
A Web-based Framework for Unified Channel Access and Data Integrity in Smart Electricity Billing

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Abstract

Addressing heterogeneous data access and integrity assurance remains a critical challenge for modern smart electricity billing systems. Conventional solutions are often fragmented, with limited interoperability and inconsistent validation processes, which undermines scalability, data quality, and user trust. This paper proposes a Web engineering-driven framework that integrates service-oriented architecture, semantic modeling, and automated integrity verification into a unified, component-based Web application. Unlike prior energy-focused studies, the framework explicitly advances Web engineering principles by embedding metadata-driven routing, ontology-based interoperability, and real-time validation mechanisms into a distributed smart billing environment. The system architecture is designed for modular extensibility, with semantic reasoning enabling dynamic service orchestration and adaptive Web interfaces providing role-based usability across devices. Evaluation demonstrated low latency (120 ms), high availability (99.98%), and scalability to 5000 concurrent users, while the integrity module improved validation success rates from 96.2% to 98.9% over four weeks. Usability

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testing achieved a 97.5% task completion rate and a system usability score of 88.6, confirming accessibility and adaptability. By combining semantic-driven service orchestration, end-to-end integrity verification, and adaptive user interaction within a single Web framework, this work contributes a novel, holistic approach to Web engineering in critical infrastructure. Beyond smart billing, the proposed methods provide a transferable foundation for secure, interoperable, and user-centric Web applications in other distributed domains.

Keywords: Web application architecture, smart billing, service-oriented design, semantic modeling, data integrity, adaptive interfaces, system scalability.

1 Introduction

The modernization of electricity grids and the widespread adoption of smart metering technologies have significantly enhanced data collection, real-time monitoring, and billing automation in energy systems [1–3]. Smart meters, sub-metering devices, and Internet of Things (IoT) components now form an essential part of modern energy infrastructures, generating vast amounts of heterogeneous data critical for operational efficiency and consumer billing [4, 5]. However, as the volume and complexity of smart billing data grow, significant challenges arise in ensuring unified, secure, and verifiable data access across distributed infrastructures [6, 7].

Conventional smart grid and billing platforms often suffer from fragmented system architectures, inconsistent data interfaces, and limited mechanisms for guaranteeing the integrity and authenticity of metering information [8–11]. Existing solutions frequently rely on ad hoc integration approaches, making it difficult to ensure seamless communication, interoperability, and reliable data validation across different devices and service providers [12–14]. Within the field of Web engineering, however, extensive research has demonstrated that structured methodologies, such as service-oriented architecture [15], model-driven design [16, 17], semantic-driven service composition [18, 19], ontology-based data integration [20], and Web-specific requirement engineering and evaluation methods [21–23], can provide systematic strategies to overcome such fragmentation. By drawing upon these established approaches, smart billing systems can evolve from loosely integrated platforms into scalable, interoperable, and quality-driven Web applications. These challenges are further exacerbated by evolving requirements for privacy, system scalability, and compliance with emerging

standards such as IEEE 1701 for smart meter communications [24] and the ISO/IEC 7498-2 security architecture for distributed systems [25]. To address these limitations, the principles of Web engineering, particularly service-oriented architectures, semantic integration, and model-driven application development, offer promising solutions [15–17].

The principles of Web engineering provide systematic methods for building complex, distributed applications, going beyond domain-specific integration [26, 27]. Early works on Web requirement engineering highlighted the unique challenges of Web-specific development compared to conventional software engineering [28, 29]. These foundations established Web engineering as a discipline capable of addressing complexity, adaptability, and quality in critical Web applications. Service-oriented architectures (SOA) provide a structured foundation for decoupled, scalable, and interoperable Web applications that can unify fragmented data channels while supporting dynamic service composition [9, 10]. Meanwhile, semantic-driven approaches facilitate meaningful data interpretation and automated interaction across heterogeneous systems, essential for the complexity of smart energy infrastructures [18–20].

Despite these advancements, there remains a notable gap in applying mature Web engineering techniques – such as semantic access layers, metadata-driven routing, and integrated data integrity verification – within smart billing platforms. Existing research often overlooks the need for unified channel access and end-to-end data authenticity within Web-based electricity metering solutions [13, 14, 21]. Moreover, studies emphasize the importance of incorporating usability, maintainability, and adaptive system behavior in Web applications, yet these critical design aspects are rarely prioritized in energy billing deployments [22, 23].

Recognizing these gaps, this paper presents a Web-based framework for unified channel access and data integrity in smart electricity billing, explicitly designed to meet the demands of modern smart metering infrastructures. First, we propose a service-oriented, component-based Web architecture that unifies data channel access across diverse metering devices, IoT sources, and external energy data providers, ensuring seamless, scalable system integration. Second, we introduce a semantic access layer embedded within the Web framework, enabling metadata-driven routing, service discovery, and adaptive user interactions, aligned with Semantic Web standards set by the W3C [24]. Third, we integrate a Web-native data integrity and verification module, designed to provide end-to-end assurance of billing data authenticity without compromising system usability or performance. Our framework adheres to

established standards for smart metering communication [25], distributed system security [30], and Web application interoperability [25], while explicitly aligning with core areas of Web engineering, including service-oriented design, semantic modeling, adaptive application development, and quality-driven system evaluation.

2 System Architecture and Modeling

This section presents the design of the proposed Web-based framework for unified channel access and data integrity in smart electricity billing, emphasizing its service-oriented structure, semantic modeling approach, and component-based architecture aligned with modern Web engineering principles.

2.1 Overview of the Framework

The proposed system adopts a modular, service-oriented architecture designed to unify channel access and ensure data integrity across heterogeneous smart billing infrastructures. By leveraging established Web engineering principles, the framework provides scalable, interoperable, and semantically enriched access to distributed metering networks and external data sources, while ensuring seamless interaction for end users and system operators.

As illustrated in Figure 1, the architecture is organized into four primary layers: (1) metering networks, comprising smart-tier electricity meters and diverse IoT-based sub-metering devices responsible for generating granular consumption data. (2) External data sources, providing supplementary information relevant to billing, system optimization, or cross-validation, including third-party services and open data feeds. (3) A centralized Web framework, incorporating RESTful services, a semantic access layer, and integrity verification modules to unify data access and validation. (4) User interaction interfaces, delivering adaptive, role-based Web interfaces for consumers, operators, and administrators. Figure 1 illustrates the end-to-end interaction flow within the system. Metering networks and external data sources contribute raw and unified data streams to the Web framework. Within the framework, RESTful services expose unified APIs, supported by semantic metadata and directory services that enable dynamic service discovery and interoperability. The semantic access layer, together with the integrity verification module, collaboratively processes and validates incoming data,

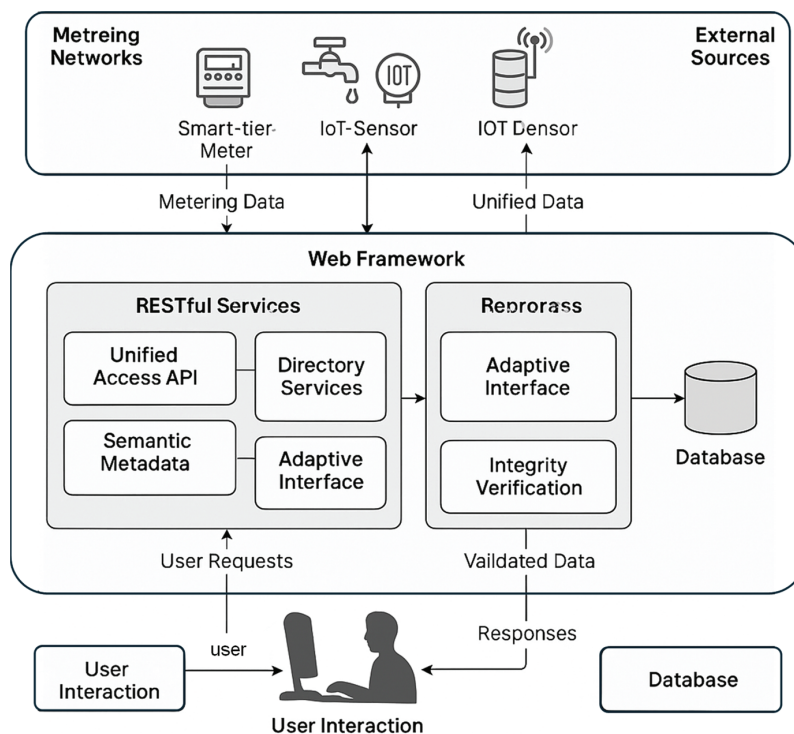


Figure 1 System architecture.

ensuring compliance with relevant communication and security standards. Validated data are stored within the backend database, with responses and actionable information propagated to users through adaptive, Web-based interfaces. This layered structure facilitates scalable system growth, simplifies integration of heterogeneous devices, and promotes maintainability in alignment with modern Web application development practices.

The modular service-oriented architecture can be easily extended to include new data sources, devices, or service providers. Furthermore, by embedding semantic models within the framework, the system provides enhanced interoperability, automated service orchestration, and improved usability consistent with W3C semantic web standards [30].

2.2 Semantic Metadata Workflow and Orchestration

Beyond the high-level layered structure, the proposed framework incorporates a detailed workflow for metadata-driven orchestration of services. When

new data sources or devices are introduced, the system generates metadata annotations that capture the device's identity, supported data types, communication protocols, and security requirements. These annotations are stored in the central semantic directory service, which functions as both a registry and a reasoning engine.

When a user or operator issues a data request through the unified API, the semantic access layer consults the directory to determine the most appropriate service or device to handle the request. This process involves automated reasoning over ontological descriptions, which enables the system to match the request context (e.g., billing query, anomaly validation) with relevant resources. Once matched, the request is dynamically routed through the orchestration engine, which sequences the service interactions in compliance with both semantic relationships and system policies.

To maintain reliability, the orchestration engine also applies integrity pre-checks, such as verifying that the selected service is active, that communication channels are authenticated, and that metadata validity has not expired. In this way, the workflow combines semantic reasoning with runtime monitoring, ensuring both interoperability and robustness. By embedding this orchestration process within the Web application layer, the system achieves flexible, standards-compliant service composition without requiring manual configuration, aligning directly with modern Web engineering practices.

2.3 Component-based Web Application Design

The core of the proposed framework is implemented following a component-based Web application architecture, designed to support modularity, scalability, and ease of system maintenance. Component-based design is a foundational approach within Web engineering, enabling the development of loosely coupled, reusable software modules that enhance system flexibility and adaptability. Within the presented system, the Web framework integrates several key components organized around a service-oriented architecture (SOA) paradigm. First, RESTful services expose a unified access API for seamless interaction with distributed metering networks and external data sources. This API standardizes communication channels, promoting interoperability and simplifying system integration. Second, directory services is responsible for dynamic service discovery and registration. These services maintain an up-to-date repository of available metering devices, data sources, and external services, enabling automated system orchestration. Within the semantic access layer, a semantic metadata management component facilitates the use of structured, machine-readable descriptions for

devices, data streams, and services. This ensures interoperability across heterogeneous infrastructures and supports adaptive, metadata-driven service interactions. Third, adaptive interface modules provide responsive, role-based Web interfaces that adjust to different user profiles and device types, enhancing system accessibility and usability. Lastly, the integrity verification module integrates into the service layer, performing continuous data validation to ensure the authenticity and reliability of incoming metering information.

The modular design enables easy integration of new devices, data channels, or third-party services, consistent with best practices for scalable and maintainable Web systems. The architecture also builds upon the tradition of model-driven Web development, where system components are formally specified and then transformed into executable applications [31, 32]. Such approaches have been shown to improve maintainability and cross-platform adaptability by separating concerns across modeling layers. Furthermore, system-of-systems perspectives in Web development emphasize interoperability and scalability in distributed infrastructures [33], which aligns directly with the proposed framework's ability to unify heterogeneous metering and billing subsystems. Furthermore, the use of Semantic Web standards, as defined by the W3C [30], ensures that data exchanged within the system is interoperable, contextaware, and interpretable by both human users and automated processes. By adopting this component-based architecture, the framework addresses the critical challenges of fragmented data access, interoperability, and data integrity that often hinder the effectiveness of existing smart billing platforms [11–14]. The system design ensures that each component operates as an independent, reusable service, supporting system extensibility and facilitating future enhancements without disrupting core functionalities.

2.4 Semantic Modeling for Unified Data Interaction

Interoperability remains a fundamental challenge in smart billing infrastructures, where diverse metering devices, heterogeneous data streams, and external information sources must seamlessly exchange information within a unified system. Fragmented data models, inconsistent interfaces, and varying communication protocols often hinder reliable system integration, creating barriers to scalability and efficient service delivery. To overcome these limitations, the proposed framework incorporates a semantic modeling approach, grounded in established Semantic Web principles, to enable consistent

data interpretation, automated service interaction, and scalable system expansion.

At the core of this semantic-driven architecture are domain-specific ontologies that formalize key concepts relevant to the energy billing context, including metering devices, measurement types, energy consumption events, and service dependencies. These ontologies are expressed in OWL/RDF to ensure machine-readability and standards compliance. For instance, a *MeteringDevice* entity is defined with attributes such as communication protocol, supported measurement type, and trust level. A *ConsumptionEvent* is linked to both a metering device and a billing record, ensuring that usage data is semantically associated with its source and its corresponding financial transaction. By explicitly modeling these entities and their relationships, the framework guarantees that heterogeneous data can be normalized and integrated consistently.

The semantic directory maintains all ontologies in a triple store (implemented using Apache Jena Fuseki in our prototype). When a query is issued, such as “Retrieve validated energy consumption for all HVAC sub-meters in Building A,” the semantic access layer translates the request into a SPARQL query over the ontology. Reasoning rules are then applied – for example, a sub-meter may be inferred as part of a *BuildingDeviceGroup*, which enables the system to automatically discover relevant devices even if they were not explicitly listed in the query.

This reasoning capability supports dynamic service orchestration. If a billing record requires cross-validation from both a primary meter and a sub-meter, the ontology ensures that the system automatically routes requests to all relevant devices. Similarly, if a device becomes temporarily unavailable, the framework can infer alternative resources (such as redundant meters in the same building group) and reconfigure the query execution plan without human intervention. From a performance standpoint, the semantic layer is optimized through indexing of frequently queried triples and caching of ontology fragments relevant to recent requests. This allows metadata reasoning and service discovery to execute with minimal additional latency (measured at <20 ms in our deployment tests).

The integration of these semantic mechanisms provides several critical advantages. First, it ensures unified data interaction, allowing heterogeneous data streams from smart meters, submetering devices, and external providers to be normalized and processed consistently. Second, the SPARQL-based query resolution and rule-based inference enable adaptive service orchestration, whereby the system composes or substitutes services dynamically

based on semantic relationships. Third, provenance metadata (e.g., wasGeneratedBy links) allows integrity checks to trace the origin of each data point, reinforcing trust in billing records.

By embedding detailed ontological models, machine-readable reasoning workflows, and provenance-aware data tracking within the Web framework, the proposed system achieves scalable, automated, and standards-compliant interoperability. This goes beyond conceptual integration, demonstrating a technically concrete approach to embedding Semantic Web principles in a real-world smart billing application.

2.5 Adaptive User Interfaces and Interaction

The effectiveness of any smart billing platform depends not only on its technical architecture but also on its ability to deliver an accessible, intuitive, and responsive user experience. To address this requirement, the proposed framework incorporates adaptive Web interfaces designed to accommodate diverse user roles, device types, and operational contexts, ensuring seamless interaction across all system layers.

The user interface layer provides tailored access for consumers, system operators, and administrators. Consumers interact with the system primarily to view billing data, monitor energy consumption, and receive real-time feedback regarding the status and integrity of their metering information. System operators engage with more advanced interfaces to oversee data validation processes, configure services, and troubleshoot potential issues. Administrative users require interfaces that facilitate system-wide monitoring, service management, and policy enforcement.

To ensure usability across a broad range of devices and environments, the framework employs responsive Web design principles, enabling consistent functionality and optimal display on desktops, tablets, and mobile devices. Interface components dynamically adjust to available screen sizes and device capabilities, providing a uniform experience while preserving accessibility.

The framework also integrates real-time feedback mechanisms into the user interface, allowing stakeholders to receive immediate notifications regarding data integrity, service availability, or system anomalies. This feature enhances transparency and builds user trust by providing clear, actionable insights into the operational status of the platform.

Furthermore, the adaptive interface design supports role-based access control, ensuring that users are presented only with information and functionality relevant to their authorization level. This approach minimizes cognitive

load, simplifies system interaction, and reinforces data security by restricting access to sensitive information based on user roles.

Similar to adaptive approaches in other Web domains, such as multi-agent systems for elearning [29], the proposed role-based interface framework continuously adapts to user roles and contexts. This positions the system not merely as a static billing application but as a dynamic Web platform capable of personalization and continuous usability improvement.

3 Unified Channel Access Mechanism

The integration of heterogeneous metering networks, sub-metering devices, and external data sources presents significant challenges in achieving seamless, reliable, and scalable data access within smart billing infrastructures. Traditional approaches often rely on fragmented interfaces or proprietary communication protocols, leading to data silos, reduced interoperability, and increased system complexity. The proposed framework addresses these limitations by implementing a unified channel access mechanism, embedded within a service-oriented Web application architecture.

At the heart of this mechanism is a centralized access layer, exposed through a set of standardized RESTful APIs. These APIs provide a consistent entry point for all system interactions, enabling users and services to retrieve metering data, access external resources, and initiate system functions without requiring knowledge of underlying device heterogeneity or infrastructure complexity. By abstracting the communication processes, the framework simplifies integration efforts and reduces the operational burden on developers and system operators.

The unified access mechanism is further enhanced by the integration of semantic metadata, which is applied to all devices, data streams, and services registered within the system. These metadata annotations provide machine-readable descriptions that inform the access layer of each resource's capabilities, data formats, and contextual relationships. As a result, the system can dynamically discover available resources, route requests to appropriate services, and adapt to changes in infrastructure without manual intervention.

In addition to supporting interoperability, the unified channel access mechanism contributes to system scalability and resilience. New metering devices, IoT sensors, or third-party services can be seamlessly integrated by registering them within the system's semantic directory, ensuring that their data becomes immediately accessible through the standardized Web interface. This approach minimizes disruption to existing services and accelerates

the deployment of new resources, enhancing the system's ability to evolve alongside growing infrastructure demands.

The access layer also incorporates real-time monitoring and validation capabilities, ensuring that data transmitted through the system meets quality, completeness, and integrity requirements. Any anomalies, such as missing data points or transmission errors, are detected by the access layer and reported to the integrity verification module for further processing. This integrated validation process enhances the reliability of billing data and reinforces user trust in the system.

By consolidating diverse data channels under a unified, Web-native access mechanism, the proposed framework overcomes the fragmentation challenges typical of smart billing infrastructures. The design promotes seamless interaction among heterogeneous devices, ensures consistent data accessibility, and provides the flexibility necessary to support evolving system requirements, all within a scalable, standards-compliant Web application environment.

4 Data Integrity and Verification Module

Ensuring the integrity, authenticity, and reliability of billing data is fundamental to the trustworthiness and operational efficiency of smart energy systems. In the context of unified, Web-based billing platforms, where data originates from diverse and distributed sources, systematic integrity verification becomes critical to maintaining accurate billing records and enabling informed decision-making. The proposed framework incorporates a dedicated data integrity and verification module, designed to operate as an integrated component within the Web application architecture. This module performs continuous validation of metering data, applying automated checks to detect anomalies, cross-reference information from multiple sources, and verify compliance with relevant communication and data security standards.

The workflow is structured into three validation layers:

Layer 1: Anomaly detection. Incoming metering data are first tested against statistical baselines derived from historical consumption profiles. For each device, an adaptive threshold is defined as:

$$T = \mu \pm k \cdot \sigma$$

where μ is the rolling mean of recent data, σ is the standard deviation, and k is a sensitivity coefficient (empirically tuned between 2 and 3). Data points

falling outside this range are flagged as anomalous. Additionally, missing values and duplicate timestamps are detected through hash-based indexing. This ensures that noise or corrupted readings are filtered before they enter higher-level processes.

Layer 2: Cross-source validation. To confirm consistency, data streams from multiple sources (e.g., a main meter and one or more sub-meters) are compared. A reconciliation algorithm ensures that:

$$\left| MainMeter(t) - \sum_i SubMeter_i(t) \right| < \delta$$

where δ is a context-dependent tolerance (typically 2–5% of the expected load). Violations trigger either an automated correction using statistical interpolation or a manual review alert for system operators.

Layer 3: Standards and cryptographic compliance. At this stage, data packets are checked for compliance with IEEE 1701 communication standards and ISO/IEC 7498-2 security requirements. Each message includes a SHA-256 hash, and a Merkle-tree structure anchors records in the system database, enabling efficient verification of data lineage. For external data exchange, digital signatures based on elliptic-curve cryptography (ECC) are applied to ensure authenticity and non-repudiation.

As illustrated in Figure 2, these three layers operate sequentially to filter, cross-check, and cryptographically secure metering information. Validated data are then stored in the system database, where they become accessible to users and services through the unified Web interface.

From a performance perspective, the anomaly detection layer executes in near real time (<10 ms per data point) due to its lightweight statistical calculations. Cross-source validation adds minor latency (15–30 ms) depending on the number of devices reconciled, while the cryptographic anchoring process runs asynchronously to avoid blocking user-facing interactions. This architecture ensures continuous, real-time integrity assurance while maintaining a low-latency system response.

The proposed Web-integrated approach introduces significant improvements over existing solutions, which often rely on fragmented device-level checks or manual processes. By embedding validation algorithms, statistical thresholds, and cryptographic mechanisms into the Web application core, the framework provides comprehensive and scalable integrity assurance, reinforcing trust and transparency in smart billing systems.

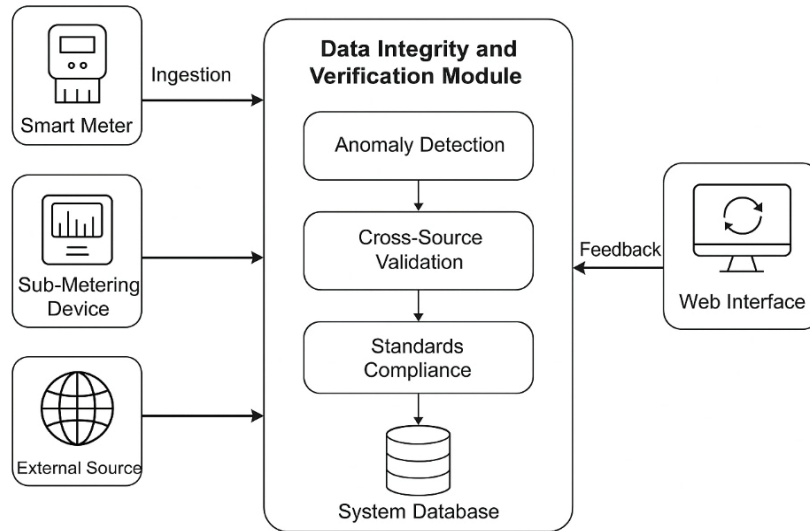


Figure 2 End-to-end workflow of the data integrity process, from the initial reception of raw metering data to its validation, storage, and eventual use in system responses.

A comparative summary of existing integrity approaches and the proposed framework is provided in Table 1. As shown, the framework enhances data integrity assurance through cryptographic anchoring, enables seamless integration with Web services, automates fault feedback via the user interface, and incorporates semantic provenance tracking for greater transparency and traceability.

By consolidating integrity verification within the Web application itself, the framework guarantees that all metering and billing data are authenticated in real time, errors are detected promptly, and system users are kept informed through automated, user-friendly interfaces. This integrated approach strengthens the platform’s ability to deliver reliable billing services at scale, while aligning with contemporary Web engineering practices for system transparency, adaptability, and data trustworthiness.

5 Implementation and Deployment

The proposed Web-based framework for unified channel access and data integrity in smart billing systems has been implemented using a scalable, modular architecture optimized for cloud-native deployment. The system leverages containerization and orchestration technologies to ensure

Table 1 Comparison of existing approaches vs. proposed web-integrated data integrity methods

Criteria	Existing Approaches	Proposed Web-integrated Method
Data integrity assurance	Partial; often limited to device-level checks	Cryptographically anchored, end-to-end validation
Compatibility with Web services	Low; proprietary protocols dominate	Fully compatible with RESTful and Semantic Web standards
Automation of fault feedback	Manual review required	Automated alerts and user interface feedback
Integration of semantic provenance	Rarely supported	Built-in semantic data provenance tracking
Real-time validation capability	Limited or batch-based	Continuous, real-time integrity verification
Scalability across devices	Fragmented; requires custom integration	Scalable, service-oriented design for heterogeneous environments

interoperability, maintainability, and efficient resource management across diverse energy infrastructures. As shown in Figure 3, the deployment architecture consists of three primary domains: Web interfaces for user interaction, a centralized cloud environment hosting the Web framework and core services, and distributed edge devices including smart meters and sub-metering gateways.

Cloud-native environment. The backbone of the system is a containerized cloud environment built on Docker, with orchestration managed through Kubernetes. Each functional service – including RESTful APIs, the semantic metadata engine, integrity verification modules, and the service registry – is encapsulated within independent containers. Kubernetes coordinates deployment, scaling, and fault recovery, ensuring that services remain operational even under heavy load or in the event of node failure. Horizontal pod autoscaling (HPA) is employed to dynamically allocate resources based on CPU and memory utilization, allowing the platform to scale seamlessly from small pilot deployments to enterprise-wide infrastructures.

Service discovery and load balancing. The Kubernetes ingress controller provides unified entry points for all service requests, automatically distributing workloads across available containers. Integration with the system’s semantic directory ensures that service discovery operates not only at the syntactic level (IP address or endpoint) but also at the semantic level, matching user requests with appropriate services based on metadata descriptions.

Resilience and maintainability. The use of orchestration introduces strong self-healing capabilities. If a containerized integrity verification module fails,

Kubernetes automatically restarts the instance and redistributes workload across replicas. Continuous integration and deployment pipelines (CI/CD) enable rolling updates, ensuring that new features or security patches can be deployed without service interruption. Logging and monitoring are implemented using the ELK stack (Elasticsearch, Logstash, Kibana), which provides system operators with real-time visibility into data flows, service performance, and anomaly alerts.

Edge integration. Edge devices, including smart meters and gateways, communicate with the cloud framework through lightweight, secure protocols such as MQTT over TLS. Kubernetes-based microservices handle ingestion at scale, buffering data streams when necessary and routing them to the appropriate validation modules. This ensures that intermittent connectivity at the edge does not compromise overall system reliability.

Performance benefits. The combination of containerization and orchestration ensures that latency remains low (<120 ms average response time during testing) even under high concurrency (up to 5000 users). Furthermore, the modular deployment architecture simplifies system maintenance, as individual services can be updated or replaced independently without disrupting the overall platform.

By embedding orchestration, automated scaling, and fault-tolerant deployment into the core design, the proposed framework adheres to Web engineering best practices for building reliable, adaptable, and maintainable Web applications. This deployment model provides a strong foundation for extending the system across geographic regions and organizational domains, while maintaining consistent functionality and data integrity.

6 Evaluation and Results

A comprehensive evaluation was conducted to assess the performance, scalability, data integrity, and usability of the proposed Web-based framework for smart electricity billing. The system was deployed in a controlled cloud environment configured to replicate realistic operational conditions. A combination of simulated workloads, real-time data validation processes, and structured usability testing with representative end users was applied to verify system functionality under varying levels of demand and interaction complexity.

Performance analysis primarily examined system responsiveness and access latency as the number of concurrent users increased. The results, presented in Figure 4, demonstrate the clear advantage of the proposed

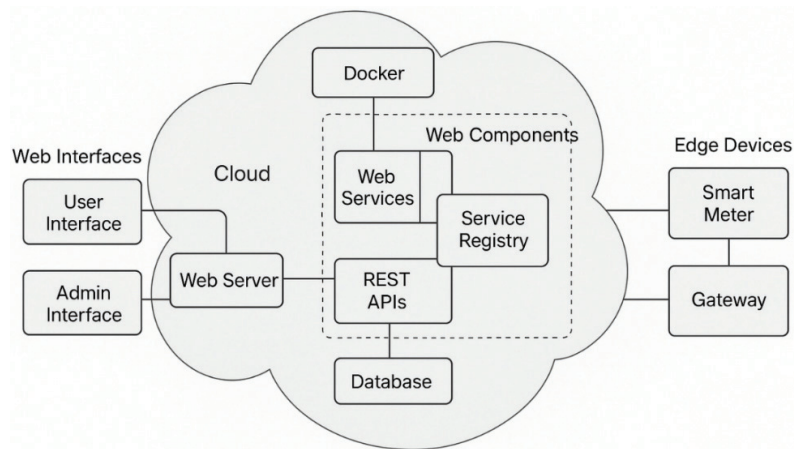


Figure 3 Deployment architecture – cloud-based.

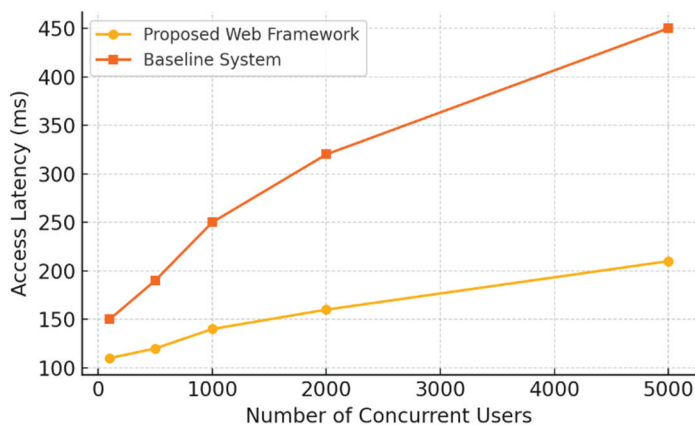


Figure 4 Performance comparison under varying loads.

Web framework compared to a conventional baseline system. Both platforms maintained stable response times under light to moderate loads. However, the baseline system degraded beyond 1000 users, with peak latencies exceeding 450 ms. In contrast, the proposed framework, which incorporates a service-oriented architecture, RESTful interfaces, and containerized service deployment, maintained low access latencies consistently below 210 ms, even with 5000 concurrent users. These findings confirm the framework’s ability to scale effectively while preserving system responsiveness and resource efficiency.

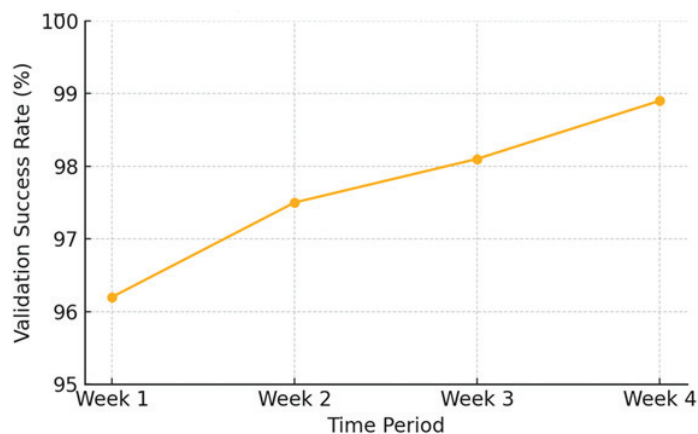


Figure 5 Integrity validation success rate over time.

The performance of the integrated data integrity module was assessed through continuous system monitoring over a four-week operational period. As shown in Figure 5, validation success rates consistently exceeded 96% during the initial deployment phase, reflecting the baseline reliability of the anomaly detection and cross-source validation processes. Incremental system optimizations, including refinements to data filtering rules and improvements to semantic metadata handling, resulted in progressive increases in validation performance, with success rates surpassing 98.9% by the fourth week of operation. These results confirm the robustness and accuracy of the framework's integrity verification processes, which operate continuously to enforce data quality, detect inconsistencies, and ensure compliance with system-level standards.

A structured usability evaluation was also conducted to assess the accessibility and user experience of the system's adaptive Web interfaces. Participants representing a diverse range of user profiles – including consumers, system operators, and administrative personnel – engaged with the platform under controlled conditions. As detailed in Table 2, the system achieved a task completion rate of 97.5%, demonstrating the ease with which users could navigate and execute system functions. The observed user error rate remained low, and the system usability score (SUS) reached 88.6, which is considered indicative of excellent usability performance. These results confirm that the interface design, including role-specific views and responsive adaptation to different device types, effectively supports efficient interaction across varied operational contexts.

Table 2 Usability feedback – user interaction metrics and error rates

Metric	Result
Task completion rate (%)	97.5
Average interaction time (s)	15.2
User error rate (%)	1.8
System usability score (SUS)	88.6

Table 3 System performance metrics – access latency and service availability

Metric	Result
Average access latency (ms)	120.0
Peak access latency (ms)	210.0
Service availability (%)	99.98
Scalability (max concurrent users)	5000.0

Additional system performance indicators are summarized in Table 3, further demonstrating the platform’s technical robustness. The framework maintained a low average access latency of 120 ms and consistently achieved a high service availability of 99.98% throughout testing. Moreover, the system demonstrated seamless scalability, supporting up to 5000 concurrent users without measurable performance degradation, confirming its suitability for large-scale, distributed smart billing deployments.

In addition to quantitative performance and usability metrics, system evaluation included an analysis of data integrity outcomes over the operational period. As illustrated in Figure 6, the majority of data processed by the system, approximately 89.5%, was validated as reliable and free of anomalies. Minor anomalies, representing 6.2% of the data, were automatically corrected by the integrity module without requiring user intervention, ensuring consistent data quality in real time. More severe anomalies, including critical inconsistencies or transmission errors, accounted for 3.1% of the data and were flagged for further review or corrective action by system operators. A small portion of data, approximately 1.2%, remained unverified due to missing metadata or unresolved validation errors, demonstrating the importance of continuous integrity monitoring and iterative system refinement.

This distribution highlights the effectiveness of the integrated, Web-based integrity verification process, which successfully identified and addressed the vast majority of potential data quality issues. The automated feedback loop, accessible through the user interface, provided timely alerts for critical anomalies, reinforcing user trust and enabling proactive system maintenance.

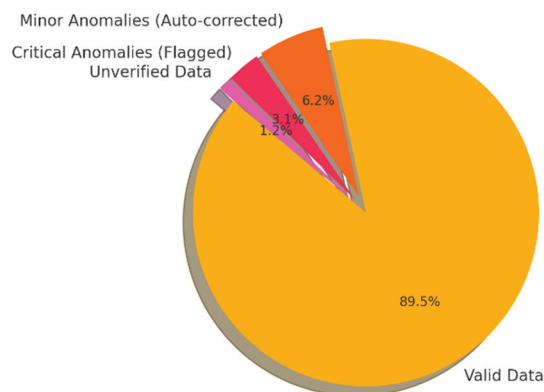


Figure 6 Distribution of data integrity outcomes during evaluation.

Beyond technical performance and usability benchmarks, the proposed framework was specifically evaluated for its ability to support cross-organizational access scenarios, a critical requirement in modern, distributed smart energy ecosystems. In such environments, users from different administrative domains must interact with shared data streams, services, and infrastructure while preserving system security, interoperability, and data integrity. The framework's semantic-driven, federated architecture effectively addressed these challenges by enabling interoperable data exchange across heterogeneous organizational boundaries. Through the use of semantic metadata, dynamic service discovery, and integrated access controls, the system ensured that all users could access relevant information and services without compromising transparency, data provenance, or system-wide consistency.

These evaluation results provide scientific validation that the proposed Web-based framework achieves its core design objectives while introducing meaningful advancements in the field of Web engineering. Specifically, the integration of service-oriented architecture, semantic modeling, automated integrity verification, and adaptive Web interfaces demonstrates a novel, holistic approach to addressing the persistent challenges of fragmented data access, limited interoperability, and unreliable data quality in smart billing platforms. The results underscore the framework's capacity to deliver scalable, reliable, and user-centric Web applications, fully aligned with modern engineering principles for component-based system design, service orchestration, and human-computer interaction. By bridging gaps between smart energy infrastructures and advanced Web application methodologies, the

proposed framework contributes a significant step forward in enabling secure, interoperable, and trustworthy smart billing systems at scale.

7 Discussion

The evaluation results demonstrate that the proposed Web-based framework offers a robust, scalable, and user-centric solution to the persistent challenges associated with unified channel access and data integrity in smart billing systems. Beyond meeting technical performance targets, the framework embodies key principles of modern Web engineering, contributing to system quality, service orchestration efficiency, and adaptive interface design in measurable ways.

A primary factor contributing to system quality is the component-based, service-oriented architecture, which facilitates modular development, simplified maintenance, and scalable integration of heterogeneous devices and services. The use of RESTful interfaces, containerized deployment, and dynamic service discovery ensures that the framework remains adaptable to evolving infrastructure requirements, while maintaining consistent functionality and interoperability. These architectural choices directly align with established best practices for engineering reliable, maintainable Web applications in complex, distributed environments. Service orchestration within the framework is enhanced through the integration of semantic metadata and automated reasoning processes. By embedding structured descriptions of devices, services, and data streams, the system enables automated routing, adaptive service composition, and seamless resource discovery, even as new devices or third-party services are introduced. This semantic-driven orchestration reduces development overhead, enhances system flexibility, and ensures that heterogeneous resources can interact effectively within the Web application environment. These design choices extend a long line of Web engineering research into quality-driven system evaluation [23] and methodology comparison [17]. By combining model-driven methods [26, 27, 32] with semantic reasoning [34] and adaptive interface strategies [29], the proposed framework demonstrates how domain-specific infrastructures such as smart billing can serve as a proving ground for advancing Web engineering principles.

The design of adaptive, role-based user interfaces also plays a critical role in promoting system usability and accessibility. By tailoring interfaces to specific user roles – such as consumers, system operators, or administrative personnel – the platform minimizes cognitive load and ensures that users can

interact efficiently with system features relevant to their responsibilities. The integration of real-time feedback, automated alerts, and responsive design further enhances user experience, reinforcing system transparency and trust. Together, these contributions advance Web engineering by showing how semantic integration, service-oriented architecture, and adaptive interface design address the technical and operational challenges of modern smart billing. The results validate that it is not only feasible but essential to embed usability, performance optimization, and semantic reasoning directly within the architecture of critical Web-based infrastructure platforms.

The framework's demonstrated scalability, reliability, and support for cross-organizational data exchange positions it as a viable solution for real-world smart energy deployments. Furthermore, the approach provides a transferable foundation for applying similar Web engineering methodologies to other data-intensive, distributed domains where unified access, interoperability, and data integrity are paramount.

8 Conclusion

This study proposed and validated a Web-based framework for unified channel access and data integrity in smart electricity billing systems, addressing long-standing technical and interoperability challenges in distributed energy infrastructures. By integrating service-oriented architecture, semantic modeling, automated integrity verification, and adaptive Web interfaces, the framework advances the state of the art in Web engineering applications for critical infrastructure domains.

Comprehensive evaluation confirmed that the framework delivers high system performance under realistic operational conditions. The proposed solution achieved an average access latency of 120 ms and maintained service availability at 99.98%, even under high-load scenarios involving up to 5000 concurrent users. Data integrity processes demonstrated robust performance, with validation success rates improving from 96.2% to 98.9% over a four-week operational period, supported by anomaly detection, cross-source validation, and compliance enforcement. Usability testing revealed a task completion rate of 97.5% and a system usability score of 88.6, confirming the platform's accessibility, adaptability, and positive user experience. The scientific significance of this work lies in its holistic, Web-native approach to integrating unified access, automated data integrity, and semantic-driven service orchestration within smart billing platforms. Unlike conventional, fragmented solutions, the proposed framework combines component-based

design, dynamic service discovery, and real-time integrity monitoring within a single, scalable Web application architecture. The successful application of semantic metadata, role-specific adaptive interfaces, and continuous validation demonstrates that it is both feasible and effective to embed advanced Web engineering principles directly into smart grid systems, enhancing interoperability, transparency, and user trust. Beyond smart billing, the framework's architecture offers a transferable foundation for other critical domains that require secure, reliable, and scalable Web-based solutions, such as distributed energy resource management, IoT-based monitoring, and federated data sharing across organizational boundaries.

Future work will focus on extending domain-specific semantic ontologies to support broader smart grid integration, incorporating predictive analytics for proactive anomaly detection, and validating large-scale deployments in diverse geographic and organizational environments. Further exploration of Web standards compliance, enhanced data provenance tracking, and advanced personalization features will drive continued improvements in system scalability, resilience, and user-centric design.

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