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Smart Energy: Trends, Opportunities, and Challenges

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Abstract. The energy production and consumption ecosystem is undergoing a profound transformation with the emergence of smart energy technologies. This survey examines the trends, opportunities, and challenges of promoting smart energy, with a comprehensive analysis of its evolution, current state, and prospects. This research employs a mixed-methods approach, combining quantitative data analysis with qualitative insights from industry experts, policymakers, and academics. Through surveys and interviews, key themes and trends are identified, including the drivers of smart energy solution adoption, the opportunities they offer for sustainability, efficiency, and resilience, and the challenges hindering their widespread implementation. Findings reveal a notable shift toward decentralized energy systems, renewable energy integration, and the Digitalisation of energy infrastructure, driven by the need to mitigate climate change, ensure energy security, and capitalize on technological advancements. It also emphasizes the significance of ethical considerations and legal frameworks in shaping the future of technology-driven, sustainable, and efficient energy practices. These encompass cybersecurity vulnerabilities in interconnected systems, operational issues arising from the use of diverse technologies, regulatory complexities that hinder rapid adoption, and the need to address equity concerns in the energy transition. Hence, this survey study contributes towards understanding Smart Energy's trajectory.

1 Introduction

Smart energy projects are not traditional single-energy-supply projects; they often involve the entire chain of generation, grid, load, and storage [1]. They more often bear the historical mission of energy transition and revolution, "two replacements" (clean alternatives and electricity alternatives), energy and power system reform, and market diversification construction, covering almost all aspects such as generation, grid, load, storage, combined heat and power, new energy vehicle substitution, digital management enhancement of integrated energy services, and ecosystem construction [2]. Smart energy is a core means to promote the optimized evolution of the energy system [3, 4]. Therefore, the demonstration construction or genuine promotion of smart energy projects must be holistically planned from multiple dimensions. This cannot be covered by simple project-level analysis; strategic planning, project planning, operation technology system, strategic and implementation planning, and financial and management planning are all indispensable.

This paper analyses the core features of smart energy at the social appeal level, examines the medium- and long-term path from the strategic framework level, and elaborates on the whole-process implementation plan framework for smart energy from the perspectives of infrastructure, digital operations, and integrated planning.

2 Social Appeal and Core Demands of Smart Energy

2.1 Social survival and development demands

The basic demands of social survival and development urgently require: increasing the proportion of renewable energy substitution on the power supply side and energy consumption side; enhancing the absorption capacity for renewable power on the transmission and distribution side; increasing the proportion of electricity substitution in transportation, scattered heating, and island power supply; improving the cascade utilization level of heat networks and power grids; optimizing demand-side response and habits, reducing peak energy supply costs. This is the core clue for smart energy development, primarily achieved through technical means at the planning and operation optimization levels [5,6]. An important foundation for the above transformation is the high-level

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integration of energy, information, and value flows within the physical and communication network frameworks. Information, communication, and automation technologies not only provide the foundational guarantee for the energy-information flow architecture but also offer technical pathways for developing and realizing final-value applications based on such architectures [7].

2.2 Industrial environment construction demands

The construction of the industrial environment is an important factor. It requires the synchronous advancement of distributed energy (including storage), electric vehicles, incremental distribution networks, diversified transactions, and power reform policies. It requires creating a market-oriented environment for energy transition and energy efficiency improvement, while promoting collaborative development across related fields. This is primarily achieved through market-oriented policy means in areas such as pricing, ownership and settlement rights, and subsidies [8]. Against the backdrop of the global energy transition, concepts such as smart energy, smart grid, and smart power abound. Although their definitions vary, the direction of change is easy to reach consensus on. The proportion of traditional thermal power as base load gradually declines, replaced by a continuously increasing share of renewable energy. The integration of renewable energy sources such as wind and solar changes the previously centralized energy network architecture, replacing it with more flexible distributed network topologies that focus on regional energy optimization and distributed energy coordination and control [9].

2.3 Industrial transformation and upgrading demands

The construction process and commercial implementation of smart energy are the result of the scale and deep cooperation of related industries. Its manifestation is the reshaping of the value and development focus of the traditional energy and power system through the layout and construction of IoT measurement and control systems, cloud platform shared computing mechanisms, big data, and artificial intelligence analysis methods, by building digital service systems to improve service quality and efficiency and explore derivative value. This is mainly achieved through technical means of cross-border R&D in energy and information communication technology (ICT), as well as Fintech means from cross-border research in energy and finance [10]. Accompanying the explosive development of modern technologies such as artificial intelligence (AI), big data, cloud computing, and the IoT, future energy will evolve along two parallel dimensions: technology and models. The technological dimension emphasizes the cross-border integration of traditional energy and modern ICT technologies. In contrast, the model dimension focuses more on deep cooperation between institutional resources and private capital, thereby deriving new business demands and application scenarios and catalyzing the formation of new energy industrial structures [11].

3 Strategic Framework and Trends

3.1 Heavy asset optimisation and transformation

When it comes to governance, Germany’s practical experience and results have astonished everyone, with its core being just two words: “energy conservation.” Undoubtedly, renewable energy substitution in energy production is a focal point and starting point of the energy transition and revolution. For integrated energy service providers, configuring a reasonably sized renewable energy system is the only way to meet carbon emission quota indicators, the necessary path to initiate distributed energy service capabilities, and the foundation for establishing energy storage systems, virtual power plants, and V2G operational capabilities [12]. The energy and power system has always been a typical heavy asset service sector. Undoubtedly, before energy service providers transform from energy supply to energy use services, the revaluation of digital asset value, the establishment of continuous investment mechanisms, and the ability to track cutting-edge changes in digital assets will be among the strategic transformation focuses for integrated energy service providers [13].

3.2 Whole-process optimisation and technology integration

One of the basic environments for the development of the smart energy industry is the ongoing energy and power system reform. Systematic reforms in price mechanisms, marketisation construction, and distribution marketisation create multiple opportunities for the operation of smart energy projects and impose a series of accompanying market competition pressures on operators.

4 Methodology

This survey study employed a mixed-methods research design to comprehensively explore the trends, opportunities, and challenges within the smart energy sector. The methodology was structured to triangulate data from diverse sources, ensuring robustness and depth of analysis.

4.1 Research Design

A sequential explanatory strategy was adopted, beginning with quantitative data collection and analysis, followed by qualitative inquiry to explain and elaborate on the quantitative findings. This approach enabled the identification of broad patterns and the subsequent exploration of their underlying causes and contexts.

4.2 Data Collection

Data collection occurred in two primary phases:

4.1.1 Phase 1: Quantitative Survey

A structured online questionnaire was distributed to a purposive sample of 350 professionals across the smart energy ecosystem, including technology developers, utility managers, policymakers, project consultants, and academic researchers. The survey comprised Likert-scale items, multiple-choice questions, and ranking exercises designed to quantify perceptions on adoption drivers, technology readiness, regulatory impacts, and perceived challenges. The response rate was 68%, yielding 238 usable responses.

4.1.2 Phase 2: Qualitative inquiry

Following the analysis of survey data, semi-structured interviews were conducted with 25 key informants selected from survey respondents who indicated a willingness to participate further and who represented a balance of stakeholder groups. Interview protocols were tailored to probe deeper into themes emerging from the survey, including the intricacies of business model innovation, specific regulatory barriers, and ethical dilemmas in Digitalisation.

4.3 Data Analysis

The surveyed data (quantitative) were cleaned and analyzed using statistical software (SPSS v.27). Descriptive statistics (frequencies, means, standard deviations) summarized the data. Inferential statistics, including factor analysis and analysis of variance (ANOVA), were used to identify underlying constructs and test for significant differences in perceptions among stakeholder groups. At the same time, the qualitative data, i.e., interview recordings, were transcribed verbatim and organized. Thematic analysis was employed, following a six-phase process as outlined by Braun and Clarke [14]: familiarization with data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report. Codes and themes were merged and synthesized to identify points of convergence, complementarity, and emphasis. This process validated findings by ensuring that trends, opportunities, and challenges identified in one document (e.g., the strategic need for digital assets) were supported by technical requirements in the other.

The study received institutional review board approval. All participants provided informed consent. Survey responses were anonymized, and interview participants were assigned pseudonyms. Data were stored securely on password-protected servers.

4.4 Survey Results

The survey achieved a representative sample across key smart energy stakeholder groups, with technology developers accounting for the largest proportion of respondents (29%), followed by utility managers (24%), academic researchers (21%), policymakers/regulators (15%), and other professionals (11%). This distribution ensured balanced perspectives from both technology and operational stakeholders.

The respondents rated various factors influencing Digital Asset Value, with the top-rated drivers indicating Climate Change Mitigation ($M = 4.62$, $SD = 0.52$) and Technological Advancements (AI/IoT) ($M = 4.45$, $SD = 0.61$), whereas the most critical barriers were Regulatory Complexities ($M = 4.38$, $SD = 0.68$) and Cybersecurity Vulnerabilities ($M = 4.25$, $SD = 0.59$) (see Table 1). These results suggest that while the adoption of smart energy technologies is strongly motivated by environmental and technological imperatives, organizational and policy constraints continue to pose substantial challenges. Additionally, the ANOVA results indicated a statistically significant difference among stakeholder categories ($F(4, 233) = 8.12$, $p < 0.001$, $\eta^2 = 0.12$), demonstrating a medium effect size. Post-hoc comparisons using Tukey's HSD test revealed the following patterns: Technology developers and academic researchers assigned significantly higher value to intellectual property and software code, reflecting a strong emphasis on knowledge-based assets. Utility managers, in contrast, placed greater importance on physical, capital-intensive assets, consistent with operational and infrastructural priorities. Policymakers and other professionals exhibited intermediate ratings, balancing the valuation of digital and physical assets.

Table 1. Key Adoption Drivers and Barriers (N=238).

Category	Factor	Mean (M)	Std Dev (SD)
Drivers	Climate Change Mitigation	4.62	0.52
	Technological Advancements (AI/IoT)	4.45	0.61

	Energy Security Needs	4.10	0.75
Barriers	Regulatory Complexities	4.38	0.68
	Cybersecurity Vulnerabilities	4.25	0.59
	Undervaluation of Digital Assets	4.05	0.82

These results empirically corroborate the ethical concern regarding labor and knowledge valuation identified during the qualitative phase of this study, highlighting the divergence in how different stakeholders perceive the value of digital versus physical energy assets. Furthermore, the observed variations in stakeholder perceptions of digital and physical assets highlight the broad nature of smart energy adoption. These data not only emphasize the critical role of digital technologies and integrated infrastructure but also highlight the diverse expectations, priorities, and constraints that shape system implementation. Building on these findings, the subsequent section explores the key opportunities and challenges associated with smart energy systems, providing a framework to align technological innovation with practical deployment and policy considerations.

5 Opportunities and Implementation Pathways

5.1 Infrastructure and Digital Operation

The financial foundation of smart energy projects is stable and predictable heat and power loads [6]. Therefore, before project initiation, a comprehensive investment and forecast analysis is needed. One of the preconditions for implementing smart energy projects is the accessibility of the source, grid, and load; the other is the optimization space for energy conservation, efficiency, and renewable substitution. The biggest difference from traditional energy projects is that smart energy projects' reliance on digital operations or digital assets has reached the point where data is the service. The framework design of digital operation systems, synergistic design and layout of adjacent industries, synchronization of technology and management Digitalisation, and artificial intelligence substitution have all become the foundation for smart energy development rather than optional enhancements. The smart energy system is shown in Fig. 1.

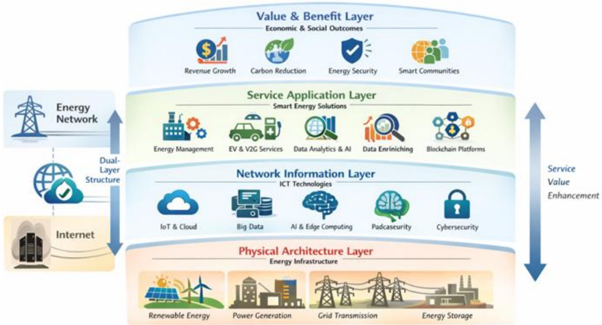

Fig. 1. Smart Energy ICT Architecture (4-layer + dual network)

5.2 Business Models and Ecosystem Construction

Smart energy needs to consider the multiple impacts of energy technology innovation, system form upgrading, and energy system reform. Smart energy services are defined as being oriented towards the terminal of the energy system, guided by customer needs, and enhancing customer benefits or satisfaction through combinations of multiple energy varieties and system integration, energy technology and business model innovation, etc. The system goal is based on the provider of smart energy services. Integrated smart energy projects, unlike simple smart energy projects, have strong business development, exploratory, and demonstrative principles. Whether it's strategic organizational structure transformation, asset operation transformation planning, medium- and long-term technical route iteration, basic business model research, core product line planning, ecosystem construction planning, external resource cooperation strategies, or human resource cultivation planning, all may be essential work before the landing of such core projects.

Table 2. Smart Grid Stack.

Layer	Primary Technology	Smart Energy Function
Perception	IoT Sensors	Smart meters, PMUs (Phasor Measurement Units), EV chargers
Transmission	5G / NB-IoT	Ultra-reliable low-latency communication (URLLC) for grid stability
Intelligence	AI / Big Data	Load forecasting, predictive maintenance for turbines/transformers
Governance	Blockchain	Carbon credit tracking, P2P trading, and immutable billing logs

The robustness of the architecture (technological backbone of the smart energy systems) is such that the technological stack (shown in Table 2) transforms a traditional, one-way power grid into a "Self-Healing Smart Grid" or Energy Internet, where [IoT] → provides data → [Big Data], and

[Big Data] → fuels → [AI / ML], and [5G / NB-IoT] → enables → [Real-time Control & Edge Intelligence], or [Cloud Computing] complements [Edge Computing], and [Blockchain] → supports → [Trust, Settlement, Multi-party Consensus].

6 Challenges

6.1 Technical and Operational Challenges

The differences in engineering design between smart energy infrastructure and traditional energy and power facilities include cost control, utilization of emerging technologies, and framework reconstruction. Specifically, it is more reflected in the structuring of primary facilities and the construction intensity of secondary ICT systems [1].

Given the conceptual definition, functional demands, and technical characteristics of smart energy, it places different demands on traditional power system communication, information, automation, and related technologies in practice. For example, smart energy, based on distributed energy integration, places more emphasis on effective complementarity of various energy sources and optimal resource allocation within a regional scope, focusing on distribution, consumption, and dispatching (small-scale regional), getting closer to the user side, emphasizing both efficiency and benefits while considering safety. Therefore, when designing the network architecture for smart energy, a distributed, economical, and hybrid network architecture is adopted.

6.2 Market and Regulatory Complexities

The construction of the industrial environment requires the synchronous advancement of distributed energy (including storage), electric vehicles, incremental distribution networks, diversified transactions, and power reform policies. From the perspective of social capital and new energy service providers, system reform, on one hand, reduces the guaranteed market for original energy services, and on the other hand, provides opportunities to grasp new energy economic cross-sections. However, obtaining market share and maintaining continuous control over new cross-sections must rely on ongoing investment in supply chain cost control, loss control, supply-demand optimization technology, and end-user service capabilities.

6.3 Financial and Valuation Hurdles

Traditional energy projects can leverage indirect financing from the start of construction to reduce capital pressure and the opportunity costs of comprehensive financing, thereby accelerating large-scale construction. Smart energy projects not only need to improve energy efficiency, promote renewable energy substitution, and foster market diversification through technological upgrades, but also achieve lower-cost financing processes than traditional energy projects through financial technology (Fintech). The energy and power system places low importance on ICT assets and digital assets, including sensors, meters, gateways, backends, and historical and online data. In particular, the core code of the most critical basic models and data structure engines, middleware platforms, advanced applications, and smart hardware in software systems is significantly undervalued in terms of labor costs, leading not only to vicious competition in sales prices but also to nearly free system upgrades and maintenance.

6.4 Ethical Considerations and Legal Frameworks

Given the heavy asset nature and potential of energy networks, energy security requirements, and national policy requirements, only a single service operator may exist for energy operations within a single region in developing countries. As such, the communication network support system within a single region should primarily rely on self-built networks, supplemented by public networks, to ensure secure access control for various data, with a focus on the secure storage and reliable communication of regulatory data within the energy network. Moreover, during the development of the traditional energy industry, countless instances of resource misallocation in supply projects may occur due to the timing disconnect between national strategy and policy operations, indicating that existing legal and regulatory structures are inadequate for smart energy, requiring fundamental reforms in ownership rights, settlement mechanisms, and market design.

A solution to the above is necessary, not only to reduce comprehensive social costs, but also to enhance the end-user experience through online transformation. This reveals a fundamental ethical issue in labor valuation and intellectual property—the systematic undervaluation of digital work creates unsustainable conditions and discourages innovation. Thus, there is a need for new policies on pricing, ownership rights, market structures, and cybersecurity standards.

7 Conclusions

The fundamental social appeal for smart energy development lies in the survival demands for energy source-side and terminal-side transformation, the need for energy efficiency and conservation improvement, the construction of a collaborative industrial environment, and the internal motivation for the energy and power system to achieve transformation and upgrading through technologies like IoT, big data, and artificial intelligence.

The development path of smart energy is the intersection of comprehensive clues, including the optimisation and adjustment of the entire society's primary energy structure, the collaborative development of the upstream and downstream of generation, transmission, distribution, consumption, and storage, the early layout of new energy vehicles, and the normalization of digital assets. It is an industrial upgrading process that involves whole-process optimization and the utilization of disruptive technologies to enhance social welfare.

The whole-process implementation of smart energy projects is a process of refined optimization of infrastructure, open and intelligent architecture construction, the construction norm based on digital operation platform system planning, and the comprehensive realization of strategic organizational structure transformation, asset operation transformation planning, medium- and long-term technical route iteration, basic business model research, core product line planning, ecosystem construction planning, external resource cooperation strategies, and human resource cultivation planning.

The proposed ICT architecture for the smart energy system supports current popular scenarios such as smart cities and smart parks, emphasizing the cross-border integration of modern ICT and traditional energy technologies. The overall technical philosophy follows the core principle that technology serves scenarios, and that scenarios originate from demands. In summary, this is a coherent analysis that covers social appeal (drivers/trends), strategic paths & business models (opportunities), and an implementation framework (validated through trends and challenged by challenges) for smart energy from the perspectives of infrastructure, digital operations, and integrated planning.

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