment between peak generation and load profiles hampers return on investment and increases the levelized cost of electricity for prosumers. This analysis reveals a significant gap between simulation and reality in Artificial Intelligence-driven control, identifying critical vulnerabilities in cybersecurity, particularly the risk of False Data Injection. To address these gaps, this paper proposes the Integrated Smart Switching Framework, a novel technical blueprint that converges Security-by-Design (embedded Intrusion Detection System (IDS)), Graded Actuation Logic, and Human-Centric Optimization. This framework provides a structured pathway for transitioning from theoretical AI simulations to resilient, real-world solar microgrid infrastructure. It is concluded that future research must prioritize graded individual switching limits, gamified user

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engagement strategies, and embedded IDSs to ensure the resilience of next-generation microgrids.

**Categories:** Energy Efficiency and Conservation, Power Electronics and Renewable Energy

**Keywords:** cybersecurity, demand response, model predictive control, smart switching, solar energy management

## Introduction And Background

### The global energy challenge and the built environment

The escalating demand for energy and the associated rise in greenhouse gas emissions represent one of the critical challenges of the 21st century [1]. Data from the United States Energy Information Administration [2] indicate that nearly one-third of the U.S. annual $CO_2$ emissions in 2019 were directly attributed to electricity consumption. Within this landscape, the built-up areas (residential, commercial, and educational facilities) are a dominant consumer. Studies indicate that commercial buildings alone account for approximately 20% of total energy consumption in most developed countries [3]. This demand is increasingly driven by shifting trends in global heating and cooling requirements [4] and the adoption of advanced HVAC technologies in sustainable building designs [5]. A significant portion of this consumption is driven by essential services, such as space conditioning, water heating, and, most notably, lighting. Research by the National Building Controls Information Program suggests that substantial energy wastage in these sectors stems not merely from high usage demand but from systemic inefficiencies in control mechanisms, including issues with input devices, software programming, and operator interference [6]. Consequently, achieving energy sustainability requires more than just efficient appliances; it demands intelligent, granular control over how energy is distributed and consumed.

### The role of smart switching in renewable energy management

To mitigate these inefficiencies, there is an urgent need for robust Energy Management Systems capable of real-time monitoring and dynamic control. The smart switching mechanism has emerged as an indispensable tool for achieving the granularity required to remotely manage building loads [7], detect faults [8], identify locations of excessive usage [9], and remotely manage loads [10]. It is estimated that efficient power management via smart switching can yield energy savings of up to 20% [11]. This capability is particularly critical when integrating renewable energy sources, such as solar photovoltaics, into the grid. In solar energy management systems, the switching mechanism plays a pivotal role in optimizing energy distribution by balancing real-time demand against variable generation [12]. The goal is to maximize the utilization of solar energy while minimizing reliance on grid electricity and reducing overall waste.

This technological shift aligns with global sustainability frameworks, including the Sustainable Development Goals 7, 9, 11, and 13 [13], as well as national policies such as the Nigerian Electricity Act 2023 [14], which advocates for an integrated resource plan that recognizes the integration of renewable energy. Beyond technical synchronization, smart switching is a primary driver of economic viability in solar microgrids. By aligning peak generation with volatile load profiles, high-granularity switching optimizes the levelized cost of electricity and improves Return on Investment (ROI) through increased self-consumption. Furthermore, the transition from binary to graded actuation logic reduces mechanical stress on switching components, lowering long-term operating expenses by extending the hardware lifecycle.

### Research gap and objectives

While the evolution of automation has progressed from simple mechanical timers to sophisticated IoT-based smart sockets, existing literature often treats these devices in isolation or focuses solely on their hardware construction. There remains a need for a comprehensive analysis that bridges the gap between physical switching hardware and the advanced control logic, such as Model Predictive Control (MPC) and Maximum Power Point Tracking (MPPT), required for

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self-harvesting solar systems. Furthermore, as these systems become increasingly networked, they face new vulnerabilities, necessitating a design approach that treats cybersecurity not as an afterthought but as a fundamental pillar of the architecture.

### Contribution and structure

This paper moves beyond a descriptive survey to provide a critical review and taxonomy of smart switching mechanisms for solar energy management. Specifically, this work:

(i). Evaluates the state-of-the-art by reviewing current trends in Intelligent Energy Management Systems (IEMS) and the evolution of smart socket hardware;

(ii). Analyses control architectures by examining the soft architecture of these systems, focusing on algorithmic approaches like discrete-time MPC and MPPT for optimizing self-energy harvesting;

(iii). Identifies critical gaps by highlighting overlooked areas in current research, specifically the lack of graded individual switching, the need for gamified user engagement strategies, and the imperative for robust cybersecurity protocols to prevent data corruption and unauthorized access.

(iv). Proposes the Integrated Smart Switching Framework (ISSF), a multi-layered architecture that provides specific logic and security protocols to bridge the simulation-to-reality gap in smart energy management.

By synthesizing these elements, this review aims to provide a structured pathway for researchers and engineers developing the next generation of secure, efficient, and user-centric solar energy management systems.

## Review

### Review methodology and scope

To ensure a comprehensive analysis of the smart switching landscape, this review adopts a structured approach to identifying, selecting, and categorizing relevant literature. The scope encompasses the hardware evolution of smart sockets, communication protocols, and the algorithmic intelligence used in solar energy management systems.

#### *Literature Search and Selection Strategy*

The review draws upon high-impact peer-reviewed journals, conference proceedings, and relevant grey literature, focusing on developments in IEMS, Home Energy Management Systems (HEMS), and Internet of Things (IoT)-enabled switching hardware. Key databases, including IEEE Xplore, MDPI, ScienceDirect, Springer Nature and ACM Digital Library, were consulted to retrieve studies that propose novel architectures or experimental prototypes.

The search strategy utilized a combination of keywords derived from the core functional blocks of smart energy systems:

(i). Hardware Keywords: "Smart Socket", "Smart Plug", "Smart Switch", "Arduino Power Monitoring".

(ii). Communication Keywords: "Zigbee", "GSM Home Automation", "Wireless Sensor Networks", "IoT".

(iii). Control & Logic Keywords: "Model Predictive Control", "Maximum Power Point Tracking", "Demand Response", "Reinforcement Learning in HEMS".

#### *Classification Framework*

To move beyond a chronological listing of devices, this review classifies the selected literature into a novel taxonomy based on three distinct layers of the smart switching architecture:

(i). The Physical Layer (Hardware): Analysis of the physical construction of smart sockets, examining the integration of microcontrollers (e.g., Arduino, Raspberry Pi) with sensing modules (voltage/current sensors) and the trade-offs between component cost and measurement accuracy.

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(ii). The Network Layer (Communication): Evaluation of connectivity standards, specifically comparing the range, power consumption, and topology of Zigbee-based systems versus Global System for Mobile (GSM) and Wireless Fidelity (Wi-Fi) implementations in residential and commercial settings.

(iii). The Intelligence Layer (Control Logic): Examination of the decision-making algorithms that drive the switch. This includes a progression from simple direct control (on/off) to advanced logic such as load shedding, predictive self-harvesting, and AI-driven behavior modification.

*Criteria for Analysis*

Selected studies are evaluated not only on their theoretical design but also on their implementation feasibility. Key metrics for this analysis include the system's ability to handle load demand analysis (Base vs. Peak load), its capability for grid interaction (synchronization and islanding), and the integration of user-centric features such as remote monitoring.

This structured methodology ensures that the subsequent sections provide a balanced critique of the soft and hard architectures required for next-generation solar energy management.

## General overview

*Trends in the Intelligent Energy Management System*

Research in IEMS focuses on refining architectural, technological, and algorithmic approaches to enhance energy efficiency.

Architectural Taxonomies and IoT Integration: The fundamental structure of Energy Management Systems has evolved from rigid monitoring tools to flexible, layered architectures. Earlier research [15] provides a foundational analysis of the architectural and algorithmic requirements for efficiency, while further studies [16] extend this by integrating Smart Appliances into the control loop.

Some researchers [17] offer a standardized IoT-based architectural framework consisting of three distinct functional layers:

(i). Perception Layer: Responsible for data acquisition via sensors and smart meters.

(ii). Network Layer: Facilitates robust data transmission and connectivity protocols (e.g., ZigBee, Wi-Fi, 5G).

(iii). Application Layer: Where the high-level control logic and user interfaces reside.

Further, Building Energy Management Systems have been categorized [18] based on their modeling methodology, distinguishing between white-box (physics-based), black-box (data-driven/empirical), and grey-box (hybrid) models to assess their impact on consumption factors.

AI-Driven Analytics and Anomaly Detection: Data-driven approaches rely heavily on the quality and granularity of consumption data. Recent surveys [19,20] synthesized over 50 distinct power consumption databases, ranging from residential high-density urban apartments in Europe to commercial office complexes in Asia. By benchmarking these cases against sampling frequencies (varying from 1 Hz to 15-minute intervals), the research identifies that anomaly detection performance is highly contingent on building typology, suggesting that a “one-size-fits-all” AI model fails in diverse architectural environments.

Central to their research is the development of a novel dataset for Anomaly Detection. This is critical because detecting deviations in energy patterns allows for:

(i). Proactive Fault Detection: Identifying equipment failure before catastrophic breakdown.

(ii). Wastage Mitigation: Pinpointing unnecessary consumption cycles.

(iii). System Resilience: Enhancing the security of energy grids against external or internal shocks.

Algorithmic Optimization: The literature marks a transition from static scheduling to dynamic, intelligent controllers. Load scheduling is increasingly managed through Artificial Neural Networks (ANN) [21], Fuzzy Logic [22], and Heuristic Optimization [23]. However, Deep Reinforcement Learning (DRL) has emerged as the most promising frontier for autonomous building management [24]. Table *1* highlights the algorithmic approaches, their advantages and challenges.

| Technology | Advantages | Challenges |
|---|---|---|
| RL/DRL | High adaptability; improves efficiency in complex, non-linear environments | High training latency; limited real-world testing |
| Heuristics | Fast computation; easy to implement for specific tasks | May settle for local optima; lacks generalization |
| Meta-heuristics | Effective for large-scale scheduling | Computationally intensive for real-time applications |

**TABLE 1: Advantages and Challenges of the Algorithmic Approaches**

Refer to [25,26]. DRL, Deep Reinforcement Learning; RL, Reinforcement Learning

Research [27] exemplifies this by utilizing DRL to optimize solar energy self-consumption, specifically managing indoor temperatures and domestic hot water through predictive control.

Multi-Agent Systems and Ambient Intelligence: To handle the complexity of IEMS, researchers utilize Multi-Agent Systems [28]. In these systems, an agent is defined as a coupling of perception, reasoning [29], and acting components [30]. For distributed intelligence, an architecture has been proposed [31] where agents are grouped into functional clusters: Control and Monitoring, Information, Application, and Management and Optimization. The ambient intelligence paradigm creates an invisible user interface augmented with AI [32], embedded within the physical environment to enhance comfort and financial efficiency [33].

Emerging Trends and the Socio-Technical Transition: The future of the Internet of Energy is shaped by several emerging technologies identified by researchers [34]:

(i). Blockchain: Enabling decentralized, P2P energy trading and secure IoT platforms.

(ii). Context-Aware Computing: Systems that adapt to real-time environmental and user-comfort feedback.

(iii). Resilience-Oriented Management: Ensuring stability in decentralized grids.

The technical success of these systems is intrinsically linked to human factors [35]. Since residential consumption accounts for 72% of global greenhouse gas emissions [36], researchers like [37] and [38] argue that energy management must be coupled with regulatory frameworks designed to incentivize and sustain behavioral changes in occupants.

### *Smart Switch Development*

The concept of automation has a longstanding history, originating from rudimentary electromechanical coupling, such as early experiments linking clock mechanisms to lighting circuits. Over time, proprietary systems were developed to manage alarms, sensors, and surveillance, establishing the foundation for the first automated building infrastructures [39].

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Early iterations of the Smart Home Automation System (SHAS) include the voice-controlled architecture [40] utilizing Zigbee protocols. In this model, user commands are transmitted between a base station and remote stations. Alternatively, GSM-based Home Automation Systems facilitate control via Short Message Service (SMS). These systems typically interface a GSM modem with a switching module via a microcontroller.

While researchers have extensively explored GSM and Zigbee-based control, these protocols present distinct limitations. Short-range transmission capabilities constrain Zigbee, whereas GSM reliability is strictly dependent on cellular signal coverage [41]. Table *2* summarizes the foundation of early automation systems and their limitations.

| Technology | Description | Limitation |
|---|---|---|
| Voice-Controlled, Zigbee-based SHAS | Enabled user control of in-home appliances via voice commands communicated over a ZigBee wireless network between a base and remote station | Limited Range: ZigBee's maximum effective communication distance is a critical constraint without mesh repeaters |
| GSM-based Home Automation System | Controlled appliances by sending SMS texts from a mobile phone to an in-home GSM modem, interfaced with a switching module via a microcontroller | Signal Dependence: Required adequate and stable GSM mobile network coverage for functionality |

**TABLE 2: Description and Limitations of Early Automation Systems**

SHAS, Smart Home Automation System; GSM, Global System for Mobile; SMS, Short Message Service

Contemporary smart switches increasingly integrate embedded devices with software ecosystems, leveraging the IoT [42]. This paradigm shift allows for:

(i). Ubiquitous Access: Enabling control from any location.

(ii). Resource Optimization: Significantly reducing energy waste.

(iii). Enhanced Security: Providing real-time monitoring.

Despite the emergence of various residential network types, GSM wireless transmission remains a critical, cost-effective component of automation. While previously implemented in irrigation controllers, digital energy metering, and traffic monitoring, this study specifically targets energy conservation in residential and commercial environments. The primary objective is to develop an automated switching system capable of remote monitoring and regulation, thereby optimizing energy resource usage via a mobile platform [43]. The proposed control logic is implemented using an Arduino Uno microcontroller based on the ATmega328P architecture (operating at 16 MHz). The Arduino acts as the central processing unit, interfacing with the following key components:

(i). Communication: An Ethernet shield and Teleduino middleware for internet connectivity.

(ii). Power Management: A 7805 voltage regulator and external power supply.

(iii). Actuation: Relays driven by transistors and diodes to switch high-voltage appliances.

The system logic is programmed in C. The ATmega328P utilizes its digital I/O pins (specifically Pulse Width Modulation capabilities) to manage switching states. The system establishes a modern automation framework where appliance status is monitored globally. Commands originate from an Android application, traverse the internet via the Ethernet interface, and are processed by the microcontroller to trigger the relay modules, effectively bridging the gap between digital control and physical appliances. Figure *1* is the operational flow diagram for the smart switch system [43].

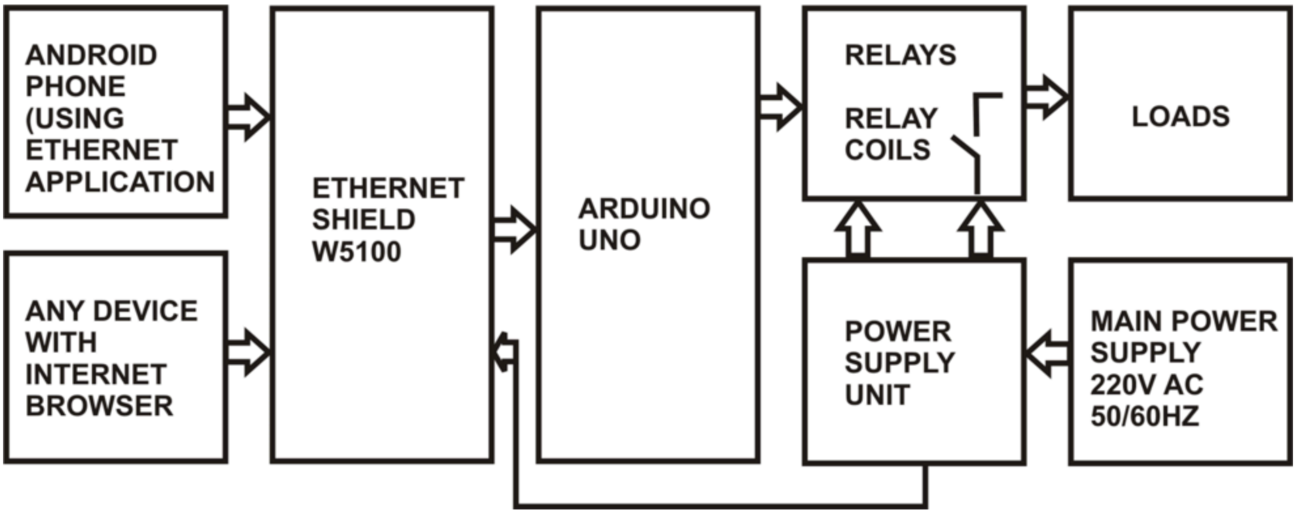

**FIGURE 1: Schematic of Smart Switch System**

### *Advancement in Smart Socket Development*

The evolution of smart sockets has focused heavily on retrofitting existing infrastructure without intrusive rewiring. Early prototypes [44] utilized the Zigbee wireless protocol (operating on the 2.4 GHz ISM band) to enable remote actuation of appliances. Expanding on this, subsequent designs integrated power metering capabilities. For instance, a Zigbee-based socket developed in [45] utilized a resistive voltage divider network to step down mains voltage for a power metering chip. While functional, these early iterations exhibited significant performance variances across different deployment cases. For instance, Zigbee-based prototypes in residential settings reported a 15% packet loss when operating behind reinforced concrete walls, whereas GSM-based cases in rural irrigation trials maintained 98% connectivity but suffered from high latency (up to 5 seconds) during peak network congestion [46]. This highlights a critical need to match communication protocols to the specific physical constraints of the building environment.

A significant portion of the literature focuses on trade-offs between hardware complexity and measurement accuracy. Two primary approaches exist:

(i). Current-Only Sensing: Several designs simplify hardware by measuring only current and assuming a constant reference voltage for power calculations. An Arduino Duemilanove-based plug was developed [47] using a current transformer and Ethernet connectivity. Similarly, an ATmega328 microcontroller was employed [48] to manage a Zigbee transceiver and relay. Both systems suffer from accuracy degradation as they fail to account for fluctuations in the root-mean-square voltage of the main supply.

(ii). Full Power Sensing: To address the limitations of constant-voltage assumptions, a Zigbee PRO-based design that measures both voltage and current was proposed [49]. Data are transmitted to a master computer for power calculation. However, this centralized processing approach is susceptible to calculation errors caused by packet loss during transmission.

Researchers [50] advanced the architecture by integrating a Raspberry Pi as a master controller within a Zigbee network. This design utilizes a step-down transformer and a full-bridge rectifier for signal conditioning. However, the use of magnetic transformers for voltage measurement introduces phase shifts between primary and secondary voltages, potentially leading to erroneous power factor calculations [49,51]. Further complexity is noted in active voltage regulation designs [50,52], where the resolution of the analogue-to-digital converter can limit the precision of active power reduction measurements.

Beyond basic switching, researchers have explored advanced interaction models:

(i). Voice Control: A speech-operated system was proposed [53] utilizing a command executor architecture (environment interface, statement interface, reasoning module, and command generator). While novel, the system lacks power monitoring capabilities and relies on rigid, pre-programmed command sets.

(ii). Motion and Presence Detection: To mitigate standby power consumption, motion sensors were integrated [54]. The socket completely cuts power when no user is detected and restores it upon return. However, this design relies on binary state detection rather than real power monitoring.

Cloud Integration and IoT modern iterations, such as the socket proposed [55] by integrating Zigbee communication with dedicated power metering chips to transmit Time-of-Use (TOU) data to cloud servers. While this facilitates remote data access and billing analysis, this specific design iteration is limited to monitoring only, lacking the control logic required to remotely actuate the appliance.

## Taxonomy and critical analysis of smart switching mechanisms

To systematically evaluate the state-of-the-art in solar energy management, this review classifies existing switching mechanisms into a three-layered taxonomy (Figure *2*). The following subsections provide a detailed technical critique of these layers, starting with the evolution of control logic from deterministic rules to adaptive learning.

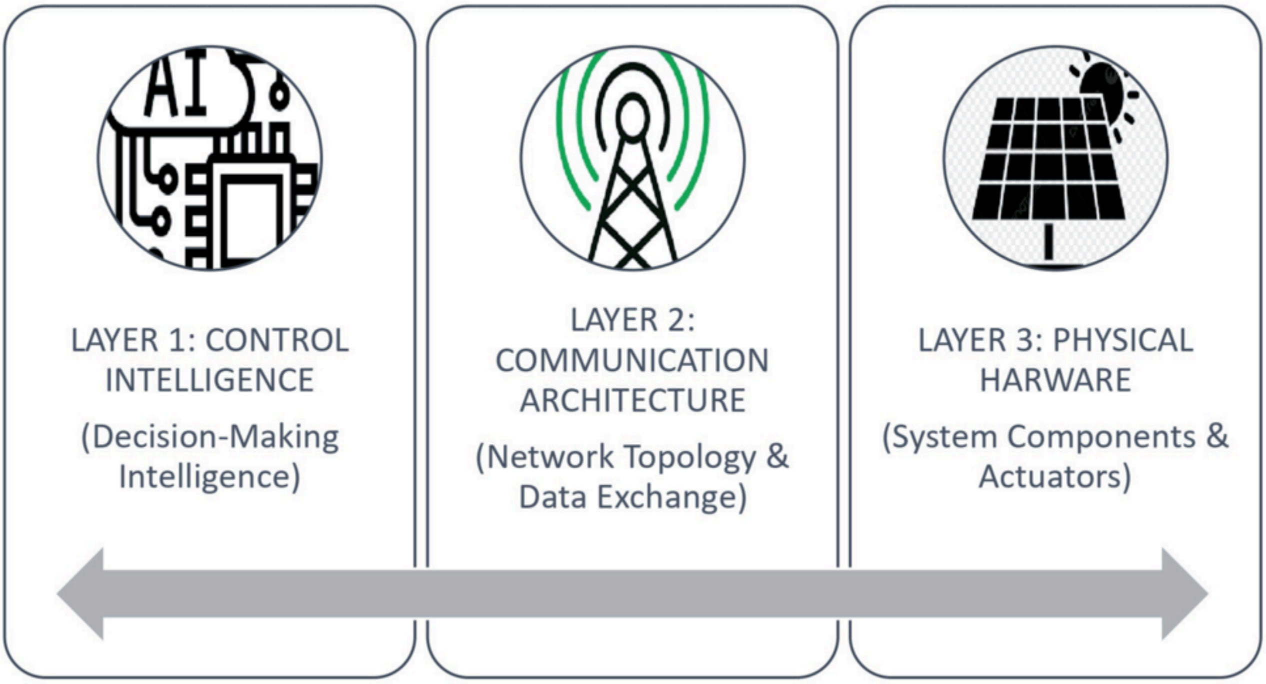

**FIGURE 2: Proposed Three-Layered Taxonomy for Smart Switching Mechanisms**

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### *Classification by Control Logic*

The sophistication of its decision-making algorithm fundamentally defines the efficacy of a smart switch. The following literature demonstrates a clear evolution from rigid, rule-based systems to adaptive, artificial intelligence-driven control.

(i). Deterministic and Threshold-Based Control: The most fundamental control level utilizes deterministic logic gates (AND, OR, NOT) and switching theory to execute actions based on pre-set thresholds. These systems operate on strict "if-then" rules [56,57]. For instance, a Home Manager Algorithm that employs a flowchart-based logic to switch dynamically between four modes - MPPT, partial discharging, float charging, and fast charging - based strictly on the battery's state of charge and instantaneous PV power availability. While robust, these systems are reactive and cannot anticipate future load fluctuations [58].

(ii). Model Predictive Control (MPC): A significant leap in complexity involves MPC. Unlike threshold systems, MPC utilizes a discrete-time model of the system to predict behavior over a finite time horizon [59]. Research has shown that Forward-Difference Euler approximation is employed to discretize continuous-time models, allowing the controller to calculate optimal inputs that drive the system toward a reference trajectory while satisfying constraints. MPC is particularly effective in managing the non-linear dynamics of self-harvesting systems, such as regulating the output of flyback converters via proportional-integral-derivative controllers to maintain MPPT [60,61].

(iii). AI-Driven and Reinforcement Learning: The frontier of smart switching lies in Computational Intelligence. Recent surveys [25] analyze the application of Reinforcement Learning (RL) and DRL in HEMS. While standard RL improves energy efficiency, DRL algorithms are capable of learning more complex policies for tasks like indoor temperature control [62]. Despite their promise, these approaches face a simulation-to-reality gap. These researchers [24] note that DRL algorithms are often too slow for real-time training on physical hardware, resulting in only 12% of such approaches being tested in real-world scenarios.

A critical synthesis of the literature reveals that the intelligence layer suffers from a fundamental decoupling between algorithmic complexity and physical execution. While DRL and MPC offer superior theoretical optimization for solar self-consumption, they frequently ignore the stochastic nature of hardware-level variables, such as sensor noise and relay actuation latencies. Most studies assume a perfect sensing environment, yet real-world smart switches operate in high-interference settings where packet loss can lead to delayed or erroneous switching decisions. This simulation-to-reality gap is further exacerbated by the high computational cost of running deep neural networks on low-power microcontrollers like the ATmega328P. Consequently, many systems that appear efficient in simulation risk becoming unstable or unresponsive when deployed in a live microgrid, highlighting a critical need for hardware-aware control logic that integrates physical constraints directly into the reward functions of the learning agents.

### *Communication and Network Architecture*

The scalability and reliability of smart switching systems are dictated by their communication protocols. This review identifies three dominant architectures, each with distinct trade-offs regarding range, power consumption, and topology.

(i). Zigbee and Mesh Networking: Zigbee (IEEE 802.15.4) is the predominant protocol for local device communication due to its low power consumption and support for mesh topologies [63]. Designs typically utilize modules like the XBee-Pro S2C, which offers an indoor range of up to 100 meters and utilizes the DigiMesh protocol to allow router nodes to sleep, conserving power [64]. The mesh topology is critical for overcoming signal obstruction in complex building environments, a limitation often cited in earlier point-to-point designs [65].

(ii). GSM and Wide-Area Control: For remote monitoring where local Internet infrastructure is unreliable, Global System for Mobile (GSM) communication is favored. Researchers [66,67] highlight the utility of GSM in transmitting SMS-based control commands to switching modules via a modem interface. This architecture is essential for the Smart Hub concept, bridging the internal building network to external cellular networks for authorized remote access.

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(iii). Hybrid Internet of Things Architectures: Modern frameworks increasingly adopt a hybrid approach. For example, the prototype analyzed in this survey integrates an Arduino Nano microcontroller with an Ethernet shield for internet connectivity, while simultaneously using radio frequency or Zigbee for local sensing. This layered approach described [17] as consisting of perception, network, and application layers enables the integration of smart sockets into the broader IoT ecosystem.

Figure *3* does a topology comparison by illustrating how the Zigbee Mesh Networks allow device-to-device hopping to extend range, whereas GSM/Star topologies require direct connection to a central node.

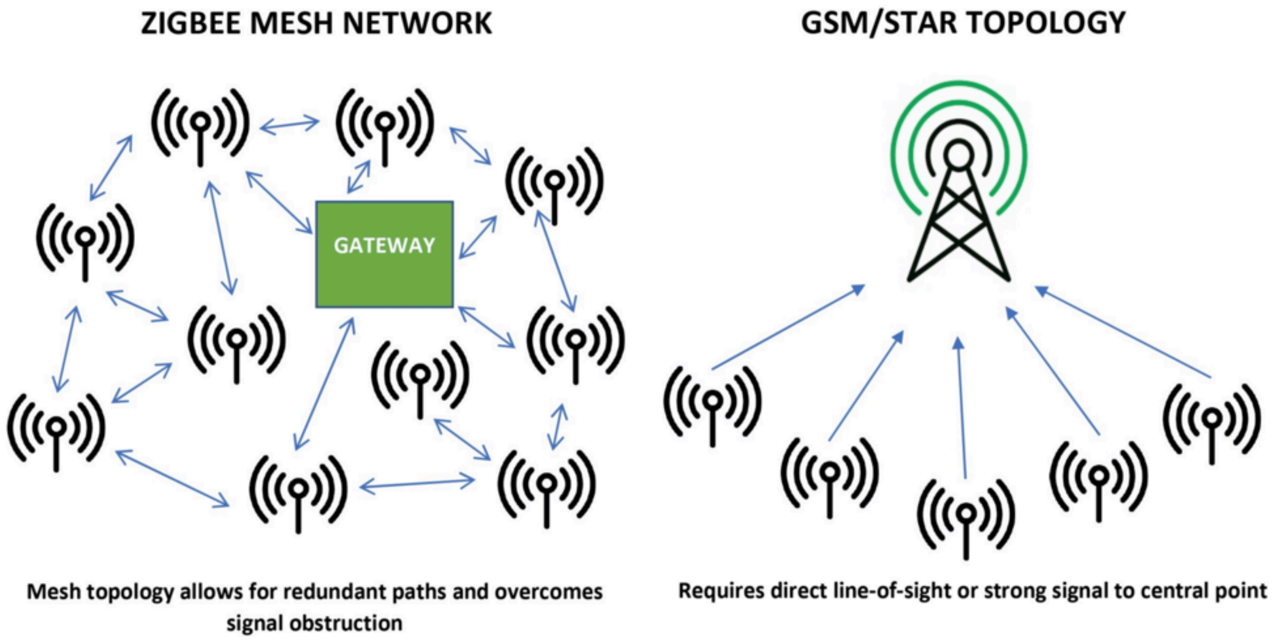

**FIGURE 3: Network Topology Comparison**

Beyond the selection of specific protocols, a balanced analysis of current literature reveals a critical trade-off between communication reliability and system scalability that remains largely unresolved. While mesh-based architectures, such as Zigbee-Pro, offer robust range extension for complex indoor environments [64], they introduce significant multi-hop latencies that can disrupt real-time load-shedding commands in time-critical energy scenarios. Conversely, the widespread reliance on GSM for remote monitoring in developing regions [68] exposes systems to packet-drop vulnerabilities during peak network congestion, where a failed handshake between the sensor and the cloud can result in a stuck switch state. Furthermore, the lack of standardized encryption across these disparate communication layers creates a fragmented security landscape. Most reviewed studies prioritize data throughput over integrity, overlooking the risk of man-in-the-middle attacks that could maliciously toggle high-power loads to destabilize the local inverter. This suggests that future communication frameworks must move toward network-agnostic protocols that can maintain state synchronization even during intermittent connectivity loss.

*Comparison of Optimization Targets*

Smart switching mechanisms are not monolithic; they are designed to optimize specific operational metrics. These targets are categorized into three primary domains:

(i). Grid Stability via Load Shedding: In solar microgrids, the primary optimization target is often stability. Smart switches execute load-shedding strategies to disconnect non-essential loads when demand exceeds generation, preventing system frequency collapse. Chandra and Pradhan [69] emphasize that this must be done strategically to minimize user

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disruption while protecting inverter equipment.

(ii). Economic Optimization (Demand Response): For grid-tied systems, the target shifts to cost reduction through Demand Response (DR). Researchers [70,71] discuss how smart switches integrate with price-based DR programs, shifting consumption to periods of high solar irradiance or low grid prices. This allows the system to participate in peak shaving, reducing reliance on expensive peaker plants.

(iii). Energy Autonomy (Self-Harvesting): In self-harvesting architectures, the goal is to maximize independence [72]. The system prioritizes the use of locally generated DC power (from PV and ultracapacitor buffers) for active electronics, switching to the AC grid only as a last resort. This ensures that critical infrastructure remains operational during blackouts, a feature vital for developing regions with unstable grid supplies [73].

*Synthesis and Comparative Analysis*

While the literature extensively explores cost minimization and grid stability as primary optimization targets, a critical gap remains in the integration of user-centric comfort and device longevity into these mathematical models. Most current optimization frameworks [31,68] operate on a “greedy algorithm” basis, prioritizing immediate load shedding to achieve energy savings. However, this balanced analysis identifies a recurring failure to account for the physical degradation of switching hardware; frequent micro-switching, often a byproduct of high-frequency AI optimization, leads to relay contact pitting and premature failure of the switching mechanism itself. Furthermore, the social dimension of energy management is frequently neglected, as studies often assume that users will tolerate abrupt power transitions if it results in a 5% cost reduction, ignoring the psychological and functional impact of frequent power cycling on sensitive household electronics. Therefore, a significant issue in current research is the lack of a weighted multi-objective approach that reconciles economic gain with hardware health and consumer behavior, suggesting that future frameworks must move toward human-in-the-Loop optimization.

To systematically evaluate the state-of-the-art in solar energy management, the existing switching mechanisms can be synthesized into a comprehensive comparison. A truly balanced analysis requires moving beyond classification to examine the specific findings and technical bottlenecks identified in recent literature. Table *3* provides a synthesis of key studies, highlighting their contributions to the field alongside the persistent issues, such as simulation-to-reality gaps and hardware-induced errors, that continue to hinder fully autonomous deployment.

| Study Category | Key References | Deployment/Case Context | Important Findings & Contributions | Identified Technical Problems/Issues |
|---|---|---|---|---|
| Architectural Frameworks | 1 | Global/Multi-Sector (Residential, Commercial, & Industrial) | Established a three-layered IoT model (Perception, Network, Application) for energy management | Lack of integration between physical hardware latencies and high-level soft architecture. |
| Control Logic & AI | 2 | Residential/Thermal Loads | Demonstrated that DRL models can optimize solar self-consumption and manage thermal loads | A significant simulation-to-reality gap exists; only 12% of DRL models are validated on physical hardware |
| Communication Protocols | 3 | Urban Residential vs. Rural Agricultural | Proven reliability of Zigbee Mesh for local range extension and GSM for remote cellular access | GSM dependence on cellular coverage; Zigbee's inherent range constraints without repeaters |
| Hardware & Sensing | 4 | Laboratory/Controlled Environment | Advanced the use of full power sensing (voltage and current) to improve data granularity | Hardware complexity leads to phase shifts and packet loss errors during centralized processing |
| Security & Optimization | 5 | Critical Microgrids & Prosumer Clusters | Integration of Blockchain and Demand Response for decentralized economic optimization | High vulnerability to false data injection and malicious actuation in networked switches |

**TABLE 3: Comparative Analysis of Findings from Selected Studies in Smart Switching Mechanisms**

1 [15,17], 2 [24,62], 3 [64], 4 [60,50], 5 [50,71]. DRL, Deep Reinforcement Learning; IoT, Internet of Things; AI, artificial intelligence

The findings summarized in Table *3* underscore a clear technological trajectory; while sensing and communication hardware have reached a level of commercial maturity, the intelligence layer remains reactive. As identified in the comparative analysis, the most pressing issues are the inaccuracies in hardware-level sensing and the computational overhead of AI-driven control.

### *Summary of Taxonomy and Critical Synthesis*

The three-layered taxonomy presented in this section, encompassing control logic, communication architecture, and optimization targets, reveals a significant technological maturation in the individual components of smart switching. However, the synthesis of these layers remains fragmented. While "Classification by Control Logic" section demonstrated the evolution toward adaptive AI-driven control, these advancements are often throttled by the physical constraints discussed in "Communication and Network Architecture" section, where network latencies and hardware sensing inaccuracies (such as phase shifts in voltage transformers) undermine algorithmic precision. Furthermore, the analysis of optimization targets in "Comparison of Optimization Targets" section suggests that the industry is currently prioritizing economic gains and grid stability over hardware health and user interpretability.

This critical review confirms that the primary bottleneck is not the lack of hardware capability, but rather an integration deficit. Current systems operate as a collection of disparate parts rather than a unified, resilient framework. This lack of a holistic security-by-design and hardware-aware logic architecture leaves existing switches vulnerable to both operational failures under stochastic solar loads and external cyber-physical disruptions. These identified inconsistencies provide the necessary justification for the transition from descriptive reviews to the identification of specific research gaps in the following section.

## Critical gaps and future research directions

While the taxonomy illustrates significant progress in hardware and control logic, this critical analysis reveals substantial gaps that hinder the widespread, secure deployment of smart switching mechanisms. The transition from theoretical prototypes to robust, real-world infrastructure requires addressing the following:

### *The Cybersecurity Imperative in Smart Actuation*

As smart switching mechanisms increasingly rely on wireless communication modules (Zigbee, Wi-Fi, GSM) and cloud-based smart hubs, they expand the attack surface of the energy grid. This review identifies a critical vulnerability in current software architectures: the susceptibility to False Data Injection and malicious actuation. Cyber attackers actively target these systems to corrupt smart meter data, spoof user credentials, or inject malware. In a solar energy management context, a compromised switch could force a battery to discharge during peak generation or disconnect critical loads, destabilizing the microgrid.

Future design initiatives must move beyond basic password authentication. There is an urgent need for research into IoT Forensics and intrusion detection systems (IDSs) embedded directly within the microcontroller hardware. Security must be treated as a pillar of product design, implementing threat modeling to pre-emptively identify risks before deployment.

### *Human-in-the-Loop Engagement and Interpretability*

A recurring limitation in existing indirect control systems is the alienation of the end-user. While automation increases efficiency, recommendation systems often suffer from the cold-start problem, where the system fails to engage users effectively before it has learned their specific behaviors. Users frequently disregard automated suggestions because the reasoning behind a particular switching decision (e.g., load shedding activated due to low solar irradiance) is not clearly communicated or interpretable.

To bridge this gap, future research should explore Gamified Energy Management Frameworks, particularly in institutional settings like university hostels. Studies [74] suggest that gamification is more effective than conventional automation in fostering long-term behavioral change and energy awareness among students.

### *Advanced Control from Binary to Graded Switching*

Most current smart sockets operate on a binary basis (ON/OFF). This review proposes a shift toward Graded Individual Switch Control. Unlike simple scheduling, a graded system would enforce power limits at the individual socket level. If an appliance exceeds the grade or power rating allowed for that specific node (e.g., a high-wattage heater in a low-power circuit), the switch would autonomously prevent it from powering on. This adds a layer of safety and demand-side management that current binary switches lack.

To implement such granular control, future systems must integrate RL. As noted [24], RL frameworks are capable of learning complex, multi-tasking policies that traditional neural networks cannot handle. Research opportunities lie in developing multi-tasking RL frameworks that can simultaneously optimize for user comfort, battery health, and graded power limits.

*Comparative Benchmarking*

Finally, there is a distinct lack of comparative studies between these novel computational approaches (Graded/RL-based) and traditional non-graded switching mechanisms. Future work must establish standardized metrics to quantify the efficiency gains of AI-driven switching against standard rule-based automation in real-world solar plants.

### Proposed framework: the ISSF

While the preceding sections categorize the current state of the art, this section proposes a novel ISSF. The ISSF is designed to bridge the simulation-to-reality gap by providing a technical blueprint for the next generation of resilient solar management switches. Figure 4 illustrates the proposed ISSF architecture, showing the convergence of physical sensing, embedded security, graded actuation logic, and human-centric feedback.

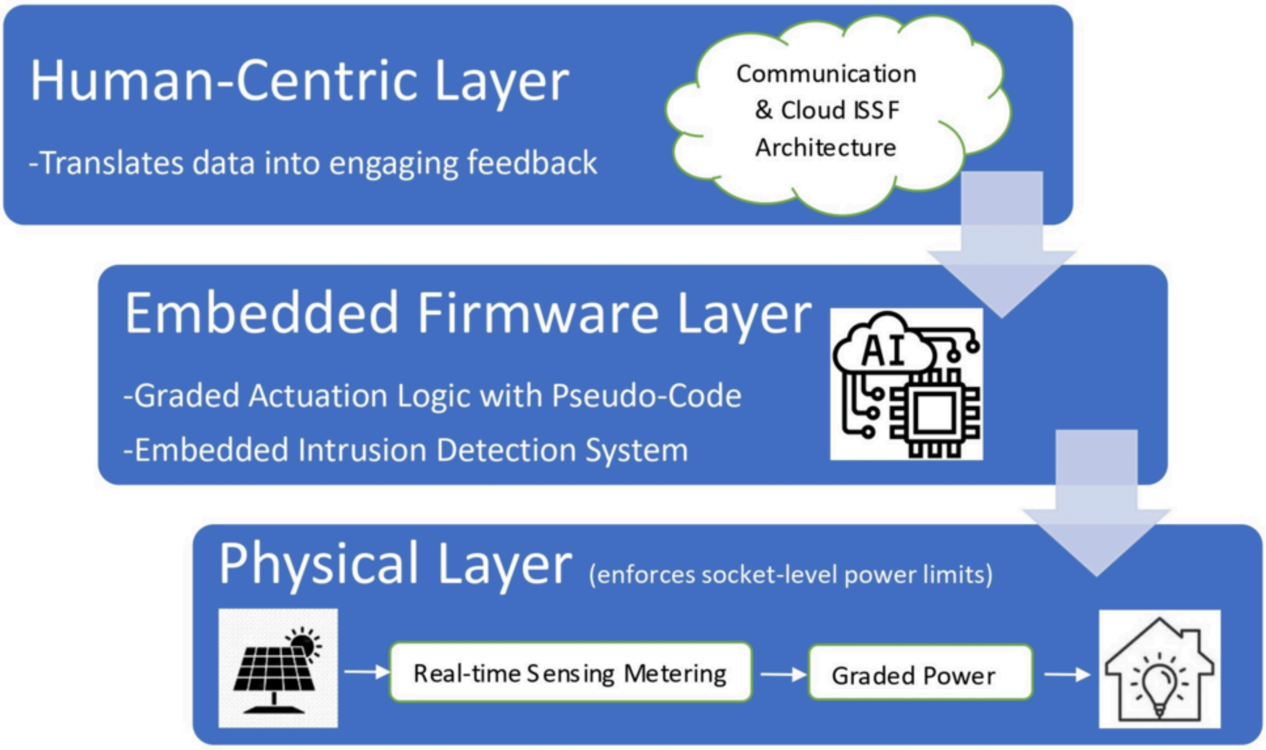

**FIGURE 4: The Proposed ISSF Architecture**

ISSF, Integrated Smart Switching Framework

To bridge the gap between algorithmic potential and physical deployment, the ISSF intelligence layer is designed to be context-aware and experience-agnostic. A primary barrier identified in existing RL implementations is the "Cold-Start" problem, where an agent lacks sufficient historical data to make reliable switching decisions. To mitigate this, the ISSF employs heuristic bootstrapping. During the initial deployment phase, the framework operates on a deterministic safety-first layer, utilizing established rule-based logic while the AI agent conducts shadow-learning in the background. Control is incrementally transitioned to the AI only once predictive confidence intervals reach a predefined accuracy threshold.

Furthermore, the ISSF specifically targets the identified 12% hardware validation gap by resolving three primary physical barriers:

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(i). Computational Pruning: Large neural networks are compressed into lightweight integer-based models (INT8) to execute on 32-bit microcontrollers without sacrificing accuracy.

(ii). Asynchronous Compensation: The control loop incorporates a temporal buffer to anticipate hardware latencies (5-15 ms) in electromagnetic relays.

(iii). Kalman Filtering: Digital filters are employed at the firmware level to smooth noisy sensor data and correct phase-angle errors, ensuring stable AI orchestration in real-world environments.

This hybrid approach ensures immediate system stability and prevents the user frustration typically associated with stochastic learning phases.

*Graded Actuation Logic*

Unlike traditional binary switches that operate in a simple $S \in \{0, 1\}$ state, the ISSF introduces Graded Actuation Logic (GAL). This logic allows the switch to function as a dynamic power governor.

Mathematical Model: The power allocated to a specific node $(P_n)$ is no longer a simple 'ON' command but a function of Total Available Renewable Power $(P_{res})$, Battery State of Charge $(SoC)$, and Load Priority $(L_p)$ (Equation 1):

$$P_n = \int (P_{res}, SoC, L_p) \cdot \eta \, (1)$$

where $\eta$ represents the efficiency coefficient of the graded control (e.g. PWM-based voltage regulation at the socket level).

Pseudo-Code for Embedded Implementation:

```
# Logic for Graded Individual Switch Control
Define MAX_THRESHOLD = Battery_Safety_Limit
Define Load_Priority = [Critical, Essential, Non-Essential]

Function Manage_Switch(Current_Demand, Solar_Input):
    Available_Buffer = (Solar_Input + Battery_SoC) - Critical_Loads

    If Current_Demand > Available_Buffer:
        # Instead of total cutoff, apply Graded Limit
        Target_Power = Available_Buffer / Active_Essential_Loads
        Apply_PWM_Limit(Target_Power)
        Status = "GRADED_ACTIVE"
    Else:
        State = ON
```

*Security-by-Design: The Embedded IDS Layer*

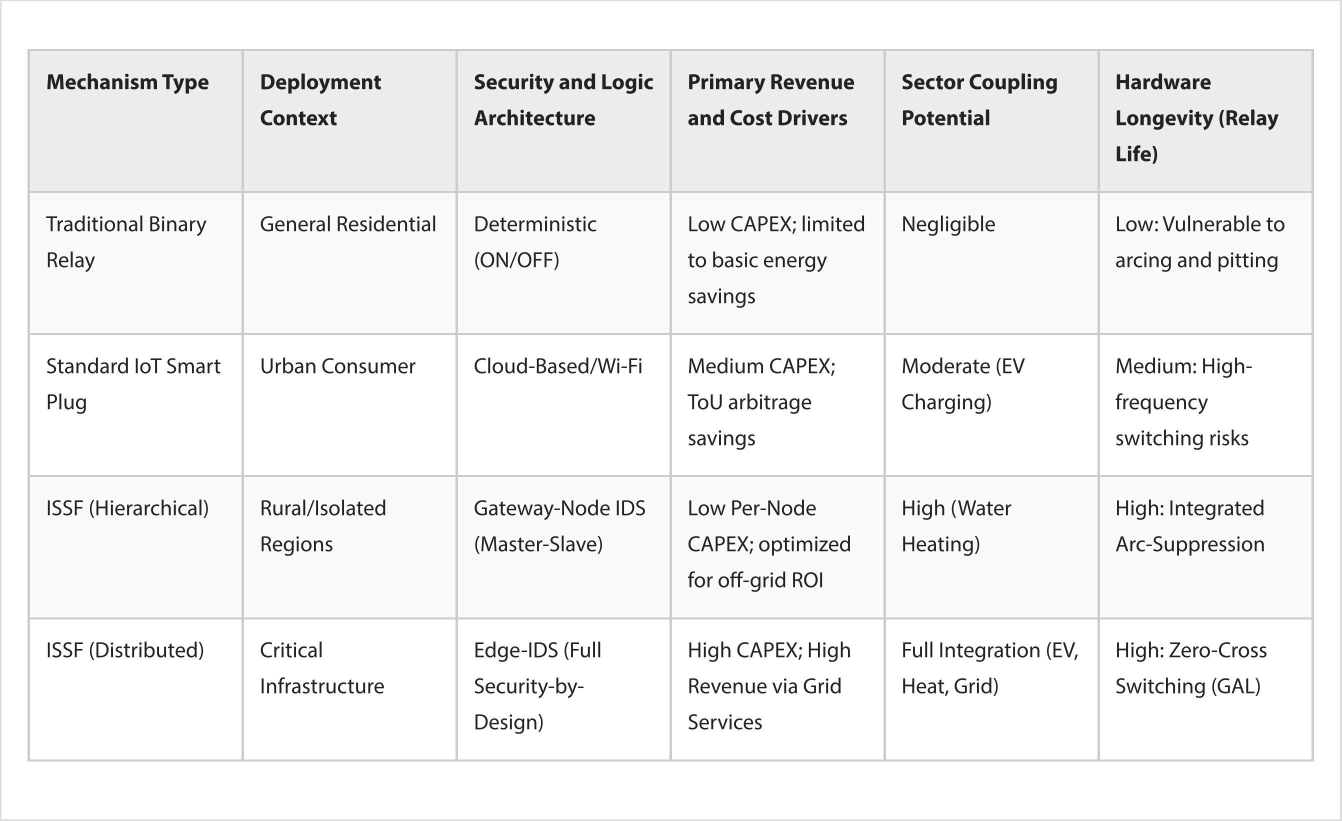
To address the identified vulnerabilities in FDI, the ISSF proposes an embedded IDS sitting between the sensing firmware and the Wi-Fi/ZigBee stack.

This layer employs a Statistical Anomaly Filter. If a sensor reports a power spike that exceeds the physical capacity of the connected relay or contradicts the voltage readings of the inverter, the IDS intercepts the command before the switch is activated, preventing potential hardware damage or severe energy drains caused by cyber-attacks.

*Human-Centric Interpretability Layer*

To address the cold-start and engagement issues, the ISSF maps complex optimization outputs to a Gamified Interpretability Interface. Instead of displaying Kilowatt Hours Saved (which users often find abstract), the switch logic translates efficiency into System Health Points or Eco-Credits. This creates a feedback loop where the autonomous Graded Actuation is explained to the user as a collaborative effort to maintain Grid Stability, significantly increasing user retention and behavioral change.

While the ISSF is designed as a high-performance control architecture, its real-world viability depends on its adaptability to varying economic landscapes and hardware constraints. As discussed, the implementation of GAL provides a dual benefit; it enables the granular power steering required for effective sector coupling while simultaneously mitigating the physical risk of relay contact pitting through zero-cross synchronization. This intersection of hardware longevity and multi-sector utility directly influences the ROI for solar prosumers. To clarify the relationship between these technical features and their economic outcomes, Table 4 provides a comparative cost-benefit analysis of the ISSF against traditional switching mechanisms across different deployment contexts.



| Mechanism Type | Deployment Context | Security and Logic Architecture | Primary Revenue and Cost Drivers | Sector Coupling Potential | Hardware Longevity (Relay Life) |
|---|---|---|---|---|---|
| Traditional Binary Relay | General Residential | Deterministic (ON/OFF) | Low CAPEX; limited to basic energy savings | Negligible | Low: Vulnerable to arcing and pitting |
| Standard IoT Smart Plug | Urban Consumer | Cloud-Based/Wi-Fi | Medium CAPEX; ToU arbitrage savings | Moderate (EV Charging) | Medium: High-frequency switching risks |
| ISSF (Hierarchical) | Rural/Isolated Regions | Gateway-Node IDS (Master-Slave) | Low Per-Node CAPEX; optimized for off-grid ROI | High (Water Heating) | High: Integrated Arc-Suppression |
| ISSF (Distributed) | Critical Infrastructure | Edge-IDS (Full Security-by-Design) | High CAPEX; High Revenue via Grid Services | Full Integration (EV, Heat, Grid) | High: Zero-Cross Switching (GAL) |

**TABLE 4: Techno-Economic Cost-Benefit and Scalability Analysis of Switching Mechanisms**

ISSF, Integrated Smart Switching Framework; ToU, Time-of-Use; ROI, Return on Investment; GAL, Graded Actuation Logic

Table 4 underscores the scalability of the ISSF. In resource-constrained or isolated regions, the hierarchical master-slave topology ensures that the cost of entry remains competitive with standard IoT solutions while providing superior protection against false data injection. Conversely, in high-stakes critical infrastructure environments, the distributed model justifies a higher initial CAPEX by unlocking significant revenue streams from demand response and grid-balancing services. By internalizing the cost of hardware fatigue and the potential for sector integration, the ISSF moves beyond theoretical optimization toward a techno-economically resilient framework for modern energy orchestration.

## Conclusions

This review moves beyond traditional descriptive analysis to propose the ISSF, a technical blueprint designed to bridge the simulation-to-reality gap in renewable energy management. The analysis highlights that while hardware development has reached maturity, exemplified by cost-effective Arduino-based sensing and robust Zigbee topologies, the intelligence layer faces critical implementation hurdles. Specifically, advanced RL remains largely confined to simulation due to computational constraints, while a lack of embedded cybersecurity protocols leaves microgrids vulnerable to malicious actuation and subsequent financial loss.

To resolve these challenges, the ISSF converges on three transformative pillars: Security-by-Design, embedding IDS directly into microcontroller firmware to thwart data corruption; Graded Actuation, evolving beyond binary (ON/OFF) states to autonomously enforce socket-level power limits; and Human-Centric Optimization, adopting gamified frameworks to foster long-term behavioral change. Beyond these technical milestones, the ISSF introduces a robust economic dimension by optimizing the levelized cost of electricity through enhanced self-consumption and life-cycle extension of switching hardware. By facilitating "Sector Coupling", integrating solar yield with thermal storage and electric vehicle charging, the framework transforms the smart switch from a passive actuator into an active economic agent capable of generating revenue through demand response participation. Ultimately, the ISSF provides the secure, profitable, and interdisciplinary infrastructure required to transition from simple energy convenience to a resilient, self-sustaining renewable energy economy.

## Additional Information

### Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

**Concept and design:** Samuel E. Akpan, Aniekan Offiong, Simeon Ozuomba, Adamson Oloyede

**Acquisition, analysis, or interpretation of data:** Samuel E. Akpan

**Drafting of the manuscript:** Samuel E. Akpan, Adamson Oloyede

**Critical review of the manuscript for important intellectual content:** Aniekan Offiong, Simeon Ozuomba

**Supervision:** Aniekan Offiong, Simeon Ozuomba

### Disclosures

**Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

### Data Availability Statements

Data sharing is not applicable. This work is theoretical; no datasets were generated or analyzed.

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