

REVIEW PAPER

ECOLOGICAL INFORMATICS

# Smart Energy Management Systems: The Perspective of Artificial Intelligence, SDG and Developing Countries for Good Governance: A Review

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## ABSTRACT

Smart Energy Management Systems (SEMS) are truly transforming how we think about energy use, allowing us to reduce carbon emissions and foster sustainability in our modern world. As global electricity demand is expected to soar by an incredible 50% by 2050 as per International Energy Agency, innovative technologies—like Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, and big data analytics—are playing a pivotal role in creating intelligent, decentralized energy networks. But SEMS goes beyond just efficiency; it's a catalyst for attaining the United Nations Sustainable Development Goals (SDGs), promoting sustainable economic growth while bolstering the resilience of our energy grids and expanding renewable energy adoption. In an era of rapid technological advancements and growing environmental concerns, energy management has become a critical challenge. Smart Energy Management Systems (SEMS) by changing how energy is generated, controlled, and used. Through AI integration, SEMS gain the ability to monitor operations in real time, utilize predictive insights, and execute automated control measures. These capabilities significantly enhance efficiency and help reduce the overall environmental

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footprint. This paper explores how Artificial Intelligence contributes to contemporary energy management, focusing on the core technologies involved, the main benefits it offers, current challenges faced, and the future prospects of smart energy systems.

**Keywords:** Smart Energy, SDGs, Energy Management, Developing Countries, Sustainable Development, Artificial Intelligence, SEMS

In this paper an exhilarating exploration of SEMS—delving into its core principles, its dynamic growth, and strategic approaches to implementation. With engaging real-world case studies, insightful policy perspectives, and groundbreaking technological advancements, we illustrate how SEMS is actively redefining energy management in smart cities, industries, and beyond. Whether you are a researcher, policymaker, or practitioner, this exploration is packed with practical insights to navigate adoption hurdles and scale SEMS, paving the way for a cleaner, smarter, and more sustainable future in energy. The global energy landscape is experiencing an exciting transformation, driven by three vital factors:

**Escalating Demand:** The world is on the brink of a significant shift, with global energy consumption forecasted to surge by 50% by 2050 (IEA, 2023). This remarkable growth emphasizes the urgency for innovative solutions in energy management.

**Resource Depletion:** Our finite fossil fuel reserves and growing concerns about energy security compel us to rethink our energy strategies. We need to develop sustainable alternatives that ensure a reliable energy supply for the future.

**Climate Urgency:** The immediate need for rapid decarbonization to meet Paris Agreement targets has never been more pressing. We must act decisively to protect our planet and mitigate climate change impacts. SEMS stands at the forefront of addressing these formidable challenges by:

- ❑ **Real-time Optimization of Energy Flows:** By continually assessing and adjusting energy usage, SEMS ensures that energy is utilized efficiently, preventing waste and enhancing sustainability.
- ❑ **Intelligent Integration of Renewable Sources:** SEMS promotes the seamless incorporation of renewable energy sources, making it easier to transition from traditional energy systems to greener alternatives.
- ❑ **Automated Demand-Response Mechanisms:** With advanced automated systems, SEMS can dynamically adjust demand in real-time, ensuring optimal energy usage and reducing costs for consumers.
- ❑ **Decentralized Control via Microgrids and Peer-to-Peer Trading:** SEMS facilitates more localized energy management through microgrid systems and innovative peer-to-peer trading models, empowering communities to take control of their energy resources.

This paper will systematically explore the core components and technological foundations of SEMS, its evolving and adaptive nature, strategic implementation models, as well as its real-world applications and future trajectories. Here Fig. 1 depicts about the stakeholders and components of SEMS, in brief.

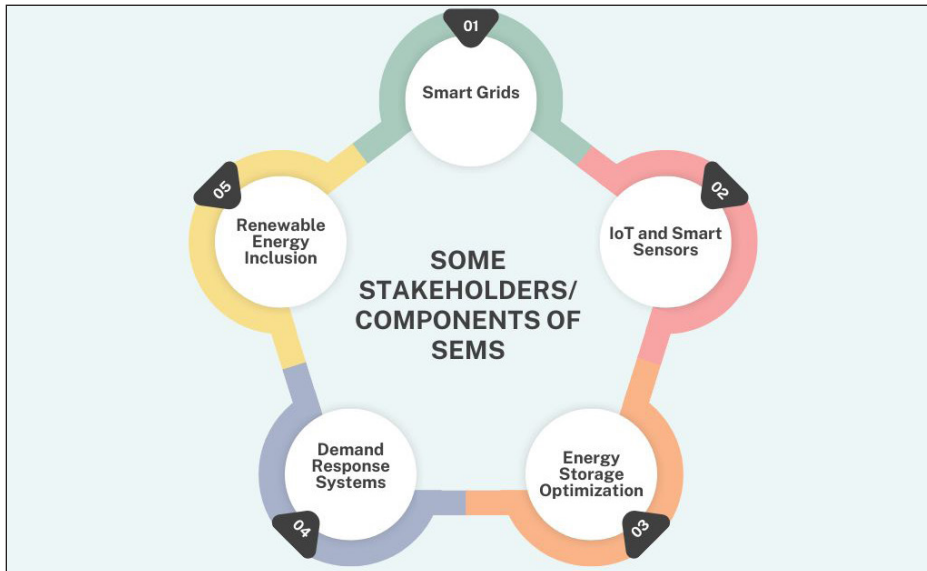


**Fig. 1:** Some Stakeholders and Components of SEMS for new age Energy Systems

## Objective and Methods

Regarding the paper ‘Demystifying Smart Energy Management Systems: the perspective of Artificial Intelligence, SDG and Developing Countries: *A Review*’ main objective are include (but not limited to)—

- ☐ To learn about the basic of Smart Energy Management systems with reference to the fundamental principles and core features.
- ☐ To learn about the fundamental components and Impact of Artificial Intelligence including allied technology like Deep Learning in Smart Energy Management Systems.
- ☐ To learn about the existing works related to SEMS, AI based SEMS, SEMS potentiality in Developing Countries.
- ☐ To find-out the Strategic Implementation Frameworks in SEMS with proper examples and utilization.
- ☐ To gather about the status of Smart Energy Management Systems in Developing Countries specially the current scenario.
- ☐ To gather about the Energy Crisis in Developing Nations with special reference to the Current Implementation Scenario
- ☐ To find-out the Common issues, challenges and Barriers Across Countries in respect of AI based SEMS and ways for advancement in SEMS in Developing Countries.

## Methods adopted

Present work is completely theoretical in nature and thus for preparing the work existing works studied related to the Smart Energy Management Systems (SEMS), AI based SEMS, SEMS potentiality in Developing Countries and here result of Google Scholar has been used up-to 10 pages and out the results best and relevant works are considered and analyzed. Thematically all the sections are prepared based on existing works only. To identified latest on-going of the SEMS several websites have been studied those are engaged in SEMS and allied industries to drag a real and latest pictures.

## Existing Works:

This paper entitled ‘Demystifying Smart Energy Management Systems: the perspective of Artificial Intelligence, SDG and Developing Countries: *A Review*’ is prepared based on existing works and among the works few are here provided in this section in tabular format (refer Table 1).

**Table 1:** Existing Works related to the fields with limitations and suggestions

| Sl. No. | Works                                               | Major Identification                                                                                                                                                                         | Limitations                                                                                                                                                                                          | Suggestions/ Recommendation                                                                                                                                                        |
|---------|-----------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1       | Alijoyo, F A. 2024                                  | The paper highlights the synergy of AI and IoT in smart buildings, focusing on predictive maintenance, deep learning, and adaptive energy load balancing for sustainability.                 | Lacks quantitative data to validate deep learning outcomes. Case studies are illustrative but do not present rigorous performance metrics or cross-regional comparison of smart building efficiency. | Incorporate empirical evidence, such as energy consumption data pre- and post-AI implementation, and provide a comparative study across different smart city infrastructures.      |
| 2       | Awogbemi, O., Von Kallon, D.V., & Kumar, K.S., 2024 | Explores how AI and digitization can democratize clean energy access. Emphasizes real-time analytics, digital twins, and blockchain technologies in modern energy infrastructure.            | While broad in scope, the review lacks specificity regarding developing countries and underrepresents barriers to implementing such technologies in low-income or poorly connected regions.          | Include a focused section on the digital divide and propose solutions for equitable AI adoption in regions with limited technological and infrastructural readiness.               |
| 3       | Bedi, P. <i>et al.</i> 2022                         | Presents AI-IoT integration in smart cities through adaptive systems like microgrids. Advocates a multidisciplinary approach to address energy flow optimization and citizen engagement.     | Fails to detail the long-term sustainability or economic feasibility of the proposed technologies in non-developed regions with infrastructural and policy shortcomings.                             | Suggest implementing pilot projects in developing cities and assessing cost-benefit frameworks that validate scalability and real-world impact of AI-based energy systems.         |
| 4       | Fan, Z., Yan, Z., & Wen, S. 2023                    | Connects deep learning innovations with SDGs, renewable energy, and environmental health. Highlights AI's predictive capabilities and its relevance to climate change mitigation strategies. | Lacks focus on regional implementation frameworks. It generalizes AI's global benefits without addressing infrastructural disparities or regulatory gaps in emerging economies.                      | Add context-specific applications of deep learning in low-income countries. Discuss tailored frameworks for integrating environmental AI with local governance and policy systems. |

|    |                                          |                                                                                                                                                                     |                                                                                                                                                               |                                                                                                                                                                              |
|----|------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 5  | Huseien, G.F., & Shah, K.W. 2022         | Explores 5G's role in optimizing smart building energy systems in Singapore. Emphasizes real-time monitoring, low latency, and advanced diagnostic tools.           | Limited to Singapore, the study lacks wider applicability to different urban contexts. It overlooks socio-political and economic challenges elsewhere.        | Expand analysis by comparing 5G energy integration in diverse cities. Examine cost structures, data privacy policies, and rural-urban differences in technology acceptance.  |
| 6  | Mishra, P., & Singh, G. 2023             | Analyzes IoE-based energy systems in smart cities. Emphasizes predictive analytics, real-time response, and scalability using AI and decentralized grid structures. | Focuses heavily on technical architecture, ignoring social, economic, or behavioral barriers to smart city technology adoption in developing countries.       | Include interdisciplinary insights—urban planning, sociology, and economics—to better understand user adoption and policy integration for IoE-driven smart energy systems.   |
| 7  | Obaideen, K. <i>et al.</i> 2024          | Conducts a bibliometric analysis of wireless power transfer and its synergy with AI for sustainable goals. Tracks emerging themes and research patterns.            | The study lacks depth in practical WPT applications and real-world limitations. It does not evaluate implementation feasibility in low-resource environments. | Incorporate applied case studies showcasing WPT use in developing nations. Suggest collaborative funding models for research-to-practice transition in underdeveloped areas. |
| 8  | Okpala, B.C., & Nzeanorue, C.C. 2024     | Focuses on AI and IoT for energy management in Nigeria. Emphasizes localized innovation and predictive load optimization for sustainable urban growth.              | Lacks detailed implementation data or long-term metrics to track progress. The scalability of the proposed model remains under-explored.                      | Add quantitative impact analysis and outline a national roadmap to scale AI-IoT energy projects across multiple urban and semi-urban Nigerian regions.                       |
| 9  | Parvin, K. <i>et al.</i> 2021            | Presents a technical overview of intelligent controllers and optimization algorithms in energy-efficient building management aligned with SDG goals.                | The review is too theoretical. Practical integration challenges like retrofitting older infrastructure or cost concerns are not well addressed.               | Propose real-life implementations of the controllers. Discuss funding avenues, return-on-investment models, and workforce training for algorithm-based system adoption.      |
| 10 | Pigola, A. <i>et al.</i> 2021            | Provides a comparative view of AI-driven SDG strategies in Brazil and Portugal, stressing digital inclusion and policy-guided technological deployment.             | The study leans on case studies but doesn't delve into measurable outcomes or impact indicators to substantiate its claims.                                   | Integrate impact metrics and post-implementation assessments to validate effectiveness. Recommend standard monitoring frameworks for AI-driven SDG interventions.            |
| 11 | Segun-Falade, O.D. <i>et al.</i> 2024    | Explores software innovations for industrial energy management using AI and ML. Highlights real-world industrial applications and compliance benefits.              | Primarily focused on developed sectors; it under-represents challenges in resource-constrained industrial environments lacking digital readiness.             | Address training needs and infrastructure deficits in small-to-medium industries. Suggest public-private models to extend AI software access at lower cost.                  |
| 12 | Serban, A. C., & Lytras, M. D., 2020[49] | Reviews AI's influence on Europe's renewable energy future. Showcases successful smart infrastructure and decentralized models in urban energy systems.             | Highly Eurocentric. The model's scalability in developing regions is not considered, nor are economic feasibility and local constraints.                      | Encourage policy comparison with non-EU nations. Suggest partnerships for knowledge transfer and localized adaptation of Europe's smart energy innovations.                  |

## Fundamental Principles and Core Components of SEMS

### Definition and Architectural Framework

Welcome to the fascinating world of Smart Energy Management Systems (SEMS)! SEMS is not just a technological advancement; it's an intelligent ecosystem where multiple facets come together harmoniously. This unique synergy includes physical infrastructure—think smart grids and sensors that form the backbone of our energy networks—combined with digital technologies like AI, IoT, and blockchain that facilitate unprecedented efficiency and connectivity<sup>[3],[19]</sup>.

### Critical Technological Components

The heart of SEMS lies in its critical technological components. Let's take a closer look (also refer Table 2).

- ❑ **Smart Grid Infrastructure:** This innovative structure enables bidirectional energy and data flows, allowing for real-time interaction between consumers and providers. A prime example of this progress can be seen in the interoperability standards established by the EU Smart Grid Task Force<sup>[4],[33]</sup>, which set the stage for seamless integration across systems.
- ❑ **IoT Sensor Networks:** Smart meters are revolutionizing how we collect and analyze energy consumption data by providing granular insights into usage patterns. Meanwhile, wireless sensor networks play an essential role in monitoring industrial equipment health, ensuring optimal performance and longevity. Additionally, environmental sensors are crucial for tracking weather impacts on renewable generation, leading to more informed energy decisions<sup>[9],[6],[3]</sup>.

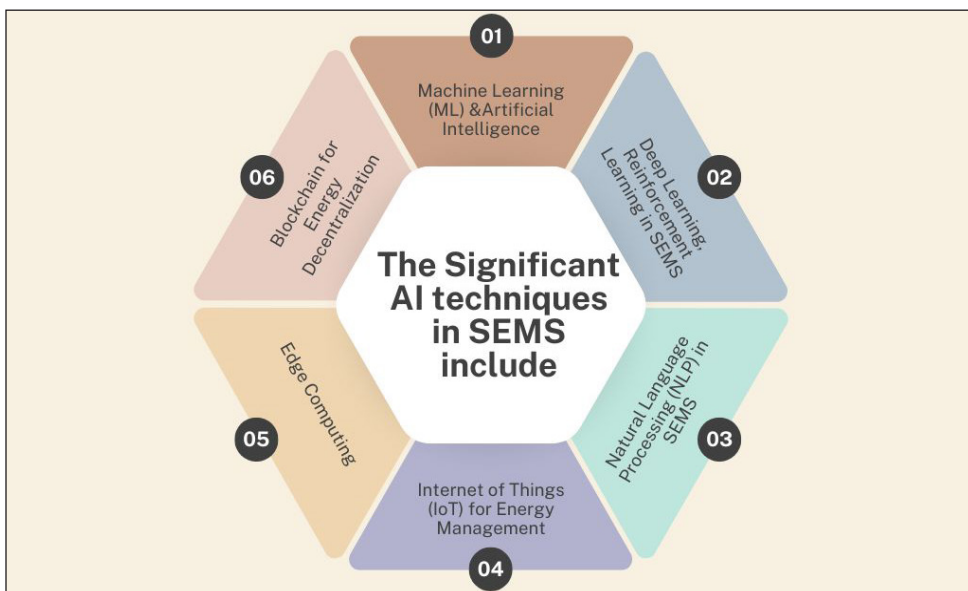


**Fig. 2:** Significant AI Techniques in Smart Energy Management (SEMS)

- ❑ **Artificial Intelligence Core:** Underpinning the efficiency of SEMS is its artificial intelligence

core (refer Fig. 2 for understanding significant AI technique in SEMS). By utilizing predictive maintenance, enterprises can reduce downtime by an impressive 30-50% (Siemens, 2023). Moreover, advanced load forecasting achieves an accuracy rate exceeding 95% thanks to deep learning techniques<sup>[59]</sup>, enabling better resource allocation.

- ❑ *Blockchain Applications*: Finally, blockchain technology ushers in a new era of energy transactions with its ability to facilitate transparent peer-to-peer energy markets. The Brooklyn Microgrid, for instance, showcases this potential with over 500 participants trading energy locally<sup>[34],[60]</sup>.
- ❑ *Edge Computing in SEMS*: Edge computing significantly reduces latency in industrial SEMS by enabling real-time data processing at the source, enhancing decision-making speed and efficiency<sup>[2],[21]</sup>. This technology minimizes reliance on centralized cloud systems, improving responsiveness in critical applications like predictive maintenance and load balancing<sup>[12],[18]</sup>.

The innovation of these key components ensures that we are not just passively consuming energy but engaging with it in a way that is intelligent and forward-thinking.

**Table 2:** Different emerging Technologies used in SEMS with examples

| Component             | Function                                                          |
|-----------------------|-------------------------------------------------------------------|
| Smart Grids           | Enable bidirectional energy flow between suppliers and consumers  |
| IoT Sensors           | Monitor real-time energy usage, temperature, and equipment health |
| AI & Machine Learning | Predictive analytics for load forecasting and fault detection     |
| Blockchain            | Facilitates peer-to-peer (P2P) energy trading in microgrids       |
| Edge Computing        | Reduces latency in industrial SEMS decision-making                |

### ***Comparative Advantage Over Traditional EMS***

In comparison to traditional Energy Management Systems (EMS), SEMS offers a groundbreaking advantage as there are several differences (as depicted in Table 3). The benefits are clear, positioning SEMS as the future of energy management solutions<sup>[16],[34]</sup>. Advantages of AI based SEMS depicted in Fig. 3.

**Table 3:** Features of various Traditional EMS and Smart EMS at a glance

| Feature            | Traditional EMS               | SEMS                               |
|--------------------|-------------------------------|------------------------------------|
| Data Granularity   | Hourly/daily readings         | Sub-second IoT data streams        |
| Response Time      | Manual interventions          | Millisecond automated responses    |
| Renewable Capacity | Limited to 15-20% penetration | Enables 50%+ renewable integration |
| Failure Recovery   | Hours-days                    | Seconds-minutes (self-healing)     |
| Consumer Role      | Passive recipient             | Active prosumer                    |

### **The Evolving Nature of SEMS**

Smart Energy Management Systems (SEMS) is changing rapidly with several systems and mechanism and very recently huge potentiality emerged in AI based SEMS, viz.

## Adaptive Intelligence

The world of Smart Energy Management Systems (SEMS) is constantly transforming, thanks in large part to continuous learning capabilities inherent in AI models. These models are designed to adapt and evolve as they are fed new data patterns, ensuring that they remain at the cutting edge of energy management<sup>[8],[32]</sup>.

## Decentralization Paradigm

One of the most exciting trends in SEMS is the rise of microgrid proliferation, which has experienced an impressive 450% growth since 2015. Communities are taking charge of their energy futures, illustrated by German villages achieving 100% renewable autonomy<sup>[19]</sup>.

## Interconnected Ecosystems/Cyber-Physical Integration

SEMS play a vital role in creating interconnected ecosystems, opening doors to synergies that enhance efficiency. For instance, in the realm of Smart Cities, traffic lights are now adjusting their timing based on real-time energy availability, promoting smoother flow and energy conservation. In Industry 4.0, factories are utilizing digital twins to simulate and optimize energy usage, showcasing innovation at its best. Furthermore, the Vehicle-to-Grid (V2G) concept positions electric vehicles as mobile storage units during peak demand, demonstrating how interconnectedness can lead to smarter energy use and greater sustainability<sup>[29],[48]</sup>.

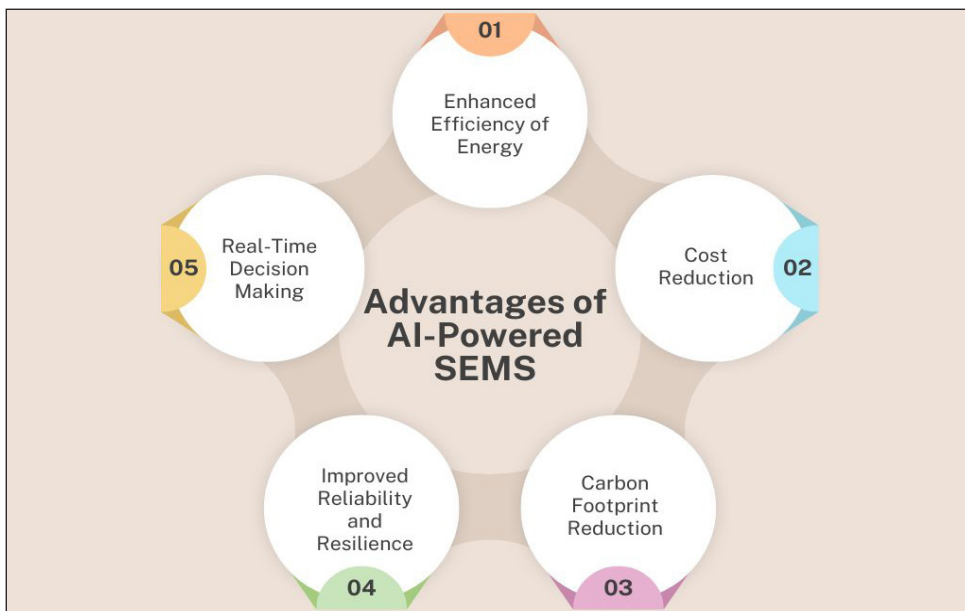


**Fig. 3:** Core Advantages of AI powered SEMS

## The Role of AI in Smart Energy Management Systems

Artificial Intelligence significantly boosts the capabilities of Smart Energy Management Systems (SEMS) by enabling automation, forecasting, and intelligent decision-making based on data insights. AI-powered

systems analyze vast amounts of data from various sources such as smart grids, IoT sensors, weather forecasts, and consumer usage patterns to dynamically enhance energy efficiency in real time<sup>[1],[17]</sup>. The significant AI techniques deployed in SEMS include:

- ❑ **Machine Learning (ML)& Artificial Intelligence:** ML algorithms predict energy demand and supply fluctuations, enabling proactive adjustments in power distribution and consumption. Artificial Intelligence and Machine Learning are at the forefront of revolutionizing energy management<sup>[13],[46]</sup>. *Predictive analytics* enable accurate forecasting of energy demand, ensuring resources are allocated efficiently<sup>[5],[14]</sup>.
- ❑ **Deep Learning, Reinforcement Learning, & NLP:** AI agents develop efficient energy management strategies by constantly analyzing live data and adapting their performance to improve effectiveness over time. NLP facilitates human-AI interaction in SEMS, enabling voice-activated controls and AI-powered energy audits<sup>[10],[45]</sup>.
- ❑ **Internet of Things (IoT) and Edge Computing:** The incorporation of IoT and edge computing transforms energy monitoring and management. *Smart meters, Distributed energy resource (DER) management, Vehicle-to-Grid (V2G)*, etc. play a leading role.
- ❑ **Blockchain for Energy Decentralization:** Blockchain technology offers a groundbreaking approach to decentralizing energy markets<sup>[15],[56]</sup>. *Transactive energy markets* empower prosumers to actively participate in the energy economy, creating a more interactive marketplace<sup>[8]</sup>.

### ***Components of AI-Driven Smart Energy Management Systems***

An efficient SEMS comprises various interconnected components, working together to optimize energy consumption. These include:

- ❑ Smart Grids
- ❑ IoT and Smart Sensors
- ❑ Energy Storage Optimization
- ❑ Demand Response Systems
- ❑ Renewable Energy Inclusion

### ***Barriers to Adoption AI-Based SEMS***

Though AI based Systems are impactful in SEMS but there are some issues and barriers and some of them are analyzed in this section, refer Fig. 4.

***Data Privacy and Security,*** Given the massive volume of data generated by IoT devices and smart grids, protecting this data is crucial. Cybersecurity threats pose risks to AI-driven energy systems, necessitating robust encryption and protective measures.

***High Initial Investment,*** Deploying AI-powered SEMS requires substantial investment in infrastructure, technology, and training. The long-term benefits outweigh the costs, but the initial expenditure can be a deterrent for small-scale users<sup>[3],[53]</sup>.

**Complexity in Implementation,** AI-based energy solutions involve complex algorithms, requiring skilled professionals to develop, deploy, and maintain them. Organizations must invest in AI expertise to fully leverage smart energy technologies<sup>[20],[31]</sup>.

**Integration with Existing Systems,** Many traditional energy management systems lack compatibility with AI-based solutions. Integrating AI into existing legacy systems demands thoughtful strategy and investment in updated infrastructure.

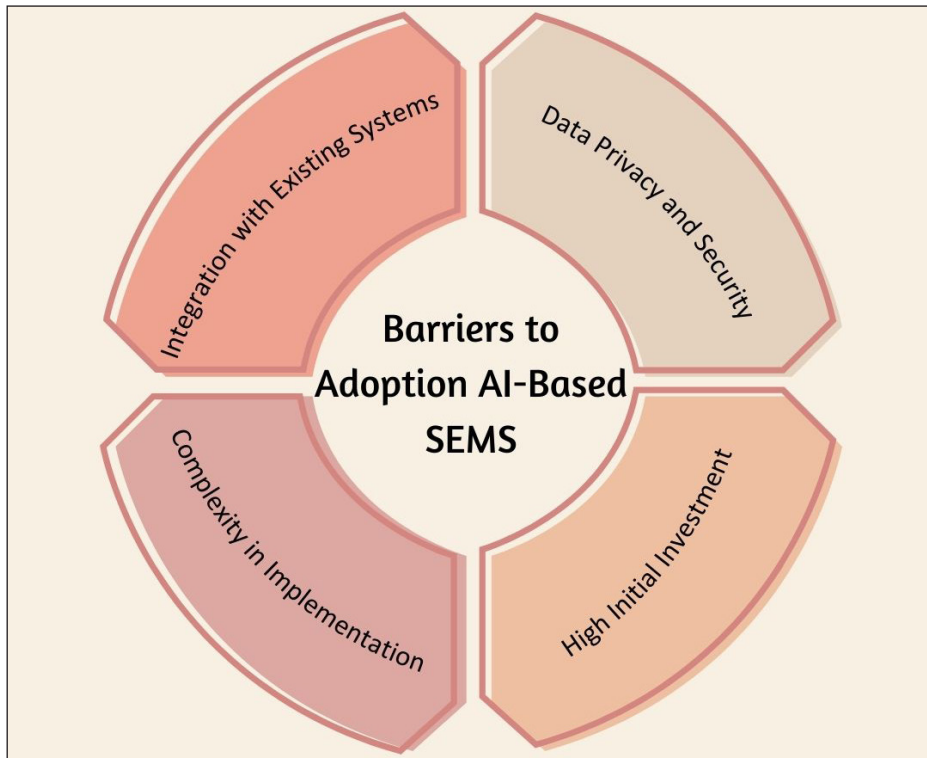


**Fig. 4:** Major Barriers in AI based SEMS

## The Use of Deep Learning and Machine Learning in Smart Energy Management Systems

Key Applications in Energy Management using DL and ML are include as follows (refer Fig. 5 too)—

### ***Load Forecasting and Demand Prediction***

ML algorithms are experts in taking already existing historical energy consumption data, weather patterns, latest information, and future energy demand predictions at a higher accuracy rate, hence enabling the utilities and energy providers to markedly adjust their generation and distribution strategies while maximizing waste reduction and operational costs<sup>[3]</sup>.

## ***Grid Management and Optimization***

The role of ML is central to the operation of smart grid management because it deals with data coming from numerous sensors and IoT devices distributed throughout the grid to detect anomalies, forecast possible issues, and furnish recommendations for preventive action. Such real-time monitoring helps foster grid stability, reduce outages, and improve reliability. ML algorithms aid in the formulation of energy conservation policies from their analysis of peak hours consumption and thereby optimize energy distribution.

## ***Predictive Maintenance***

One of the most valuable applications of ML in energy systems is predictive maintenance. ML algorithms analyze real-time equipment data to predict possible failures before their onset, thereby enabling timely interventions. The approach optimally reduces downtime and maintenance costs while increasing the lifespan of energy infrastructure.

## ***Enhanced Energy Efficiency***

The implementation of ML-driven SEMS saw vast increases in energy efficiency. Smart systems are capable of constantly analyzing consumption patterns and automatically adjusting settings based on real-time conditions. An example is ML-based HVAC solutions that adjust current temperature settings on the fly to provide comfort while avoiding energy waste.

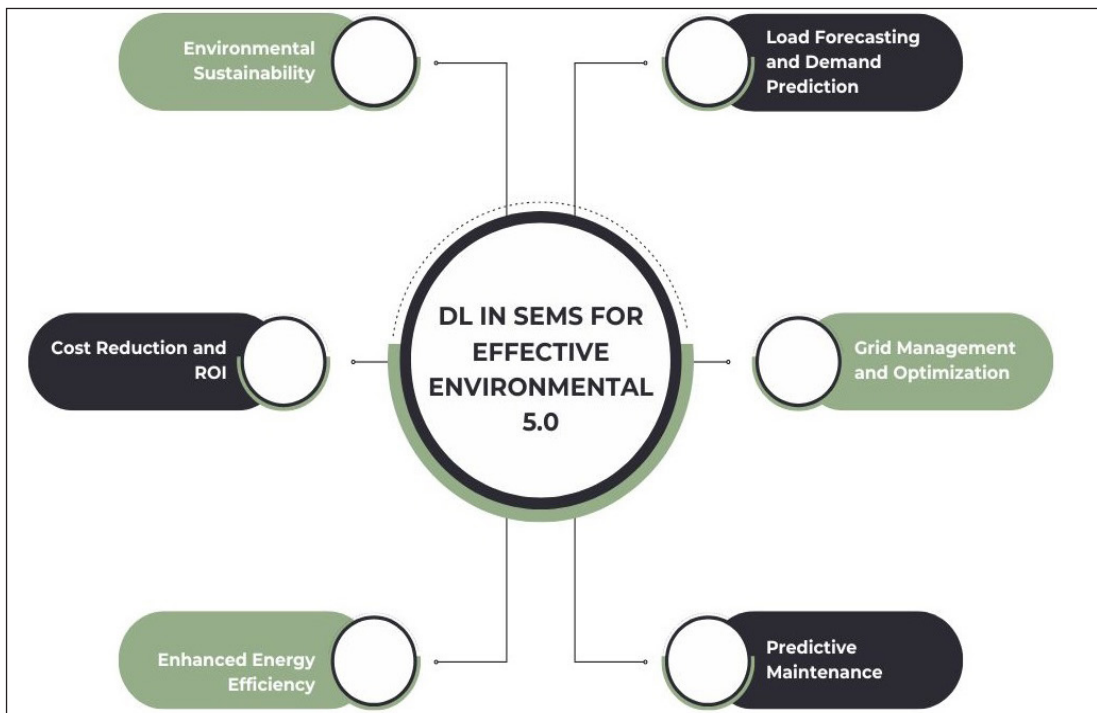


**Fig. 5:** DL in SEMS for effective Environmental 5.0

## Cost Reduction and ROI

Many companies investing in ML-enabled energy management systems are realizing incredible savings. A leading global electronics manufacturer was spending an annual \$135 million on electricity<sup>[18],[43]</sup>. In place, the manufacturer set up a machine learning-based real-time monitoring and analysis<sup>[26],[59]</sup>.

## Strategic Implementation Frameworks in SEMS:

The growth of Smart Energy Management Systems (SEMS) is significant and there are different strategies need to adopt in effective SEMS using AI and some of them are illustrated as under (also refer Table 4).

### Policy and Regulatory Enablers

To facilitate the growth and effectiveness of SEMS, it's vital to embrace policy and regulatory enablers. Financial incentives such as the U.S. IRA tax credits, which cover up to 30% of SEMS costs, are pivotal in attracting investment and encouraging adoption<sup>[35],[54]</sup>.

**Table 4:** Different strategies and implementation ways in SEMS

| Strategy             | Implementation                                                                                    | Case Example                     |
|----------------------|---------------------------------------------------------------------------------------------------|----------------------------------|
| Financial Incentives | Tax credits for SEMS adoption (30% under U.S. IRA <sup>[23],[25]</sup> )                          | U.S. Inflation Reduction Act     |
| Standardization      | IEEE 2030.5 for device interoperability                                                           | EU's Smart Grid Interoperability |
| Market Reforms       | FERC Order 2222 allows distributed resources to compete in wholesale markets <sup>[55],[57]</sup> | U.S. energy markets              |

### Technological Deployment Strategies

Following technological strategies are effective and required in SEMS implementation as mentioned below (also refer Table 5).

- ☐ AI-Powered Predictive Maintenance
- ☐ Demand Response (DR)
- ☐ Hybrid Energy Storage
- ☐ Sector-Specific Approaches<sup>[27],[59]</sup>.

**Table 5:** Comprehensive overview of sector wise SEMS Strategy, Impact

| Sector      | SEMS Strategy                         | Impact                              |
|-------------|---------------------------------------|-------------------------------------|
| Industrial  | Digital twin energy simulation        | 25% reduction in pharma plant usage |
| Commercial  | Occupancy-based HVAC                  | 30% savings in office buildings     |
| Residential | Behavioral nudging apps (Ohm Connect) | 12% lower household consumption     |

### Consumer Engagement Models

Following consumer engagement models are useful and required in Smart Energy Management Systems (SEMS) based mechanism, viz.

- ☐ Gamification
- ☐ Energy communities
- ☐ Personalized dashboards<sup>[40],[58]</sup>.

## Smart Energy Management Systems in Developing Countries: The Current Scenario

In developing countries, undergoing tremendous change in energy sectors, increasing demand, decaying infrastructure, and the urgency of obtaining more efficient, reliable, and sustainable energy systems create a scenario. Thus, according to the prediction, electricity demand in these countries is going to rise by more than 50% before 2030. Electricity demand in these developing countries is anticipated to rise as strongly as more than 50% by that date, which is far ahead in comparison to their rates in the developed countries<sup>[16],[21]</sup>. Smart Energy Management Systems (SEMS) and smart grids are turning out to be revolutionary in this regard, providing capabilities for the very latest monitoring, handling, and optimization of energy flows using advanced technologies and data-driven strategies<sup>[30],[31]</sup>.

### *The Energy Crisis in Developing Nations*

About 1 billion people globally do not have access to electricity, and much of this has been urban-rural differentials-97% electrification in urban areas compared to 78% in rural ones. Extending grid infrastructure- centralized grid infrastructure to remote areas is extremely costly; besides, many of the existing ones suffer from high transmission and distribution losses, which in some instances exceed 30%<sup>[13],[16]</sup>. Impede energy access and create security and reliability problems as well. SEMS and smart grids integrate information and communication technologies for dynamic, real-time energy management to provide solutions to these inefficiencies. Some examples of these components are:

- ☐ Gateway systems for data acquisition and processing
- ☐ Software algorithms for controlling energy assets
- ☐ User interfaces for visualization and management

Smart grids also facilitate the integration of renewable sources like solar, wind, biomass, and hydroelectricity condition which is already plus in most developing parts of the world.

### *Current Implementation Scenario*

As far as *India*, out of all developing countries, India leads the way in SEMS and smart grid development. The Ministry of Power has formulated standards and policies on the smart grid, including metering based on smart meters and microgrids sourced from renewable energy. The initiatives such as solar microgrids by Gram Power in Rajasthan are beneficial of the ability of deploying smarts not only in rural areas but also for an urban application such as the GIFT City and Naya Raipur smart city projects. In *Nigeria and Haiti*, The Green Village Electricity (GVE) project is an example in Nigeria that has brought the PAYG method to provide clean energy in rural areas<sup>[44],[61]</sup>. SparkMeter is making waves in a similar way in Haiti

by demonstrating technology with pre-payment billing, load management, theft-detection capability, and other innovative approaches to broaden access while enhancing reliability.

Within *Russia*, a smart grid and SEMS deployment involves metropolitan cities such as Moscow and Saint Petersburg. The objectives of such projects include the installation of smart meters, automation of grids, and integration with renewables-all backed by national digitalization strategies such as “Digital Energy”. Progress is apparent in urban areas, but rural areas still face major challenges in terms of which to extend the benefits, investment security, and regulatory frameworks. *Brazil* was also the forerunner in the transition to smart energy in Latin America’s hemisphere. The government has targets that by the end of 2025, all homes should have smart meters installed and pilot programs in cities such as São Paulo and Rio de Janeiro work with the local population. These have led to declines in losses, efficiencies, and the economic benefits that come with grid automation. Yet, even with so much hope, there still remain challenges such as the size and complexity of the national grid, regulatory uncertainty, and lack of sufficient awareness in the public<sup>[3],[44]</sup>. Here table 6 depicts a brief overview of SEMS between India, Russia and Brazil.

### ***Common Barriers across Countries***

Barriers to large-scale implementation of SEMS and smart grids include the following, notwithstanding the success factors:

- ☐ They include high initial costs and limited access to financing.
- ☐ Infrastructure limitations and outdated grids.
- ☐ Lack of skilled manpower and know-how.
- ☐ Regulation framework and market structure that aren’t well-developed.
- ☐ Cybersecurity and data management are two concerns.
- ☐ Social and political resistance, with some saying about privacy, costs, and disruption to orthodox energy models.

**Table 6:** Comparative Overview of SEMS in India, Russia, and Brazil

| Country | Key Initiatives                           | Achievements                                                   | Main Barriers                                |
|---------|-------------------------------------------|----------------------------------------------------------------|----------------------------------------------|
| India   | Smart meters, microgrids, smart cities    | Improved rural access, real-time data, greenfield smart cities | Infrastructure, costs, skills, regulation    |
| Russia  | Smart grids, digitalization, urban pilots | Urban grid modernization, renewables integration               | Investment, rural access, regulatory clarity |
| Brazil  | Universal smart metering, grid automation | Reduced losses, improved efficiency, pilot projects            | Grid size, regulation, public awareness      |

Successful projects involving smart grids in developing countries have attested to the need for:

- ☐ Being attuned to the local needs and contexts
- ☐ Creating robust regulatory and financial support mechanisms
- ☐ Investing in capacity-building and stakeholders’ engagement

- Using existing infrastructures to optimize investments and minimize disruption.
- Some crucial elements in overcoming barriers and accelerating adoption are creating innovative financing, incentives from the government, international cooperation, and public awareness campaigns.

### ***SEMS: Move forward in Developing Countries for Good Governance***

The application of Smart Energy Management Systems in developing countries presents a remarkable transformational opportunity in the atmosphere of the energy transition. These nations struggle with electricity demand outrunning supply, dilapidated infrastructure, and grossly inequitable energy access. SEMS provides a new viable pathway to tackle these challenges and open another avenue for sustainable growth. SEMS use real-time data acquisition, advanced analytics, and automated control simultaneously to optimize energy use, minimizing losses, and increasing efficiencies in renewable resource integration<sup>[22],[36]</sup>. This transition assumes special significance in areas where traditional grid expansion has availed itself neither through cost advantages nor physical changes as such, thus effectively energizing solutions like microgrids and community energy management mechanisms to close the electrification gap.

There are many various environments in India, Russia, and Brazil in terms of configurations and benefits of SEMS<sup>[40]</sup>. In rural India, installing smart meters and microgrids in remote villages is one way of deploying technology for dependable and affordable supply of power into underserved communities. Smart grid and digitalization initiatives in urban Russia present a good case for efficiency and resilience in much-densely populated regions. Massive projects for smart metering and grid automation in Brazil show another application of large-scale modernization to cheapen losses and enhance service quality across vast, complicated, and interconnected networks. Here Fig. 6 rightly pointed the strategic ways and frameworks in AI based SEMS in brief.

To eradicate the obstacles mentioned above, a holistic perspective must be created. It is a must that policymakers build strong regulatory schemes and incentives to promote investment and innovation. Emerging capacity-building programs aimed at strengthening local expertise will ensure long-term viability of any smart energy project. Public awareness campaigns can help sow trust and a sense of ownership among communities regarding the advantages of SEMS. The other avenue to quicken these processes is the sharing of knowledge internationally<sup>[47]</sup>. This would provide an opportunity for developing countries to observe the best practices around the world and adapt solutions to their domestic contexts. If all stakeholders, including government agencies, the corporate sector, and civil society, can coordinate their efforts, this could lead SEMS to become a building block in sustainable development, economic growth, environmental protection, and improving the quality of life for millions. Lastly, despite challenges that accompany the process, the energy management momentum in the developing countries is overwhelming<sup>[28],[59]</sup>. If adequate commitment and proactive measures prevail, SEMS will take the central role in establishing resilient, just, and sustainable energy systems for the future.

India illustrates the emerging case of the adoption of smart energy technologies in developing countries. The Ministry of Power leads the forum, establishing standards and policies across India for the deployment of the Smart Grid. Smart metering installation helps collect real-time consumption data; in turn, that data allows consumers to make more informed energy decisions. Microgrids, powered by renewable energy sources, are viewed as a possible solution for rural communities. Companies such as Gram Power in India

have set up small solar microgrids (5-10 kilowatt) in very remote villages of Rajasthan and provide the consumers with smart meters to manage their consumption. Similar programs are in operation in Haiti, in which Spark-Meter technology allows for pre-payment billing, load management, and theft detection<sup>[22]</sup>. Another model for success is the Green Village Electricity (GVE) project in Nigeria, which allows the use of Pay-As-You-Go (PAYG) revenue collection systems to supply clean energy to rural communities<sup>[13],[22]</sup>. Developing countries hold strong barriers to large-scale SEMS adoption. Some barriers include:

- ☐ Infrastructure limitations
- ☐ High upfront costs
- ☐ Technical expertise gaps
- ☐ Cybersecurity concerns
- ☐ Data management issues
- ☐ Regulatory frameworks
- ☐ Social acceptance.

## ***Real-World Applications and Case Evidence***

### ***1. Urban Scale: Singapore's Smart Nation***

- ☐ **AI-optimized public transport routing:** Singapore's Smart Nation initiative showcases the power of technology in enhancing urban life. Their AI-driven public transport routing system ensures efficient travel across the city, reducing congestion and commuting times while promoting a smarter lifestyle<sup>[22]</sup>.
- ☐ **Building energy management systems achieving 20% savings (EMA, 2023):** Innovative building energy management systems have revolutionized energy use in Singapore, resulting in an impressive 20% savings<sup>[41],[51]</sup>. This significant achievement highlights the effectiveness of integrated technologies in urban environments.

### ***2. Industrial Transformation***

- ☐ **Siemens' MindSphere:** Siemens has unlocked new possibilities in energy efficiency with MindSphere, a digital platform that has led to an 18% reduction in energy consumption at automotive plants<sup>[9]</sup>. This transformation underscores the potential of digital solutions in driving sustainability within industries.
- ☐ **Tesla Gigafactory:** The Tesla Gigafactory's use of digital twins elegantly demonstrates how cutting-edge technology can optimize production. This tech manages energy flows around the clock, ensuring operational efficiency and sustainability in energy consumption.

### ***3. Community Empowerment***

- ☐ **Germany's renewable villages:** A remarkable initiative in Germany showcases 100% energy independence through the creation of renewable energy villages. These communities exemplify

how collective efforts can lead to sustainable energy solutions and empower individuals to take charge of their energy future.

- ❑ **Australian VPPs:** Virtual Power Plants (VPPs) in Australia play a critical role in providing grid stability, especially during extreme heat events. By harmonizing a network of distributed energy resources, these VPPs exemplify community-driven efforts to enhance resilience and sustainability.

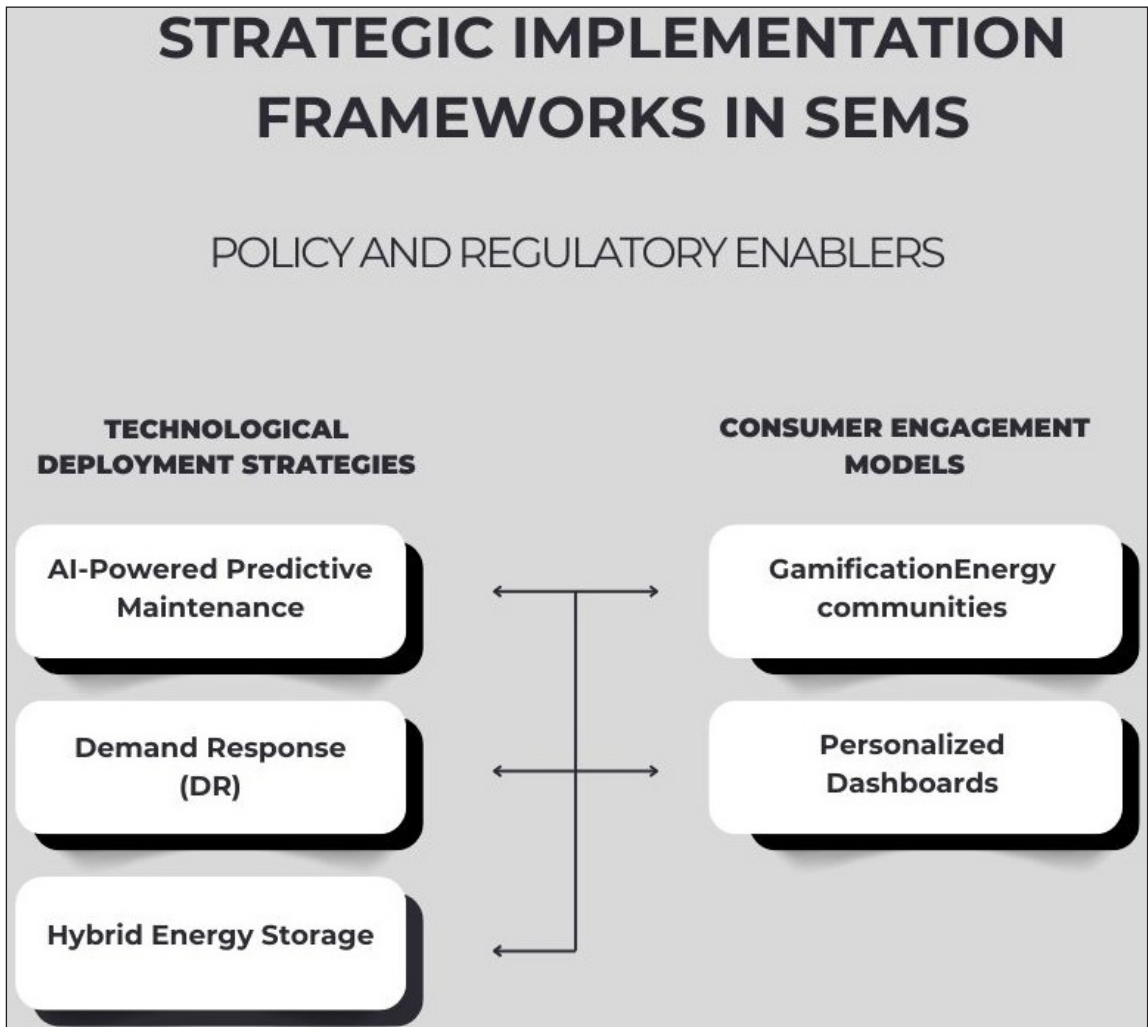


**Fig. 6:** Strategic Implementation Frameworks in SEMS

## The Perspective of Sustainable Development Goals (SDGs)

Energy management stands at the forefront of sustainable development, presenting a crucial opportunity to apply advanced technologies that redefine our approach to energy usage and minimize environmental impacts. The 2030 Agenda for Sustainable Development underscores the importance of clean, reliable,

and affordable energy as a central driver of economic and social advancement<sup>[56],[57]</sup>. However, traditional energy systems are often inefficient, carry significant carbon footprints, and are susceptible to various disruptions. This subdivision will investigate several pivotal aspects:

- ❑ **Integration with All 17 SDGs:** Beyond merely addressing SDG 7, 9, and 13, we will delve into how SEMS can integrate with all 17 SDGs, emphasizing their holistic impact on sustainable development goals and demonstrating the system's broader relevance.
- ❑ **Policy and Regulatory Challenges:** As we champion the promise of SEMS, it's crucial to acknowledge the policy and regulatory challenges that stand in the way of scaling these systems globally<sup>[56],[57]</sup>.

### ***Integration of SEMS with Sustainable Development Goals (SDGs)***

The potential of SEMS extends into the broader framework of Sustainable Development Goals, making significant contributions to our global ambitions:

#### ***1. SEMS and SDG 7: Affordable and Clean Energy***

- ❑ **SDG 7 envisions access to affordable, reliable, sustainable, and modern energy for all.** SEMS advances this goal by:
- ❑ **Optimizing energy consumption:** Using SMES real-time monitoring and demand-response systems, maximizing efficiency and minimizing waste become effectively possible<sup>[61]</sup>.
- ❑ **Integrating renewable energy sources (RES):** By facilitating the incorporation of solar, wind, and hydropower into smart grids, SEMS enhance the sustainability of energy infrastructure (IEA, 2023).
- ❑ **Reducing energy poverty:** *SEMS empower communities, particularly in rural areas, by enabling decentralized energy solutions such as microgrids, which help bridge the energy gap (UNDP, 2021).*

#### ***2. SEMS and SDG 9: Industry, Innovation, and Infrastructure*** Smart energy systems are a driving force for industrial efficiency and innovation:

- ❑ **Enabling predictive maintenance:** Through IoT sensors in manufacturing, SEMS propel industries toward higher efficiency and reduced downtime, fostering innovation<sup>[33],[41]</sup>.
- ❑ **Supporting smart cities:** They enhance infrastructure, building energy-efficient designs and robust EV networks, ultimately creating smarter and more sustainable urban environments<sup>[58]</sup>.
- ❑ **Facilitating Industry 4.0:** AI-driven energy optimization in factories are crucial for achieving the goals of Industry 4.0, propelling industries into a new era of productivity.

#### ***3. SEMS and SDG 13: Climate Action*** SEMS play an essential role in our fight against climate change, significantly contributing to the reduction of greenhouse gas (GHG) emissions by:

- ❑ **Demand-side management (DSM):** This approach helps flatten peak load demand, reducing reliance on fossil fuels and encouraging a transition to cleaner energy sources<sup>[16],[29]</sup>.
- ❑ **Carbon tracking and trading:** With blockchain-enabled transparency, SEMS facilitate the tracking and trading of carbon credits, promoting accountability and sustainability in energy consumption<sup>[7],[34]</sup>.

- ❑ *Enhancing grid resilience*: By improving the grid's ability to withstand climate-induced disruptions, SEMS ensure a stable energy supply even in challenging environmental conditions [25]. Overall, the integration of SEMS into our energy infrastructure marks a significant turning point in our journey toward a sustainable, efficient, and innovative energy future.

#### 4. SEMS and Other Key SDGs

- ❑ *No Poverty (SDG 1) & Zero Hunger (SDG 2)*: SEMS is a game-changer for rural communities! By facilitating rural electrification, it paves the way for reliable energy sources that empower agricultural mechanization, enhance irrigation processes, and enable effective food storage solutions. This innovative approach not only fights poverty but also contributes significantly to eliminating hunger in underserved areas.
- ❑ *Good Health and Well-being (SDG 3) & Quality Education (SDG 4)*: Imagine hospitals operating without interruptions and students accessing digital learning resources seamlessly—this is the reality that SEMS helps create! By ensuring a dependable energy management system, it supports the crucial aspects of health and education, leading to improved well-being and knowledge acquisition.
- ❑ *Gender Equality (SDG 5) & Clean Water and Sanitation (SDG 6)*: SEMS plays a pivotal role in advancing gender equality by reducing household labor demands, enabling women to engage more fully in their communities and economies. Additionally, it optimizes water treatment facilities, ensuring that clean water and sanitation are more accessible for all—promoting healthier living environments.
- ❑ *Decent Work and Economic Growth (SDG 8) & Reduced Inequalities (SDG 10)*: Through the creation of sustainable job opportunities, SEMS is driving economic growth while simultaneously bridging the energy access gap for marginalized communities. This initiative not only fosters decent work conditions but also allows for thriving economic participation in areas that need it most.
- ❑ *Sustainable Cities and Communities (SDG 11) & Responsible Consumption and Production (SDG 12)*: With the aid of AI-driven energy analytics, SEMS encourages a shift towards responsible consumption patterns. By promoting eco-friendly urban development, it enhances the sustainability of cities and communities, ensuring a balanced interaction with our environment.
- ❑ *Life Below Water (SDG 14) & Life on Land (SDG 15)*: SEMS takes environmental stewardship seriously! By regulating energy-intensive industrial waste disposal, it significantly mitigates ocean pollution and contributes to the preservation of marine life. Moreover, it actively works to reduce deforestation, supporting biodiversity both in water and on land.
- ❑ *Peace, Justice, and Strong Institutions (SDG 16) & Partnerships for the Goals (SDG 17)*: SEMS is not just about energy; it's about building a collaborative future! By fostering energy governance and security, it lays the groundwork for strong institutions and meaningful international partnerships. This collective effort is essential for achieving the widespread adoption of sustainable practices across the globe.

## Environment 4.0 and Energy 4.0 implementation with AI based SEMS

Artificial Intelligence (AI) has impacted every industry, including energy management systems. The growths of the population and increasing urbanization worldwide have necessitated optimizing energy resources and efficiencies. AI-driven technologies have already started helping build smart grids and buildings for intelligent energy management systems and sustainable and energy-efficient ecosystems<sup>[50]</sup>. Environment 4.0, the fourth wave of environmentalism, is driven by the urgent need to reduce greenhouse gas emissions. It harnesses innovative technologies like data analytics, Internet of Things (IoTs), blockchain, and artificial intelligence to achieve sustainability<sup>[40]</sup>.

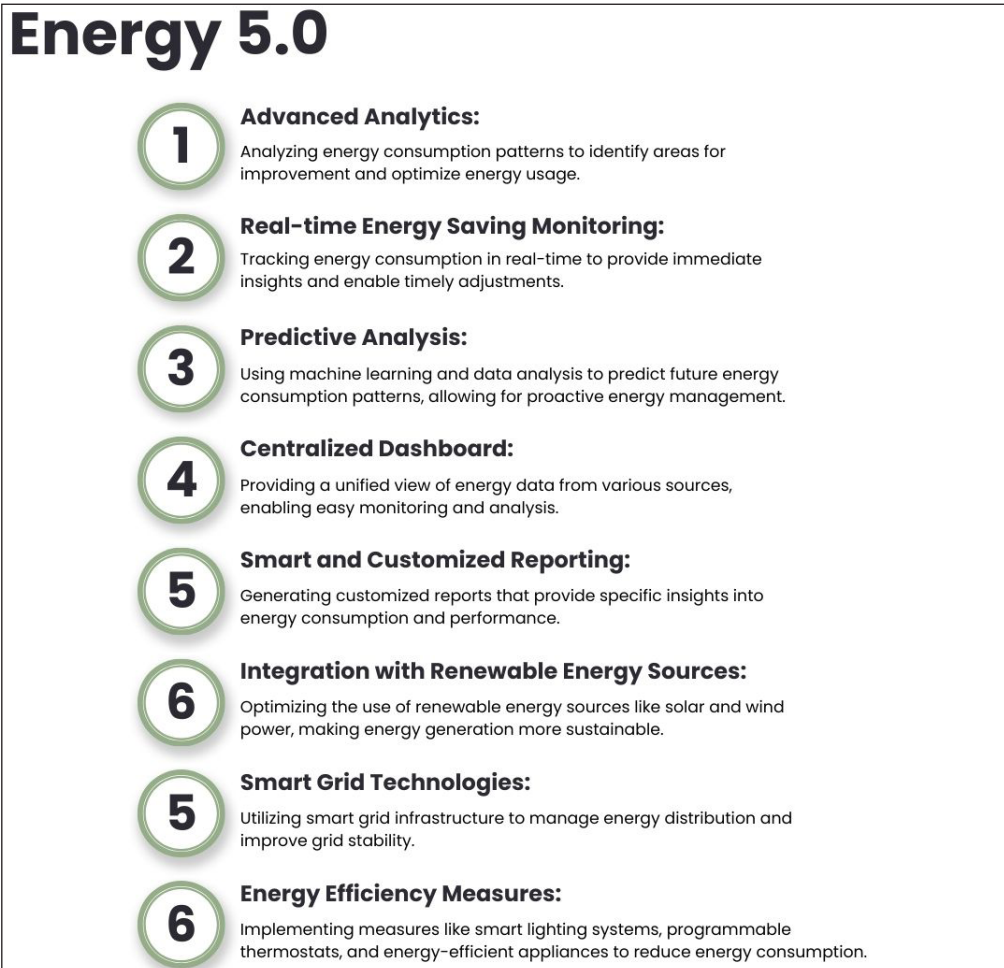


**Fig. 7:** AI Based SEMS empowers Energy 5.0 for effective eco friendly energy systems

Environment 4.0 builds upon the principles of Industry 4.0emphasizes sustainable practices, using advanced technologies like the Internet of Things (IoT), smart sensors, data analytics, blockchain, and AI to monitor and optimize energy consumption and resource use, reduce carbon footprint, reduce waste, and protect environmental ecosystems to achieve sustainability goals. Along the lines of Industry 4.0, Energy

4.0 is a general term for generating, transmitting, and distributing energy infrastructure that leverages the Industrial Internet of Things (IIoT), cloud computing, data analytics, artificial intelligence, and innovative machine learning technologies for smart energy management systems. Smart energy infrastructure helps optimize energy usage, promotes renewable energy sources, smart grids, and decentralized energy systems, and reduces carbon emissions for more reliable and safer energy infrastructure, as well as to improve environmental sustainability goals. AI is essential for optimizing energy distribution, enabling smarter grids, and enabling smart energy management systems to realize Environment 4.0. AI helps integrate decentralized renewable energy sources, like solar panels and wind turbines, to ensure a reliable, stable, and robust energy network<sup>[21]</sup>. AI-driven innovative energy systems can reduce non-essential energy usage, help with more efficient energy management, and lower operational costs<sup>[37],[38]</sup>.

AI-driven smart grid infrastructure holds great promise in transforming energy management by optimizing smart grids, facilitating renewable energy integration, and ultimately improving the efficiency and resilience of energy networks. Artificial Intelligence (AI)—driven smart grids will undoubtedly lead to smarter, greener, and more resilient systems for realizing the environment 4.0; however, technical, financial, regulatory, and other challenges hinder widespread adoption of AI-based smart Energy Management Systems. One of its biggest challenges is integrating AI into existing legacy energy infrastructure, as well as solar, wind, and other renewable energy sources<sup>[41],[56]</sup>.

The current legacy grid infrastructure has data in different, inconsistent, and fragmented formats and sources, posing a challenge for consolidating reliable data to accurately forecast energy demand and consumption. Smart Grid infrastructure necessitates substantial capital investments or upfront costs, and who will bear these costs and how it will impact consumers would be another challenge<sup>[24],[54]</sup>.

## Policy and Regulatory Frameworks for SEMS in AI and SDGs Context:

The advancement of Smart Energy Management Systems (SEMS) is bolstered by supportive policies and regulatory frameworks. The EU's Clean Energy Package (2023) mandates the rollout of smart meters, paving the way for a smarter energy infrastructure. In India, the National Smart Grid Mission (NSGM) is instrumental in promoting the adoption of SEMS, driving innovation in energy management (MNRE, 2023). To further safeguard these systems, adherence to cybersecurity standards established by NIST (2022) is paramount to protect smart grids from evolving cyber threats. Future Policy Recommendations and essential Direction are as follows as far as Key Takeaways—

- ❑ SEMS delivers 20-40% efficiency gains across sectors
- ❑ Requires holistic integration of technology, policy, and consumer engagement
- ❑ Critical for achieving net-zero targets while maintaining grid reliability

## Strategic Recommendations

- ❑ **Governments:** It is vital for governments to implement carbon pricing and provide subsidies to support SEMS adoption. Such initiatives can motivate both industries and consumers to embrace sustainable practices.

- ❑ **Industries:** Industries should place a high priority on deploying digital twin technologies and invest in upskilling their workforce. These steps are essential for driving innovation and enhancing energy management capabilities.
- ❑ **Researchers:** Focusing on AI safety and breakthroughs in hydrogen storage will be crucial for advancing energy technologies. Continued research in these fields can unlock new possibilities for energy efficiency and sustainability.
- ❑ **Consumers:** Engaging in demand response programs and community energy initiatives allows consumers to play an active role in the energy ecosystem. Such participation not only benefits individual households but also strengthens community resilience and sustainability efforts.

Despite the promising benefits of SEMS, several barriers hinder their widespread adoption, viz. the high initial costs, increasing cybersecurity risks, regulatory fragmentation, Quantum computing, AI-driven energy communities, integration of green hydrogen<sup>[54]</sup>.

## CONCLUDING REMARKS

AI-driven Smart Energy Management Systems are reshaping the way we consume and distribute energy, offering unparalleled efficiency, sustainability, and cost savings. As the world moves toward a greener future, integrating AI into energy management will be pivotal in achieving carbon neutrality and optimizing resource utilization. Despite ongoing challenges, the continuous advancements in AI, IoT, and smart grid technologies will enhance the effectiveness of Smart Energy Management Systems (SEMS), resulting in more resilient, intelligent, and sustainable energy solutions. By adopting AI-driven SEMS, we are laying the foundation for a more efficient, eco-friendly, and smarter energy future. In summary, SEMS herald a significant transformation towards sustainable energy systems. By aligning with all 17 Sustainable Development Goals (SDGs), leveraging innovative technologies, and promoting policy advancements, SEMS can lead the global shift toward a low-carbon, resilient, and inclusive energy future. Future research should prioritize scalability, affordability, and interoperability to unlock the full potential of these systems and maximize their impact. A significant transition is going on in the energy world today, especially within the realm of development. Such countries have their particular set of challenges, e.g., old infrastructure, huge transmission and distribution losses, limited electrification, and energy demands growing with leaps and bounds. The electricity demand in emerging markets and developing economies is expected to increase by more than 50% by 2030, which will be much higher than any growth expected in developed countries. This represents an increasing set of challenges and opportunities for Smart Energy Management Systems (SEMS) that can forever change how these countries generate, distribute, and consume energy.

## GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

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