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The P2P-Ironing Platform: Evaluating the Software Quality and User Acceptance of a Decentralized Cyber-Physical Marketplace for Shore-to-Ship Power

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Abstract. Decarbonizing the maritime industry through shore-to-ship power (cold-ironing) requires robust transactive energy systems. However, implementing decentralized peer-to-peer (P2P) energy markets introduces significant socio-technical challenges, including the operational friction of pure Web3 applications and conflicting stakeholder demands regarding billing transparency. This paper presents the software engineering lifecycle and empirical validation of the P2P-Ironing platform, a cyber-physical marketplace designed for smart ports. Driven by a two-phase mixed-methods requirements analysis involving key maritime and energy stakeholders (N=18, N=15), the platform utilizes a decoupled, hybrid architecture to abstract blockchain complexity from the end-user. To resolve dockside billing disputes and manage unpredictable maritime loads, the system integrates hardware-in-the-loop (HIL) smart meters to automatically trigger deterministic smart-contract escrow settlements. A rigorous empirical evaluation (N=30) utilizing the Short User Experience Questionnaire (S-UEQ) demonstrated high pragmatic and hedonic software quality. The findings indicate that the proposed architecture successfully mitigates decentralized ledger friction. Furthermore, a custom operational instrument was deployed, with metrics validating stakeholder trust in the automated settlement logic, acceptance of transparent P2P market structures, and agreement on the platform's contribution to decarbonization. Ultimately, this research provides a validated, user-centric architectural blueprint capable of accelerating maritime green energy transitions, successfully operating within the constraints of nascent legislative frameworks and physical infrastructure limitations.

Keywords: Cyber-Physical Systems, Software Architecture, Empirical Software Engineering, Web2.5, Blockchain, Cold-Ironing, S-UEQ, Operational Acceptance, Transactive Energy, Smart Ports.

1 Introduction

The maritime transport sector is undergoing a structural shift driven by stringent international decarbonization mandates. A primary physical solution to this challenge is “cold-ironing”, the provision of high-voltage shore-to-ship power that allows berthed vessels to shut down their auxiliary diesel engines. However, transitioning from a theoretical concept to a fully operational, decentralized green energy ecosystem requires more than just electrical infrastructure. It necessitates robust, transactive energy management (TEM) software capable of orchestrating complex, peer-to-peer (P2P) energy trades between visiting ship operators, local port authorities, and verified green energy suppliers [1].

While blockchain and Distributed Ledger Technologies (DLT) have emerged as standard methods for ensuring trust, immutability, and automated clearing in P2P energy networks, their adoption in enterprise environments is often impeded by software usability and socio-technical friction [2]. Pure, fully decentralized applications (Web3), which interact directly with the blockchain without traditional centralized backend servers, introduce a substantial learning curve, requiring non-technical stakeholders to manage complex cryptographic keys and utilize fragmented interfaces [3]. By mitigating these specific usability barriers, the P2P-Ironing platform utilizes blockchain technology to guarantee operational transparency, execute reliable smart contracts, and secure financial settlements. Furthermore, maritime logistics introduce unique socio-technical conflicts, such as the operational demand for highly predictable, flat-rate financial settlements versus the electrical grid operator's need for dynamic penalty tracking when vessels consume more energy than forecasted [4].

To bridge the gap between immutable ledger mechanics and practical maritime operations, this paper presents the design, architectural implementation, and empirical evaluation of the P2P-Ironing platform, a cyber-physical digital marketplace designed specifically for smart ports. Rather than deploying a pure Web3 application, this research adopts a Web2.5 enterprise software architecture. This hybrid approach acts as a bridge: it utilizes traditional, familiar enterprise software components (.NET 8 middleware and a Blazor WebAssembly frontend) to manage the user interface and data routing, while confining the complex, decentralized ledger mechanics strictly to the background for critical tasks like escrow and settlement. By encapsulating the blockchain network in this manner, the platform leverages Pragmatic Decentralized Identifiers (did:pkh) and verifiable credentials to abstract cryptographic friction from the end-user. To resolve physical billing disputes and manage the unpredictable nature of maritime loads, the architecture integrates hardware-in-the-loop (HIL) smart meters to serve as deterministic cyber-physical oracles, triggering automated smart-contract escrow settlements.

Crucially, this study goes beyond architectural proposition to rigorously assess the quality in use and operational acceptance of the developed system. The specific contributions of this research are threefold:

1. **Empirical Requirements Analysis:** The presentation of a mixed-methods requirements elicitation, emphasizing the active involvement of key stakeholders and decision makers (e.g., port authorities, port administrators, electricity

grid operators, port operators, energy suppliers, policymakers, government energy ministry officials, ship owners, ship managers, researchers, and academics) that can shape the shift towards Renewable Energy Systems (RES) at Cyprus ports. This direct stakeholder involvement guided the design and development of the platform to resolve conflicting socio-technical demands.

2. **Web2.5 Architecture and Implementation Lifecycle:** The detailed architecture, workflows, full lifecycle, and implementation of the web platform, including the smart contract blockchain development. To accommodate the lack of physical cold-ironing infrastructure, the platform's workflows were simplified to closely align with the administrative logistics of port platforms. Furthermore, the methodology leveraged historical ship berthing data and vessel load profiles to algorithmically transform and amplify telemetry captured from the testbed that comprised of smart meters of conventional houses. This enabled the generation of synthetic data to accurately simulate vessel connections and disconnections to the Onshore Power Supply (OPS).
3. **Empirical Evaluation and Stakeholder Validation:** The results of a rigorous empirical evaluation of the P2P-Ironing platform by key stakeholders (N=30). The validation confirmed the platform's usability (via the S-UEQ) and stakeholder acceptance. A custom domain-specific instrument validated the operational transparency, the agreement on decarbonization and green energy prioritization, as well as robust support for automated smart meter and blockchain integration for reliable data billing and dispute resolution. Finally, this evaluation formally identified key ecosystem limitations: the regional legislative gap and the physical infrastructure deficit at the Port of Limassol.

The remainder of this paper is structured as follows: Section 2 reviews related work in maritime cold-ironing, TEM software, and blockchain usability. Section 3 details the empirical requirements engineering phase and identifies core socio-technical conflicts. Section 4 presents the decoupled Web2.5 software architecture, including the synthetic data generation and cyber-physical integration. Section 5 details the empirical evaluation utilizing the S-UEQ and operational domain metrics. Section 6 discusses the findings, architectural trade-offs, and ecosystem limitations, followed by the conclusion in Section 7.

2 Background and Related Work

To contextualize the contributions of the P2P-Ironing platform within the broader landscape of empirical software engineering and maritime informatics, this section reviews the current literature across three intersecting domains: transactive energy in maritime logistics, the usability gap in enterprise blockchain applications, and the evaluation of cyber-physical trust.

2.1 Transactive Energy Management in Maritime Logistics

The maritime industry's transition toward zero-emission ports has prioritized the physical engineering of High-Voltage Shore Connection (HVSC) systems, commonly

known as cold-ironing [5]. While the electrical infrastructure necessary to supply shore-to-ship power is well-documented, the software ecosystem required to manage these energy transactions requires further development [6]. Current port energy management systems predominantly rely on centralized, fixed-rate tariffs controlled entirely by the primary grid operator.

Recent literature has proposed Transactive Energy Management (TEM) systems to decentralize these grids, allowing peer-to-peer (P2P) trading between localized renewable energy producers (e.g., port-side solar arrays) and high-load consumers [7]. However, most of these studies focus on mathematical grid-balancing algorithms or theoretical auction models. There is a distinct lack of empirical software engineering research detailing how to operationalize these dynamic P2P models into functional, user-centric enterprise software capable of accommodating the strict logistical timeframes and physical realities of maritime operations.

2.2 The Blockchain Usability Gap in Enterprise Software

Distributed Ledger Technologies (DLT) and smart contracts have become prominent methods for establishing trust and automating financial settlements in P2P energy networks [8]. By executing deterministic code on an immutable ledger, stakeholders can trade energy without relying on a centralized clearinghouse.

Despite these theoretical advantages, the practical adoption of blockchain in legacy industries is frequently hindered by poor “quality in use” [9]. Pure decentralized applications (Web3), which interact directly with the blockchain without traditional centralized backend servers, introduce substantial socio-technical friction. Users are typically required to manage complex cryptographic keys, securely store private seed phrases, and utilize fragmented interfaces [10].

In the context of software quality, this represents a significant barrier in human-computer interaction (HCI). Enterprise stakeholders, such as ship managers or port administrators, require systems with high pragmatic quality and minimal cognitive load [11]. While several papers propose blockchain architectures for smart grids, few focus on the real-world deployment to rigorously evaluate the system's usability or user acceptance using established empirical instruments like the User Experience Questionnaire (UEQ). Consequently, there is a significant research gap regarding how to successfully encapsulate and abstract DLT complexity within familiar enterprise software paradigms (Web2.5 architectures) to achieve acceptable software quality.

2.3 Cyber-Physical Integration and Off-Chain Data Verification

A fundamental challenge in cyber-physical systems (CPS) utilizing blockchain is off-chain data verification, the inherent inability of an isolated, deterministic ledger to natively validate real-world physical events [12]. In a maritime energy market, a smart contract cannot independently verify if a ship has connected to the terminal or how many kilowatts it is currently drawing.

Existing literature frequently models ideal data streams, assuming that IoT devices will consistently transmit uninterrupted data to the ledger [13]. However, in real-world port environments, hardware degrades, network latency fluctuates, and stakeholder disputes over metered consumption are common. Resolving this requires hardware-in-the-

loop (HIL) integration, where physical smart meters act as trusted cyber-physical bridges to trigger software state changes [14] controlled by the port administrator (i.e., manually initiating and terminating the ship connection to the OPS). Evaluating how stakeholders perceive the reliability of these automated hardware triggers is critical, as a lack of trust in physical integration impedes software acceptance.

Furthermore, to practically evaluate this cyber-physical integration despite the current lack of high-voltage cold-ironing infrastructure at the Port of Limassol, this research implemented a targeted telemetry simulation strategy. By accessing existing smart meter infrastructure from conventional residential houses, the system algorithmically transforms and amplifies this baseline telemetry using historical data of ship berthing and vessel load profiles. This methodology enables the platform to generate highly accurate synthetic data streams on demand, realistically simulating the electrical load dynamics of a vessel connecting and disconnecting from the onshore power supply.

2.4 Summary of the Identified Research Gap

The current literature presents a fragmented approach: studies either focus strictly on electrical grid models, propose theoretical blockchain architectures without empirical usability testing, or overlook the socio-technical friction of enterprise deployment.

This paper addresses this specific gap. By developing the Web2.5 P2P-Ironing platform, we move beyond theoretical architecture to provide a comprehensive, empirically validated study of software quality. By measuring the platform's ability to abstract blockchain friction (via the S-UEQ) and mapping stakeholder trust in the cyber-physical market logic (via domain-specific operational metrics), this research provides a validated blueprint for engineering highly usable, decentralized enterprise systems for the maritime sector.

3 Empirical Requirements Engineering

The successful deployment of cyber-physical systems in regulated domains requires strict alignment with operational realities. Traditional requirements engineering frequently falls short in maritime logistics when it relies on isolated technical specifications rather than addressing the socio-technical factors and competing priorities among disparate ecosystem actors [15], [16]. To ensure the P2P-Ironing platform effectively addressed the logistical, financial, and physical constraints of maritime cold-ironing, a comprehensive, stakeholder-driven mixed-methods methodology was executed prior to software implementation [17].

Central to the first contribution of this paper, this requirements analysis actively engaged a diverse cohort of key stakeholders and domain experts who are directly involved in driving cold-ironing infrastructure and policy implementation in Cyprus. By systematically involving decision-makers across intersecting sectors, ranging from port authorities, administrators, and electrical grid operators to policymakers, energy suppliers, and ship managers, the requirements engineering process ensured that the platform's architectural blueprint was directly shaped by the cross-domain expertise necessary to successfully transition local ports toward Renewable Energy Systems (RES).

3.1 Methodology and Participant Demographics

The elicitation phase utilized a sequential explanatory mixed-methods approach, combining preliminary quantitative surveys (using 5-point Likert scales) with qualitative interviews and interactive focus groups. This methodology ensures that quantitative consensus is rigorously contextualized against qualitative domain expertise.

The initial ecosystem cohort comprised 18 industry experts (Phase 1: Elicitation) representing a diverse cross-section of the maritime sector. Following the synthesis of the initial requirements, a secondary workflow validation focus group (Phase 2: Validation) involving 15 stakeholders was conducted to iteratively refine the proposed software architecture. The participant distribution, strategically selected to represent the complete cold-ironing supply chain, is detailed in Table 1.

Table 1. Ecosystem Stakeholder Demographics across Engineering Phases.

Ecosystem Domain	Phase 1: Elicitation (N=18)	Phase 2: Validation (N=15)	Primary Operational Focus
Academic / R&D Experts	8	3	System architecture, maritime economics, usability.
Port Authorities & Terminal Ops.	3	4	Physical infrastructure, berthing logistics, queue management.
Grid & Market Operators	2	2	High-voltage network stability, capacity forecasting.
Energy Suppliers / Producers	2	1	Dynamic pricing, green certification, market competitiveness.
Ship Owners / Vessel Operators	1	1	Financial predictability, operational simplicity, delay mitigation.
Regulatory Bodies / Auditors	0	2	Legal compliance, standardizations, governance.
Other (Manufacturing/Tech)	2	2	Hardware integration, switchboard constraints.

3.2 Initial Requirements Analysis

The initial elicitation phase yielded quantitative data that directly established the functional and architectural constraints of the P2P-Ironing platform. The analysis of the expert responses (N=18) highlights a strong consensus in areas of market structure and automated security, alongside a measurable polarization regarding operational load management.

Market Topology and Competitive Bidding: Stakeholders exhibited a clear preference for a decentralized energy market over traditional utility monopolies. When evaluating pricing structures (see Fig. 1), 78% of respondents favored an open, competitive platform supporting dynamic pricing from multiple green energy producers, compared to only 17% who preferred a single, fixed-rate contract. This preference for

market decentralization is corroborated by an 89% consensus requiring the platform to facilitate competitive bidding, allowing ship owners to actively view and select from multiple verified supplier quotes for specific docking periods.

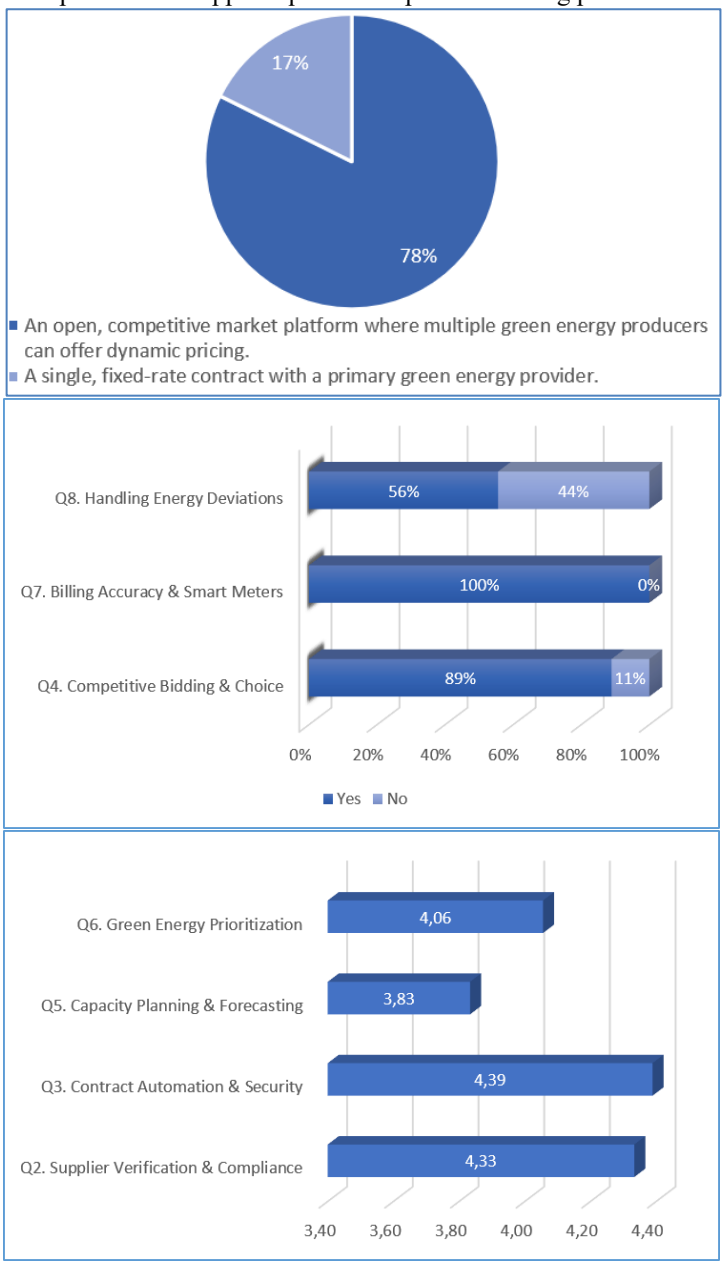


Fig. 1. Quantitative Stakeholder Consensus on Core System Requirements.

Automation, Security, and Compliance: The demand for automated trust mechanisms was a dominant operational requirement. Participants rated the importance of Contract Automation and Security highly (Mean = 4.39 out of 5.00), paired with a strict demand for Supplier Verification and Compliance (Mean = 4.33). Crucially, the cohort reached unanimous agreement (100%) that financial settlements must be strictly and automatically triggered by real-time data from physical smart meters. This absolute consensus mathematically validates the architectural decision to integrate hardware-in-the-loop (HIL) components to eliminate manual data entry and subsequent billing disputes. Furthermore, the prioritization of verified green energy sources received strong support (Mean = 4.06), aligning the platform's core escrow mechanics with international decarbonization mandates.

Capacity Planning and the "Over-Consumption Paradox": While the necessity of capacity planning and forecasting yielded a moderately high consensus (Mean = 3.83), the quantitative data exposed a significant socio-technical divide regarding the handling of unforecasted energy deviations. When asked if excess energy consumption should be managed via a simplified, flat-rate billing model, the cohort was sharply divided: 56% agreed, while a substantial 44% firmly opposed the approach. This near-even split quantitatively illustrates the "Over-Consumption Paradox." It explicitly maps the friction between the vessel operators' requirement for financial predictability and the grid operators' mandate to enforce dynamic financial penalties for grid protection. This polarization directly dictated the platform's modular architectural strategy, intentionally deferring complex penalty enforcement to off-platform regulatory mechanisms to maintain base system viability.

3.3 Operational Workflow Validation

During the secondary workflow validation phase (N=15), stakeholders quantitatively evaluated ten proposed operational workflows designed to translate the elicited requirements into concrete system logic (see Fig. 2). The overall results demonstrate a strong baseline of acceptance across the platform's core mechanics, with mean suitability scores predominantly clustering between 3.80 and 4.27 on a 5-point scale. Stakeholders exhibited the highest level of consensus regarding market integrity and physical automation. Specifically, the workflows governing Supplier Registration & Licensing (Mean = 4.27) and Smart Meter Integration & Automated Settlement (Mean = 4.27) received the strongest validation. This confirms that the architectural strategy of enforcing strict, verified gateways (supported by a mean of 4.13 for Market Operator Verification) and relying on deterministic, hardware-triggered financial settlements closely aligns with the sector's rigorous compliance expectations. Furthermore, the open-quote bidding mechanism (Mean = 4.13) was highly validated as a suitable approach for fostering a fair, competitive energy market at the port.

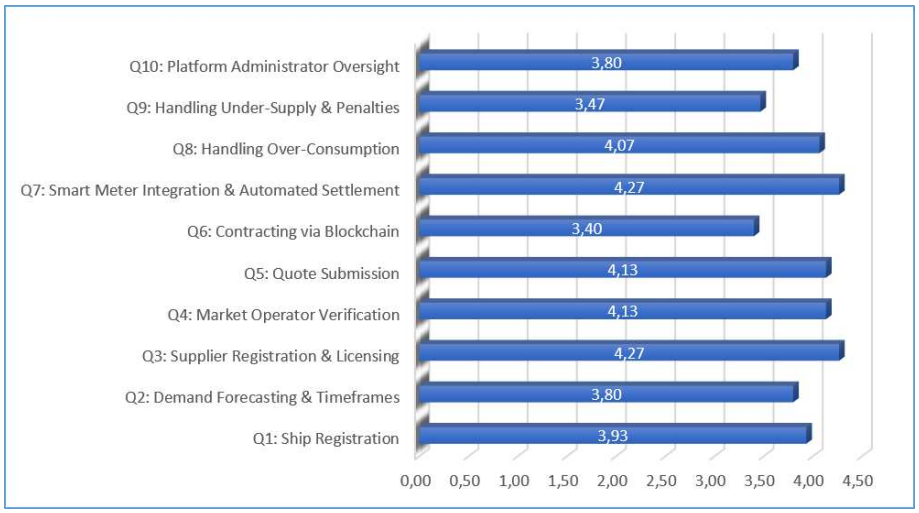


Fig. 2. Stakeholder Validation of Operational Workflows.

Conversely, workflows involving automated legal execution and penalty management yielded comparatively lower quantitative confidence, highlighting areas directly impacted by current ecosystem limitations. The proposed mechanism for Contracting via Blockchain received the lowest overall score (Mean = 3.40), while the workflow for Handling Under-Supply & Penalties also scored moderately (Mean = 3.47). Qualitative feedback from the stakeholders explicitly indicates that this apprehension does not stem from technical flaws in the proposed workflows, but rather from the severe lack of a finalized legal and legislative framework governing peer-to-peer energy trading and automated liabilities in Cyprus, as it was pointed out during open discussions.

Because the regulatory structures for enforcing on-chain contracts or external grid penalties remain unresolved by local authorities, stakeholders expressed understandable caution. These nuanced quantitative results necessitated a deeper qualitative analysis to unpack the underlying structural conflicts, such as the complexities of Handling Over-Consumption (Mean = 4.07) and Demand Forecasting & Timeframes (Mean = 3.80), which ultimately dictated the platform's modular architectural design to safely navigate this legislative vacuum, as well as the lack of a “cold-ironing” infrastructure.

3.4 The Cyber-Physical Conflict: The “Over-Consumption Paradox”

During Phase 2 validation, the quantitative survey suggested strong support for a simplified, flat-rate billing model for energy deviations, with 11 out of 15 participants rating it as highly suitable (4 or 5 on the Likert scale). However, the accompanying qualitative elicitation revealed that this quantitative consensus masked underlying role-based divisions regarding technical viability, dividing the cohort into two distinct operational priorities:

- **The Demand for Financial Predictability:** Representatives for vessel operators and port authorities advocated for the simplified flat-rate model (scores

of 4 and 5). To ensure commercial viability and minimize administrative overhead, they requested that any excess energy consumed beyond the initial forecast be billed at the standard, pre-agreed contract rate.

- **The Requirement for Grid Protection:** Conversely, technical stakeholders (such as energy engineers), researchers/academics and regulatory bodies cautioned against flat-rate over-consumption, echoing the 44.4% opposition recorded earlier in Phase 1. As illustrated in Fig. 3, while vessel operators and port authorities unanimously supported the flat rate (Scores: 4 and 5), regulatory, grid operators and technical engineering roles exhibited significant concerns (Scores: 2 – 5). They emphasized that unplanned high-voltage draws place cascading stress on port network infrastructure and incur real-time grid balancing costs, establishing a technical requirement to integrate dynamic pricing penalties to deter inaccurate capacity forecasting.



Fig. 3. Polarization of Ecosystem Roles Regarding Flat-Rate Billing versus Dynamic Grid-Fallback Penalties.

To reconcile this conflict, stakeholders introduced a critical regulatory constraint: the execution of financial penalties for energy variances requires an established legal framework by the local government. In fact, the project partners advocated and the participants agreed that these penalties can be handled at the level of the market operator, i.e., not within the platform. This empirical feedback directly dictated a strategy of technological modularity. The software architecture was engineered such that complex market logic, including dynamic pricing and variable penalty algorithms are developed as modular features that remain dormant or highly restricted, as part of the research work performed in the project [32], [33], until the overarching state regulatory framework is enacted, successfully isolating legal risk from the core software execution.

3.5 Iterative Workflow Validation and Architectural Refinements

During the secondary workflow validation phase (N=15), stakeholders evaluated the translated software logic and proposed user journeys. This evaluation generated critical architectural revisions that were prioritized for immediate implementation to ensure high software quality and user acceptance.

- **Role Nomenclature and Hierarchy Update:** Assigning platform initiation strictly to “Ship Owners” was identified as operationally inaccurate by Port Authorities. The role was standardized to “Ship Manager” within the software's identity access management (IAM) system. This critical adjustment accurately reflects the complex logistical hierarchies and administrative delegation required during physical docking procedures.
- **Granular Berthing Allocation:** The demand creation software workflow was refined to require the specification of the exact berthing station (docking terminal) rather than a generalized port location, as well as 30-minute slots for the representation of energy demands. This ensures precise load capacity management and accurately links the digital energy demand to the strict physical constraints of the terminal's hardware network.

The validation phase confirmed that the platform's core technological foundation is highly robust, successfully translating physical constraints into software architecture while deferring complex, unlegislated penalty logic to future development cycles. The revisions that were timely and appropriate in the scope of the project were adopted, while the rest of the recommendations are to be considered in future work.

4 Software Architecture and Platform Implementation

To operationalize the requirements defined by the stakeholder cohort, the P2P-Ironing platform was engineered using a strictly decoupled, hybrid Web2.5 software architecture. This approach encapsulates the immutable security of decentralized ledgers within a traditional enterprise stack, abstracting cryptographic friction from the end-user while providing high-performance transaction processing [18].

4.1 The Web2.5 Architectural Stack

The platform's frontend is implemented as a responsive Single Page Application (SPA) utilizing Blazor WebAssembly running on the .NET 8 runtime. By executing C# code directly within the user's browser, the architecture reduces server-side rendering loads and provides a seamless user experience, a methodology recognized for enhancing enterprise application performance [19]. The user interface is constructed using Bootstrap 5 and Scoped CSS to ensure component isolation, while complex data visualizations are rendered using custom native scalable vector graphics (SVGs) to eliminate dependencies on heavy third-party charting libraries.

The core backend is constructed as a .NET 8 service running on the Phoesion Glow (Firefly) microservice framework, as illustrated in Fig. 4. The backend logic is strictly

separated into functional modules with bounded contexts, including identity management, energy demands, quotes, contracts, and smart meter connections. Data persistence is managed via PostgreSQL and Entity Framework Core, serving as the primary relational store for high-speed operational queries.

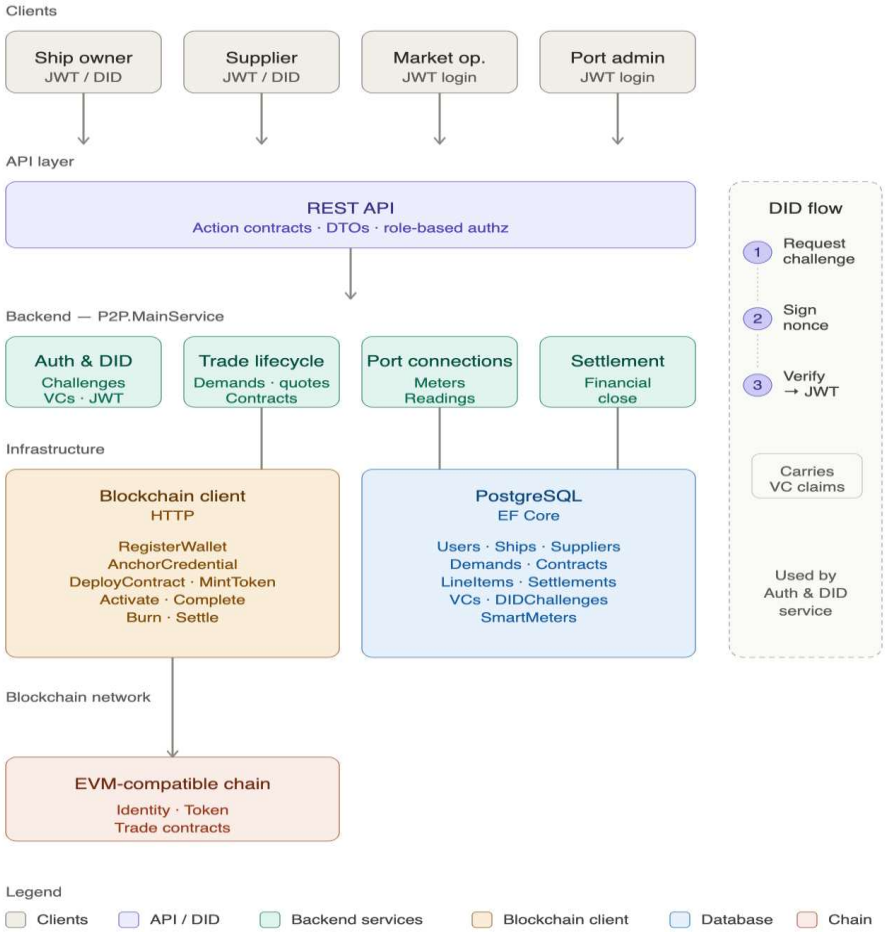


Fig. 4. System Architecture Overview.

The frontend and backend communicate exclusively via a secure REST API, automatically synchronized using the NSwag CLI to guarantee type safety across the application boundaries. Crucially, the blockchain network is not embedded directly into the core business service; it is abstracted into a dedicated external microservice accessible via HTTP. This separation of concerns ensures that all blockchain operations, managed via the Nethereum library, execute asynchronously. Consequently, Ethereum Virtual Machine (EVM) latency or network failures cannot roll back or block the platform's core operational workflows, aligning with recognized best practices for enterprise blockchain integration [20].

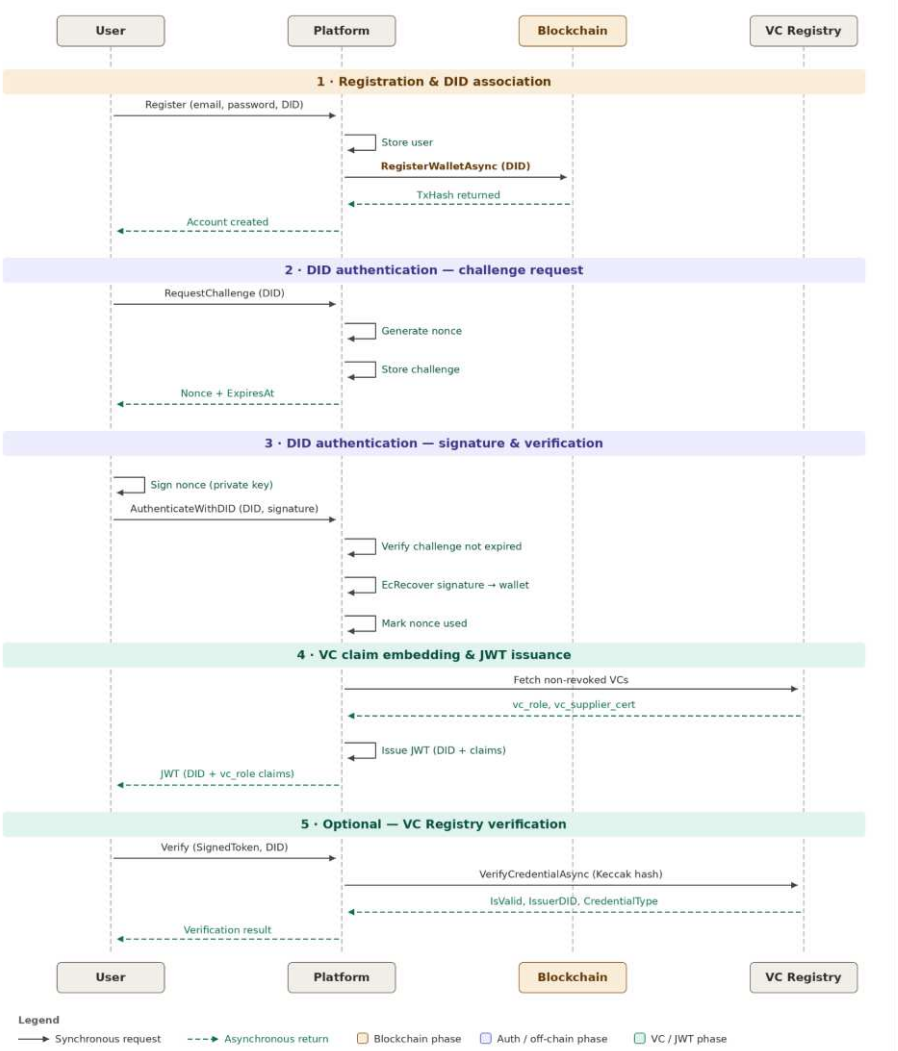


Fig. 5. Authentication Flow: registration, challenge-response authentication, VC claim embedding, and optional on-chain credential verification.

4.2 Pragmatic Decentralized Identity

To resolve the user experience barriers typical of pure decentralized applications, the platform implements a dual-path identity and access management (IAM) system, detailed in Fig. 5. Administrative roles (Market Operators and Port Administrators) utilize standard JSON Web Token (JWT) credentials established via conventional password hashing. However, transactional stakeholders (Ship Managers and Energy Suppliers) authenticate via self-sovereign Decentralized Identifiers (DIDs) established through Web3 wallets (e.g., MetaMask).

The system utilizes the did:pkh:eip155:1 standard, which derives the identifier directly from the user's blockchain wallet address, eliminating the need for complex on-chain DID registries or external resolver infrastructure. Authentication is executed via an EIP-191 challenge-response protocol. The backend issues a time-limited nonce (i.e., a token), which the user cryptographically signs via their browser. The backend utilizes elliptic curve signature verification (EcRecover) to confirm wallet ownership and subsequently issues a standard JWT for session management [21].

Furthermore, the architecture integrates a Verifiable Credentials (VC) mechanism based on the W3C data model. Upon regulatory verification by the Market Operator, suppliers are issued a SupplierCertificationCredential confirming their green energy compliance, while users are issued a RoleCredential. The Keccak-256 hashes of these VCs are anchored on-chain. When a user authenticates, the system inspects these credentials and embeds the corresponding verified claims directly into the JWT, allowing downstream authorization modules to make access decisions based on decentralized, tamper-evident trust assertions [22].

4.3 The Demand and Bidding Workflow

The platform features a structured, demand-driven operational workflow designed to mirror maritime logistics, mapped comprehensively in Fig. 6.

- **Demand Creation:** Ship Managers utilize their dashboard to broadcast precise energy demands. Rather than aggregating consumption into a single metric, demands are structured as sequential 30-minute power slots defining the required kilowatts per interval. This aligns with grid balancing standards and requires the specification of strict arrival/departure windows and exact docking terminals.
- **Quote Submission:** Energy Suppliers actively monitor open demands and submit competitive quotes, specifying available megawatt-hours (MWh) and price per MWh. Unique database constraints prevent duplicate bidding, ensuring market integrity.
- **Contract Acceptance:** The Ship Manager reviews incoming quotes and accepts the most favorable bid(s), which automatically initiates the cyber-physical execution phase.

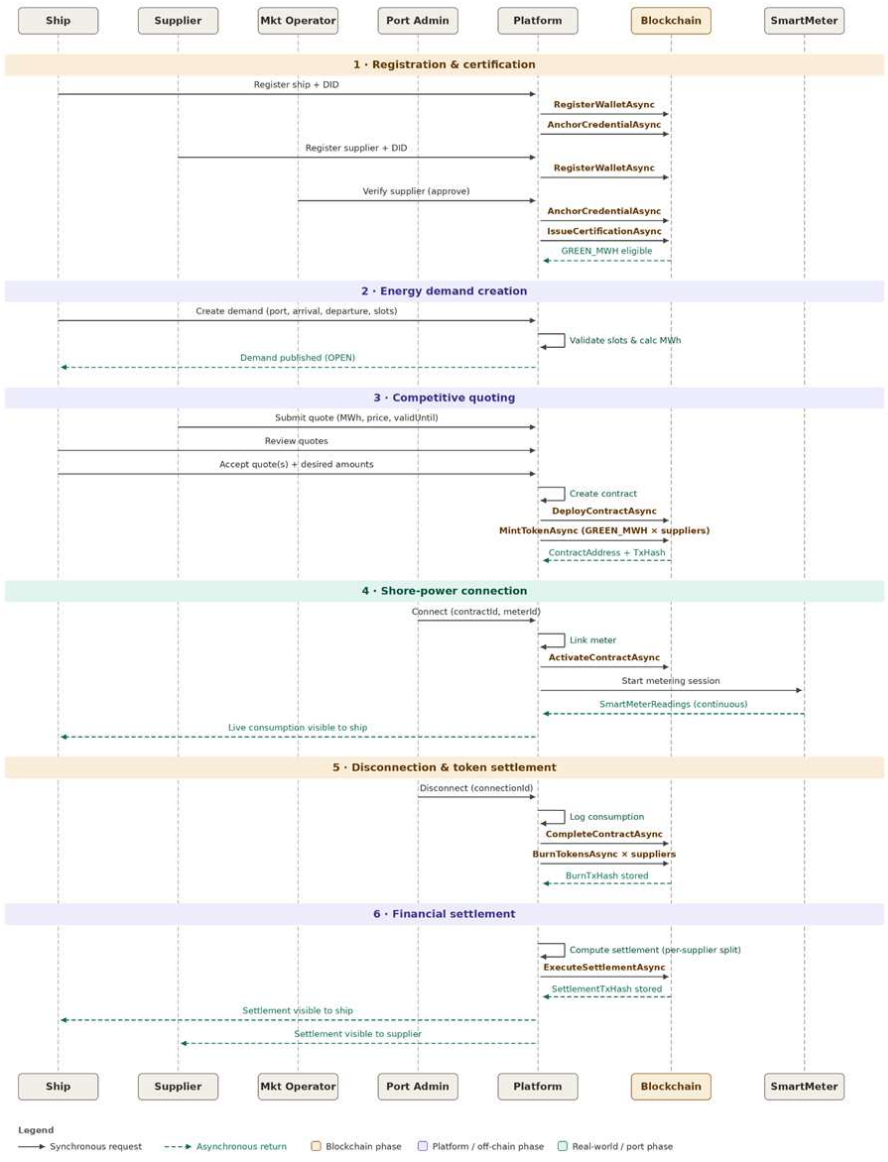


Fig. 6. Full Trade Lifecycle Sequence Diagram – mapping the interactions between Ship Managers, Energy Suppliers, Market Operators, and the Blockchain Layer.

4.4 Smart Contract and Deterministic Escrow Logic

The platform maps the physical energy trade lifecycle to a parallel on-chain operational trail, as demonstrated in Fig. 7. When a Ship Manager accepts a quote, the

backend orchestrates the deployment of a bespoke energy smart contract detailing the contracted capacity, tolerance thresholds, and supplier line items.

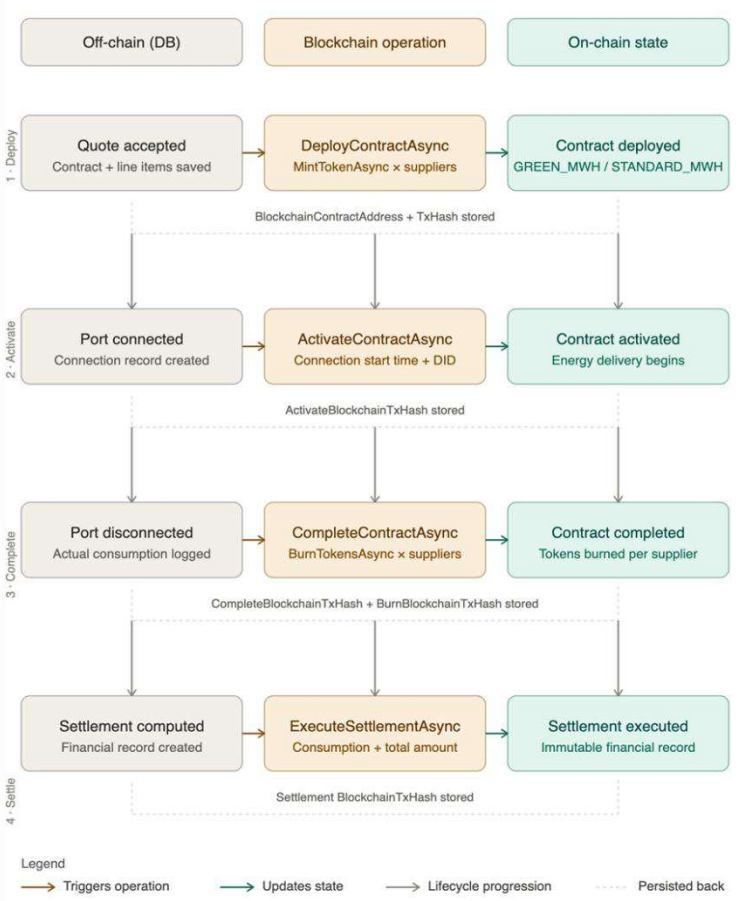


Fig. 7. On-Chain Contract Lifecycle – Demonstrating the parallel execution of off-chain database state changes and asynchronous blockchain state updates.

Simultaneously, the system mints digital tokens via an EnergyTokenRegistry. Suppliers holding a verified SupplierCertificationCredential trigger the minting of GREEN_MWH tokens, providing on-chain cryptographic escrow. These tokens remain locked against the smart contract for the duration of the physical shore-power connection, guaranteeing the supplier's energy commitment on a decentralized ledger [23].

4.5 Cyber-Physical Integration and Grid-Fallback Execution

The architecture bridges the digital and physical domains through a dedicated Port Administrator interface, serving as a human-in-the-loop cyber-physical integration point. When a vessel berths, the administrator digitally links the active smart contract

to the assigned physical smart meter at the terminal. This action officially activates the on-chain contract and initiates the real-time telemetry stream.

Upon physical disconnection of the vessel, the port administrator terminates the connection in the platform and the system immediately halts the telemetry stream, and the settlement module calculates final consumption metrics. To mathematically accommodate the “Over-Consumption Paradox” identified during the requirements engineering phase, the automated settlement engine computes exact usage against the contracted escrow. The corresponding digital tokens are burned per supplier line item to financially finalize the delivery phase. If the physical telemetry reports an energy draw exceeding the supplier's contracted capacity, the algorithm ensures the supplier is compensated strictly for their delivered capacity. The remaining uncovered deficit is logged on-chain as a “Grid Fallback” event, securely transferring the penalty resolution to off-platform regulatory mechanisms without interrupting the software's execution flow, a critical requirement for cyber-physical resilience [24].

Because live high-voltage shore connection infrastructure was unavailable at the Port of Limassol during the development phase, the platform's cyber-physical integration was validated using a hardware-in-the-loop (HIL) emulation testbed. To accurately simulate the load dynamics of a berthed vessel, the platform integrated a synthetic data generation engine. This engine ingested real-time telemetry from physical smart meters installed in conventional residential properties and algorithmically amplified the data using historical ship berthing profiles and expected high-voltage load curves. This methodology allowed the system to trigger the smart contract state changes and validate the deterministic settlement logic using live, algorithmically transformed physical hardware inputs, successfully overcoming the regional infrastructure limitations.

5 Empirical Platform Evaluation and User Validation

In the domain of cyber-physical systems and enterprise software engineering, architectural robustness is only one facet of success; end-user acceptance and perceived usability are the ultimate determinants of technology adoption [25]. To empirically validate the P2P-Ironing platform, a comprehensive system evaluation was conducted utilizing a live, interactive prototype of the Web2.5 architecture.

5.1 Evaluation Methodology

The validation phase engaged a cohort of 30 stakeholders (N=30), comprising maritime researchers, evaluators, and industry professionals. Participants were granted role-specific access to the platform (as Ship Managers, Energy Suppliers, Market Operators, and Port Administrators) and tasked with executing the core operational workflows defined during the requirements engineering phase, specifically decentralized registration, demand broadcasting, quoting, and physical connection simulation.

Following their interaction with the system, participants completed a structured evaluation survey. To ensure scientific rigor, the evaluation instrument was constructed using a proven dual-metric approach:

1. **Short User Experience Questionnaire (S-UEQ):** The standard 8-item S-UEQ [26] was deployed using a 7-point semantic differential scale (1 = Negative, 7 = Positive). The S-UEQ is highly validated in software engineering for measuring both *Pragmatic Quality* (efficiency, perspicuity, dependability) and *Hedonic Quality* (stimulation, novelty) without overwhelming the respondent.
2. **Domain-Specific Operational Acceptance:** To capture maritime-specific metrics not covered by the standard S-UEQ, a custom instrument comprising six additional questions was developed. Grounded in the foundational principles of the Technology Acceptance Model (TAM) [27], specifically regarding perceived operational usefulness and technology adoption, these questions utilized a 7-point Likert scale (1 = Strongly Disagree, 7 = Strongly Agree) to evaluate stakeholder trust in the automated smart meter integration, environmental impact, and decentralized market logic.

5.2 User Experience and Technology Acceptance

A primary objective of the Web2.5 software architecture was to completely abstract the complexities of decentralized ledger technology, such as wallet management, gas fees, and cryptographic signatures, from the end-user. The empirical data strongly indicates that this architectural goal was achieved across both primary dimensions of software quality.

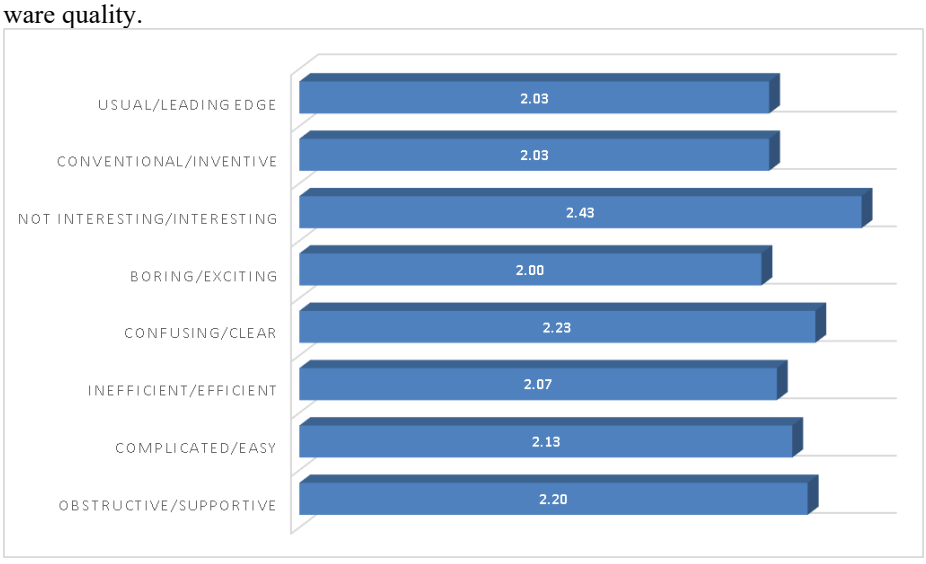


Fig. 8. System Usability and User Experience Metrics (N=30).

Regarding **Pragmatic Quality** (usability and functionality), the results presented in Fig. 8 show that the platform yielded exceptionally high means. As illustrated in the upper half of Figure 7, participants rated the platform as highly *Supportive (Mean: 6.20)*, *Clear (Mean: 6.23)*, and *Efficient (Mean: 6.07)* on the 7-point scale. Crucially,

Fig. 8 highlights that the interface was perceived as highly *Easy to use (Mean: 6.13)*. These metrics empirically prove that integrating Web3 authentication (did:pkh) within a responsive Blazor WebAssembly frontend successfully mitigates the steep learning curve and operational friction traditionally associated with blockchain applications.

Concerning **Hedonic Quality** (engagement and emotional response), the lower metrics in Figure 7 demonstrate that stakeholders strongly validated the system's innovative approach. As shown in Fig. 8, the highest overall score in the S-UEQ evaluation was *Interesting (Mean: 6.43)*, coupled with high ratings for being *Inventive (Mean: 6.03)* and *Leading edge (Mean: 6.03)*. This high level of engagement demonstrates that stakeholders did not merely find the platform functional; they found the decentralized, peer-to-peer concept highly engaging, signaling a strong market readiness to adopt modernized digital interfaces for port operations

5.3 Operational Transparency and Stakeholder Acceptance

Beyond fundamental interface usability, the evaluation assessed the viability of the core cyber-physical market logic. The TAM-based results, detailed in Fig. 9, demonstrate profound stakeholder consensus and minimal variance, validating the architectural decisions across three key operational themes.

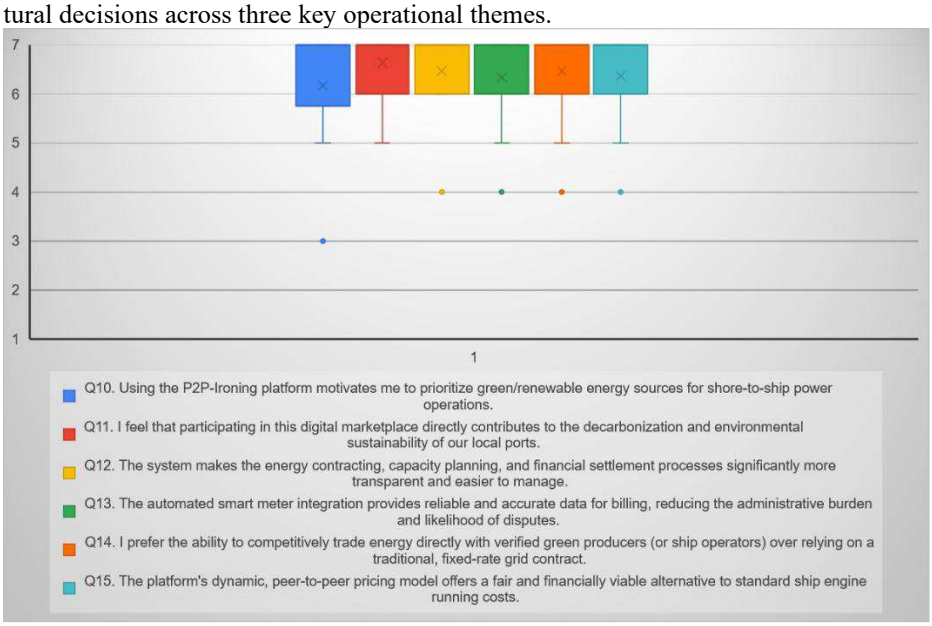


Fig. 9. Operational Transparency and Stakeholder Acceptance (N=30).

In fact, and as detailed in Figure 8, maritime stakeholders exhibited strong support for the platform's operational model across several key indicators:

- **Decarbonization and Green Prioritization:** Participants strongly agreed that participating in the digital marketplace directly contributes to the

environmental sustainability of local ports **(Q11 – Mean: 6.63/7.00)** and heavily motivates the prioritization of green energy sources **(Q10 – Mean: 6.17/7.00)**.

- **Trust in Hardware Automation:** The severe socio-technical friction identified in the early requirements engineering phase regarding dockside billing disputes was successfully resolved by the software architecture. Fig. 9 (Q13) illustrates that users demonstrated immense trust in the platform's Oracle design, strongly agreeing *(Mean: 6.33/7.00)* that automated smart meter integration provides reliable data for billing. This empirical consensus in Fig. 9 proves that hardware-in-the-loop (HIL) automation effectively mitigates administrative burden and distrust among transacting parties.
- **Market Structure Preference and Transparency:** Finally, the data presented in Fig. 9 validates the core utility of the decentralized market structure. As shown in Fig. 9 (Q14), participants strongly indicated a preference for the ability to competitively trade energy directly with verified green producers over relying on traditional, fixed-rate port grid contracts *(Mean: 6.47/7.00)*. Furthermore, Fig. 9 (Q12) confirms that the blockchain escrow system vastly improves operational visibility, with stakeholders strongly agreeing *(Mean: 6.47/7.00)* that the system makes energy contracting, capacity planning, and financial settlement significantly more transparent and easier to manage than legacy maritime procedures.

The empirical data confirms that encapsulating immutable blockchain ledgers within a user-centric, enterprise-grade Web2.5 architecture, evaluated through both standard S-UEQ and tailored operational metrics, yields a highly viable, trusted, and legally adaptable cyber-physical solution for critical maritime infrastructure.

5.4 Benchmark Analysis

To contextualize the platform's usability, the empirical S-UEQ results were evaluated against a standardized benchmark dataset. This extensive dataset comprises responses from 21,175 individuals across 468 independent studies evaluating diverse digital products, including business software and web applications. Because the S-UEQ is a relatively new instrument, this comparative analysis utilizes the comprehensive full UEQ benchmark data. Methodologically, the scale values of the short version provide a reasonably good approximation of the full version's corresponding values, allowing for a reliable initial estimation of the evaluated product's relative quality compared to established industry software. The resulting benchmark charts illustrate both the scale scores relative to the benchmark categories and their corresponding confidence intervals.

As illustrated in the benchmark analysis graph, the P2P-Ironing platform achieved an “Excellent” classification across all evaluated dimensions. Specifically, the Pragmatic Quality recorded a mean score of 2.16, placing the system in the highest possible benchmark tier. This metric quantitatively validates that the Web2.5 architectural strategy, particularly the integration of standard enterprise interfaces with background

decentralized mechanisms, effectively abstracts the operational friction traditionally associated with blockchain ledgers. By prioritizing a familiar user experience, the system ensures that complex cryptographic interactions do not impede the standard workflow of port administrators and maritime stakeholders.

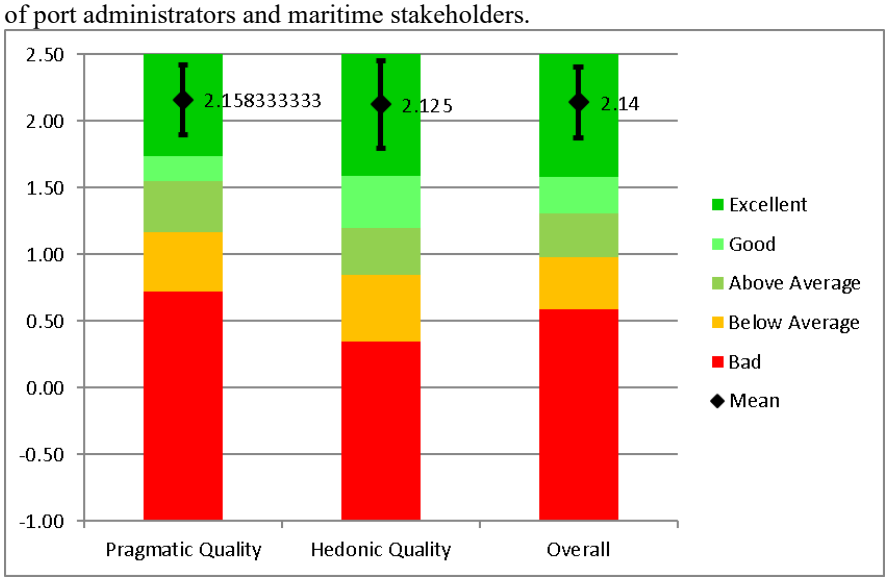


Fig. 10. Benchmark Analysis of P2P Ironing Platform (N=30).

Similarly, the platform's Hedonic Quality achieved a mean score of 2.13, firmly placing it within the "Excellent" benchmark category. This indicates that stakeholders perceived the decentralized transactive energy concept not only as functionally efficient but also as stimulating and inventive. The overall user experience score aggregated to a mean of 2.14, with the accompanying confidence intervals remaining strictly within the positive upper quartiles of the evaluation scale. Ultimately, achieving this top-tier benchmark status empirically demonstrates that the P2P-Ironing platform possesses the necessary software quality in use to foster stakeholder adoption and support the digital transition of smart ports without inducing cognitive overload.

5.5 Statistical Analysis of Software Quality

To ensure the empirical findings of this study are scientifically rigorous and practically meaningful, a comprehensive statistical analysis was conducted on the S-UEQ data. When surveying a targeted sample size, in this case, $N = 30$ maritime stakeholders, it is critical to mathematically verify that the positive feedback is reliable and not the result of random variance or survey ambiguity. This analysis focuses on two core statistical pillars: Internal Consistency and Estimation Precision.

Internal Consistency and Scale Reliability

The first phase of the analysis verified the reliability of the evaluation instrument itself (see Table 2). This was measured using the standardized Cronbach's Alpha

coefficient (α), which assesses the degree to which the items within a specific scale (such as Pragmatic or Hedonic Quality) consistently measure the same underlying usability construct. For a scale consisting of k items with an average inter-item correlation of $\bar{r}$, the coefficient is calculated as:

$$\alpha = \frac{k \cdot \bar{r}}{1 + (k-1)\bar{r}}$$

Applying this formula to the S-UEQ data, the Pragmatic Quality scale achieved an average inter-item correlation of $\bar{r} = 0.52$, yielding an internal consistency of $\alpha = 0.81$. Similarly, the Hedonic Quality scale demonstrated a strong inter-item correlation of $\bar{r} = 0.68$, resulting in $\alpha = 0.89$.

Table 2. Cronbach's Alpha coefficient – Scale Consistency.

Items	Correlation		Items	Correlation
1.2	0.20		5.6	0.82
1.3	0.52		5.7	0.70
1.4	0.38		5.8	0.67
2.3	0.53		6.7	0.60
2.4	0.66		6.8	0.50
3.4	0.81		7.8	0.79
Average	0.52		**Average**	0.68
Alpha	**0.81**		**Alpha**	**0.89**

In statistical and psychometric testing, an α score exceeding 0.70 establishes a high standard of reliability. Because the platform's scores (0.81 and 0.89) are significantly above this threshold, it mathematically confirms that the stakeholders understood the survey questions clearly and responded consistently. For instance, if a user rated the platform as efficient, they reliably rated it as easy to use. This high internal consistency guarantees that the favorable usability scores reflect genuine user satisfaction rather than random responses to poorly formulated questions.

Estimation Precision and Confidence Intervals

While the mean scores from the sample group were overwhelmingly positive, evaluating the platform's viability for broader industry adoption requires calculating the margin of error. This estimation precision is quantified using Confidence Intervals (CI) (see Table 3). Assuming a sample mean $\bar{x}$, standard deviation s, and sample size N, the $95\backslash\%$ confidence intervals ($p = 0.05$) were computed using the t-distribution to account for the finite sample size:

$$CI = \bar{x} \pm t_{\frac{\alpha}{2},N-1}\left(\frac{s}{\sqrt{N}}\right)$$

For the Pragmatic Quality scale, the average score was $\bar{x} = 2.158$. Factoring in the sample variance, the calculation yields a highly constrained $95\backslash\%$ confidence interval of $[1.898,2.418]$. The Hedonic Quality scale ($\bar{x} = 2.125$) similarly displayed a tight interval of $[1.799,2.451]$, culminating in an Overall system evaluation interval of $[1.876,2.407]$.

Table 3. Estimation Precision using Confidence Intervals – Pragmatic and Hedonic Quality.

Confidence intervals (p=0.05) per scale						
Scale	**Mean**	**Std. Dev.**	**N**	**Confidence**	**Confidence interval**	
Pragmatic Quality	2.158	0.727	30	0.260	1.898	2.418
Hedonic Quality	2.125	0.911	30	0.326	1.799	2.451
Overall	2.142	0.742	30	0.265	1.876	2.407

In practical terms, a confidence interval establishes a mathematical "safe zone" for the data. Because the evaluation relied on a sample of 30 individuals, the true average for all potential port operators across the industry might vary slightly. However, the $95\backslash\%$ confidence calculation proves that even in the most conservative statistical scenario (the lower bound of the interval), the Overall score would not drop below 1.876. On the S-UEQ scale, any score above 0.80 represents a highly positive user experience. This extremely narrow margin of error demonstrates that the findings are precise and can be confidently projected onto the broader maritime sector.

Item-Level Consensus

This macro-level statistical consensus is further corroborated by examining the standard deviations (s) of the individual questions (see Table 4). Across all eight S-UEQ metrics, the standard deviations remained strictly bounded between 0.805 and 1.174. A low standard deviation indicates that the participants' evaluations were tightly clustered rather than polarized. Consequently, the lower bounds of all item-level confidence intervals remained decisively positive. For example, the highest-rated attribute (Item 6: Assessing if the platform is "Easy", $\bar{x} = 2.433$) maintained a robust lower confidence bound of 2.112.

Table 4. Estimation Precision using Confidence Intervals – per S-UEQ Item.

Confidence interval (p=0.05) per item						
Item	**Mean**	**Std. Dev.**	**N**	**Confidence**	**Confidence interval**	
1	2.200	0.805	30	0.288	1.912	2.488
2	2.133	1.106	30	0.396	1.738	2.529
3	2.067	0.868	30	0.311	1.756	2.377
4	2.233	0.858	30	0.307	1.926	2.540
5	2.000	1.174	30	0.420	1.580	2.420
6	2.433	0.898	30	0.321	2.112	2.755

7	2.033	1.129	30	0.404	1.629	2.437
8	2.033	0.964	30	0.345	1.688	2.378

By combining high Cronbach's Alpha coefficients with narrow, uniformly positive Confidence Intervals, this analysis provides rigorous mathematical assurance of the platform's software quality. The statistical evidence concludes that the Web2.5 architectural strategy successfully delivers a decentralized transactive energy system that is highly accessible, efficient, and operationally acceptable to maritime stakeholders. Ultimately, the synthesis of high α coefficients and narrow, uniformly positive confidence intervals provides rigorous statistical assurance, verifying that the favorable platform usability scores are precise, reliable, and mathematically sound.

5.6 Qualitative Evaluation

To contextualize the quantitative S-UEQ metrics and identify specific areas for future architectural refinement, the evaluation concluded with an open-ended feedback mechanism. Participants (N=30) were prompted to provide qualitative comments regarding their experience with the platform and its applicability to real-world maritime logistics. The thematic analysis of this feedback aligns the system's current capabilities with the operational realities of regional ports, categorizing stakeholder suggestions into four primary domains:

Operational Logistics and Port Synchronization

Stakeholders highlighted the necessity for tighter synchronization between the platform's digital demand creation and physical port logistics. Specifically, participants recommended integrating directly with official Cyprus Ports Authority (CPA) docking time slots and establishing a mandatory pre-approval workflow for specific berthing assignments prior to contract finalization. Furthermore, respondents emphasized the unpredictable nature of maritime logistics. They noted that the system requires built-in flexibility to dynamically accommodate schedule deviations caused by weather or traffic delays, paired with automated checks to ensure the local high-voltage grid can safely sustain the maximum capacity loads during those shifted timeframes.

Market Integrity and Supplier Auditing

Protecting the integrity of the peer-to-peer market was a recurrent theme. To prevent collusion, particularly in localized markets like Cyprus, stakeholders proposed strict operational safeguards, such as prohibiting the withdrawal of submitted quotes and restricting the visibility of competitive bid details. Additionally, participants advocated for robust, continuous auditing of energy suppliers. Rather than relying solely on the initial market operator license verification, respondents requested the integration of user feedback mechanisms and Key Performance Indicators (KPIs) to track ongoing supplier reliability, pricing fairness, and adherence to green energy standards. Clarity regarding the classification of agreements as Over-The-Counter (OTC) contracts and the technical guarantees of energy commitment was also requested.

Financial Gateways and Payment Abstraction

While the empirical data proved that the Web2.5 architecture successfully mitigated the friction of decentralized identity management, qualitative feedback indicated a strong demand for further financial abstraction. Multiple participants emphasized that while blockchain should remain the underlying infrastructure for secure escrow and automated settlements, the frontend must eventually integrate traditional fiat payment gateways (e.g., Visa integrations). Supporting conventional, cost-effective payment methods is viewed as a critical step to accommodate ecosystem actors who do not actively manage cryptocurrency or blockchain wallets, thereby lowering the barrier to entry.

System Usability and Penalty Mechanisms

Participants suggested minor usability enhancements to optimize engagement, including automated email notifications to prompt ship managers and suppliers when new energy demands or quotes are broadcasted, and the deployment of interactive wizards or tooltips to guide new users through the onboarding process. Finally, echoing the socio-technical conflicts identified during the initial requirements engineering phase, participants reiterated the need for clear penalization mechanisms in cases of energy variance (e.g., vessels consuming more or less energy than forecasted, or suppliers failing to deliver the promised green capacity). This continuous emphasis on variance penalties reaffirms the necessity of the modular architecture discussed in Section 4, which prepares the system for dynamic penalty execution once the regional regulatory framework matures.

Overall, the qualitative sentiment strongly supported the platform's core objective, with multiple stakeholders explicitly noting its promising potential to provide cost-effective energy solutions while directly driving the decarbonization of Cypriot ports and coastal areas.

6 Discussion

The development and empirical validation of the P2P-Ironing platform yield several critical insights for software engineers designing decentralized cyber-physical systems for legacy industries. By bridging the gap between rigid immutable logic and unpredictable maritime logistics, this study demonstrates how architectural decoupling directly influences software quality and stakeholder adoption [27].

6.1 Bridging the Technical Friction Gap: Pragmatic and Hedonic Success

A persistent challenge in the adoption of Transactive Energy Management (TEM) systems is the steep learning curve and operational friction associated with fully decentralized applications [28], [29]. Maritime stakeholders, who operate under strict

logistical timeframes, cannot be expected to manage complex cryptographic workflows or navigate fluctuating underlying ledger costs.

The S-UEQ evaluation results indicate that the hybrid enterprise architecture successfully resolves this socio-technical barrier. By utilizing server-side decentralized identity protocols and challenge-response authentication, the software abstracts this friction. The high Pragmatic Quality ratings, particularly the platform being perceived as supportive and clear, validate the hypothesis that enterprise stakeholders will readily adopt digital ledger mechanics provided they are encapsulated within a familiar enterprise interface. Furthermore, the high Hedonic Quality scores suggest that beyond mere usability, the Web2.5 approach successfully drives user engagement, a critical precursor to industry-wide adoption.

However, qualitative feedback indicates that while blockchain identity friction has been mitigated, further financial abstraction is required. Stakeholders emphasized the necessity of integrating traditional fiat payment gateways (e.g., Visa) alongside the blockchain settlement layer. This indicates that for pure enterprise adoption, the software must accommodate actors who do not actively manage cryptocurrency, reinforcing the necessity of hybrid Web2.5 architectures over pure Web3 deployments.

6.2 Architectural Resolution of the “Over-Consumption Paradox”

The requirements engineering phase uncovered a fundamental conflict: Vessel Operators demanded simple, flat-rate financial predictability, while Grid Operators required dynamic penalty pricing to protect physical grid stability from capacity forecasting errors. The software architecture resolved this through technological modularity. By engineering the automated settlement engine to act strictly on exact usage against the contracted escrow, the platform satisfies the vessel operators' need for automated, predictable clearing. Simultaneously, by formally logging any excess consumption as an immutable event on the decentralized ledger, the software satisfies the Grid Operators' requirement for a tamper-proof audit trail. The domain-specific operational metrics validate this approach; stakeholders exhibited high levels of trust in the hardware-in-the-loop (HIL) smart meter integration to provide reliable billing data, effectively eliminating the dockside disputes that plague current cold-ironing implementations.

Furthermore, the qualitative analysis expanded on this need for trust by highlighting market integrity. To prevent collusion in localized markets, stakeholders recommended strict system safeguards, such as prohibiting the withdrawal of submitted quotes and hiding competitive bid details. This feedback dictates that future iterations of the smart contract logic must not only focus on energy transfer but also enforce strict anti-competitive digital barriers.

6.3 Crucial Ecosystem Limitations and Software Realities

Despite the high usability and technical readiness of the platform (TRL6), its immediate commercial execution is bounded by two systemic limitations within the regional ecosystem: the complete absence of a finalized localized peer-to-peer energy legal framework, and the current infancy of full-scale physical cold-ironing implementations.

- **The Legislative Vacuum:** At present, the execution of automated financial penalties or bilateral energy transfers between third-party green producers and visiting vessels lacks an established legal framework by the Cyprus government and the Cyprus Energy Regulatory Authority (CERA). Regulatory stakeholders flagged significant legal concerns regarding the classification of these trades (e.g., Over-The-Counter contracts) and the onboarding of international vessels outside local jurisdictions. Consequently, complex market settlement logic and penalty-pricing features were engineered as dormant, isolated modules. These modules are decoupled from the live market logic to ensure the platform remains compliant with current laws while remaining technically prepared for future regulatory activation [30]. Furthermore, qualitative feedback demands that future regulatory frameworks incorporate continuous supplier auditing via platform KPIs to ensure ongoing green compliance.
- **Physical Infrastructure and Logistical Deficiencies:** The second major limitation is the lack of live, high-voltage cold-ironing infrastructure across local ports. To maintain software engineering rigor under these constraints, the platform integrated a hardware-in-the-loop (HIL) emulation layer utilizing physical smart meters and synthetic load generation [31]. While this approach successfully validated the software state-machine, qualitative feedback stressed the need for the platform to synchronize directly with official Cyprus Ports Authority (CPA) docking schedules. Because real-world maritime logistics are highly unpredictable, future software iterations must build dynamic flexibility into the smart contracts to accommodate weather or traffic delays without triggering false grid-fallback penalties.

Future work will focus on transitioning the platform from an in-lab simulation to a physical pilot environment as local port infrastructure updates are finalized. Additionally, once the maritime legislative frameworks mature, subsequent iterations of the software will replace the centralized administrator verification step with automated, direct IoT-to-ledger data triggers, eliminating the potential for manual administrative delays. Finally, a framework can be implemented in the platform to handle overconsumption and underconsumption when the legal and legislative issues are resolved.

7 Conclusion

Decarbonizing the maritime sector through shore-to-ship power requires more than physical electrical infrastructure; it demands robust, transparent, and user-centric software frameworks to manage multi-stakeholder energy transactions. This paper presented the end-to-end software engineering lifecycle and empirical validation of the P2P-Ironing platform, a transactive energy marketplace designed for smart ports.

Driven by a rigorous, two-phase mixed-methods requirements analysis, comprising initial stakeholder elicitation (N=18) and iterative workflow validation (N=15), the system successfully navigated the conflicting operational demands of vessel managers and high-voltage grid operators. The platform was implemented using a hybrid enterprise

Web2.5 architecture that abstracts the complexities of decentralized identities (did:pkh) and smart contracts beneath a responsive .NET 8 middleware and Blazor WebAssembly frontend. To overcome regional infrastructure deficits, the system integrated physical smart meters and a synthetic data generation engine to automatically trigger deterministic contract settlements. This hardware-in-the-loop (HIL) emulation ensures cryptographic financial transparency while dynamically managing the unpredictable nature of maritime load deviations.

A final empirical system evaluation (N=30) utilizing a dual-metric approach, combining the standard S-UEQ and a custom domain-specific operational instrument, demonstrated high stakeholder acceptance. The system achieved top-tier benchmark classifications in both Pragmatic and Hedonic quality, proving that blockchain friction can be successfully abstracted to deliver an engaging and efficient interface. Furthermore, the operational metrics validated stakeholder trust in the automated hardware integration and a clear preference for transparent, decentralized market structures. Qualitative feedback further contextualized these findings, highlighting that integrating traditional fiat payment gateways and establishing dynamic synchronization with official port logistics represent the most evident and immediate next steps that arose from the qualitative evaluation.

While currently bounded by regional legislative vacuums and pending high-voltage port infrastructure, these limitations were strategically addressed through intentional technological modularity and off-chain data emulation. Ultimately, this research provides empirical evidence that encapsulating immutable ledger mechanics within a user-centric enterprise software architecture constitutes a viable cyber-physical solution. The P2P-Ironing platform establishes a validated, market-ready foundation capable of accelerating the maritime industry's transition toward decentralized green energy ecosystems.

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8 CONFLICT OF INTEREST STATEMENT

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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