Zero-Knowledge Proofs (ZKP) And Smart Contracts For Automated Cross-Border Carbon Audit : A Decentralized Techno-Economic Framework

Aldi Adi Pratama
Faculty of Engineering, Universitas Indonesia
aldi.adi@ui.ac.id

Received 08 Juli 2026 | *Revised* 11 Juli 2026 | *Published* 14 Juli 2026

Abstract

The rise of cross-border carbon regulations such as the European Union's Carbon Border Adjustment Mechanism (CBAM) demands emission verification systems trusted across multiple jurisdictions. However, conventional carbon audits remain manual, slow, costly, and prone to manipulation, while existing blockchain-based solutions require full disclosure of emissions data — conflicting with multinational corporations' need to protect confidential production information. This study proposes a decentralized framework integrating Zero-Knowledge Proofs (ZKP) and smart contracts to automate cross-border carbon auditing, employing a Design Science Research approach at the conceptual design level. The framework comprises four layers: data collection, proof generation, smart contract verification, and cross-jurisdictional interoperability, with Groth16 and the Perpetual Powers of Tau trusted setup as core cryptographic components. Techno-economic estimates derived from literature benchmarks indicate an on-chain verification cost of approximately 220,000 gas per transaction and verification times on the order of seconds to minutes, potentially far more efficient than conventional manual audit cycles that may span a year or more. This study also identifies privacy-adaptability and automation-legal flexibility trade-offs that must be managed in real-world implementation. Key contributions include the architectural design, economic feasibility analysis, and policy implications for regulators, with empirical validation through prototype development proposed as future research.

Keywords: *Carbon Audit; Carbon Border Adjustment Mechanism; Smart Contract; Techno-economic; Zero-knowledge proof*

INTRODUCTION

International trade is now facing unprecedented new regulatory pressures. Importing countries have begun demanding quantitative evidence of the carbon footprint of cross-border products. The European Union, for instance, has implemented the Carbon Border Adjustment Mechanism (CBAM), which requires importers to report the embedded emissions of products such as steel, cement, aluminum, and fertilizer. Similar mechanisms are currently being considered by the United States, the United Kingdom, and several other countries the United Kingdom has announced plans to implement its own border carbon adjustment starting in 2027, while the United States and Australia remain in the policy exploration stage (Bonnet & Baršauskaitė, 2025). Recent economic studies have even found that the EU's implementation of CBAM has been able to reduce global carbon leakage, although its impact on the equitable distribution of benefits among trading partner countries remains a matter of debate (Clausing et al., 2025). Meanwhile, Article 6 of the Paris Agreement promotes cross-border carbon credit trading, which requires a Measurement, Reporting, and Verification (MRV) system that can be trusted by multiple parties across different jurisdictions.

The problem is that conventional carbon audit systems are built on an architecture that was not designed for this decentralized, cross-border context. The audit process typically

involves a trusted third party that manually verifies emissions data, which is time-consuming (taking months), costly, and more critically prone to manipulation and reporting errors due to the lack of independent verification mechanisms that can be audited in real time. Recent studies have documented how companies frequently manipulate test reports, falsify samples, or distort the conclusions of carbon emissions reports practices that tend to remain concealed and are difficult for governments to detect due to limited real-time oversight mechanisms (Wang et al., 2023). This tension has been explicitly identified by recent research highlighting that conventional carbon emission verification methods force companies to choose between disclosing trade secrets or facing the risk of being accused of making unreliable emissions claims (for instance, due to missing or incomplete data) thus necessitating a verification method that does not disclose secrets while still producing claims that can be trusted by other parties (Man et al., 2025).

Blockchain and smart contract technologies have been widely proposed as solutions to the transparency and automation challenges in carbon MRV systems, owing to their immutable, decentralized nature and their ability to automatically execute verification and certification logic without intermediaries. However, most existing frameworks assume that all emissions data must be openly recorded on a public ledger in order to be verifiable an approach that directly conflicts with the need for corporate data confidentiality, and which in practice hinders adoption by cross-border business entities.

Zero-Knowledge Proofs (ZKP) offer a way out of this dilemma. Through schemes such as zk-SNARK and zk-STARK, an entity can prove the truth of a statement, for example, that the carbon emissions of a production process fall below a certain threshold without needing to disclose the underlying raw data. The combination of ZKP with smart contracts has the potential to deliver a carbon audit system that is simultaneously publicly and cross-jurisdictionally verifiable, preserves the confidentiality of a company's operational data, and operates automatically

Although this potential is promising, the existing literature still leaves several important gaps. Most studies discuss ZKP and blockchain for carbon accounting separately from their economic feasibility analysis, even though ZKP computational costs and on-chain transaction costs are decisive factors in real-world adoption. Second, few frameworks explicitly address cross-jurisdictional interoperability, given that each country has different carbon reporting standards and regulatory frameworks.

This paper aims to fill these gaps by proposing a decentralized framework that integrates Zero-Knowledge Proofs and smart contracts to automate cross-border carbon audits. Specifically, the contributions of this paper are : a ZKP–smart contract architecture design for cross-jurisdictional emissions verification, a techno-economic analysis covering cost structure, participant incentives, and the privacy scalability trade-off, as well as policy implications for regulators and international standard-setters.

RESEARCH METHOD

Research Design

This study employs a Design Science Research (DSR) approach at the conceptual/architectural design level, namely producing and evaluating an artifact in the form of an architectural framework along with its feasibility analysis, without accompanying software prototype development. The research is conducted in three stages: (1) problem identification and requirement elicitation based on current regulations, (2) system architecture design, and (3) techno-economic evaluation based on quantitative estimates derived from literature benchmarks.

Data Sources and Types

The data used are secondary in nature and are categorized into two groups:

1. Regulatory and Institutional Data

Sourced from official documents of the European Union's Carbon Border Adjustment Mechanism (CBAM), which entered its definitive phase on 1 January 2026, requiring importers with a volume of CBAM-covered goods above a mass-based threshold of 50 tons to apply for authorized CBAM declarant status. During this phase, the first annual declaration must be submitted no later than 30 September 2027, with a penalty of €100 per ton of excess emissions imposed on non-compliant importers (European Commission Directorate General for Taxation and Customs Union, 2026).

2. ZKP Technical Benchmark Data

Gathered from recent studies on the on-chain computational cost of the Groth16 scheme, which is the most widely used for zk-SNARK verification due to its small proof size and constant verification time. Based on experimental benchmarks published by Guo et al. (2024), the Groth16 verification gas cost on Ethereum consists of a fixed component of approximately 207,700 gas plus 7,160 gas for each additional public input in the circuit. This figure is consistent with the findings of Deng and Du (2023) and the study by Wang (2026), which each report Groth16 on-chain verification costs in the range of 230,000 – 241,000 gas for comparable circuit configurations, such that a simple circuit with two public inputs can be estimated to incur a total verification cost of approximately 220,000 gas.

Architecture Design

The architecture is designed using a layered design approach, consisting of: (i) an emissions data collection layer on the reporting entity's side, (ii) a proof generation layer using an arithmetic circuit that formalizes the emission threshold rules in accordance with the CBAM methodology, (iii) a smart contract layer for proof verification and automated certification logic execution, and (iv) a cross-jurisdictional interoperability layer that maps verification results into a format acceptable to authorities in both the importing and exporting countries.

Illustrative Scenario for Qualitative Analysis

To illustrate the application of the proposed framework, this study constructs a hypothetical scenario based on current regulatory conditions, namely the export of products from CBAM-covered sectors (e.g., iron and steel) from a producer in Indonesia to an importer in the European Union. This scenario is used as a conceptual walkthrough tool to demonstrate the workflow of each architectural layer, rather than as a basis for empirical testing of a system that has been built and run.

Techno-Economic Estimation Approach

As this study does not involve prototype development, cost and performance estimates are derived analytically from benchmark data published in recent literature, particularly the Groth16 verification gas cost formula and empirical data from similar zk-SNARK implementations in other studies. These estimates are applied to the parameters of the illustrative scenario to produce indicative figures as a basis for feasibility analysis, rather than results from direct measurement of an implemented system.

Evaluation Metrics

The techno-economic evaluation is conducted on five main metrics, analytically estimated based on literature benchmarks, namely: (1) on-chain verification gas cost per audit transaction, (2) estimated proof generation and verification time, (3) estimated proof size to be stored/transmitted, (4) projected system scalability under high cross-border transaction volume scenarios, and (5) comparison of total estimated cost against manual third-party-based carbon audit costs in line with current CBAM verification practices.

Methodological Limitations

This study is conceptual-analytical in nature and is not accompanied by empirical validation through a prototype or real-world implementation. All cost, time, and performance estimates are derived from literature benchmarks on similar systems, rather than from direct testing of the proposed framework. Furthermore, gas cost data are dynamic, fluctuating with Ether prices and network conditions, and the regulatory scenario refers to the EU CBAM framework, which is still undergoing continuous revision (e.g., the Omnibus Regulation), meaning that generalization to other cross-border carbon regimes requires further adjustment.

RESULTS AND DISCUSSION

Proposed Framework Architecture

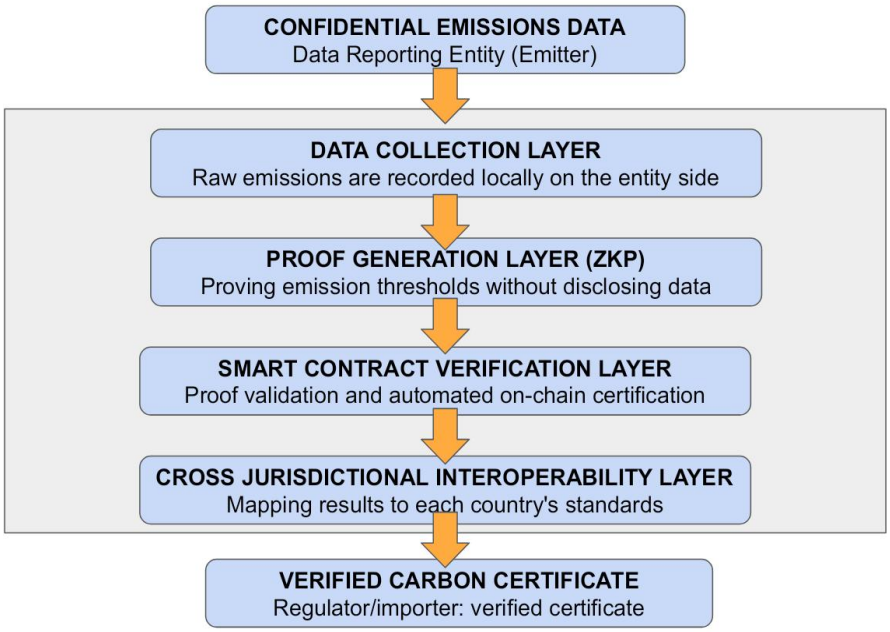


Figure 1. Architecture of Cross-Border Carbon Audit Framework Based on Zero-Knowledge Proof and Smart Contract
Source: Processed by the author (2026)

This framework is built on four sequentially arranged layers, guided by the core principle that sensitive information never leaves the control of its owner, while parties requiring assurance still obtain a guarantee of correctness through cryptographic proof.

a. In the first layer, the entire process takes place on the side of the reporting entity the producer or exporter subject to the audit. Emissions data from production is recorded and verified internally, with no involvement of external parties whatsoever at this stage. The underlying principle is that raw data, including production process parameters of competitive value to the company, never leaves the entity's environment.
b. The second layer is the critical point that distinguishes this approach from conventional audit systems as well as fully transparent blockchain systems. Data from the first layer is processed through a cryptographic circuit that represents a compliance rule for instance, the emissions threshold under CBAM provisions such that the output is not the emissions figure itself, but rather mathematical proof that the rule has been satisfied. The scheme recommended for this stage is Groth16, chosen for its verification cost efficiency compared to other alternatives, complemented by the Perpetual Powers of Tau trusted setup mechanism, which is open in nature and can involve cross-country participation, so that trust in the system does not rest on a single authority.
c. In the third layer, the generated proof is submitted and verified on-chain via a smart contract. Once the validity of the proof is confirmed, the system automatically executes the certification process without requiring manual intervention from a human auditor for each individual transaction this element of automation is what distinguishes this approach from time-consuming third-party-based audits.
d. The fourth layer bridges the certification results into a format acceptable to the importing country's authorities, while remaining aligned with the exporting country's domestic reporting framework. This function is important given that each jurisdiction has its own distinct standards and reporting mechanisms

With this layered structure, the three parties involved the reporting entity, the on-chain verifier, and the regulator in the destination country each access only the information relevant to their role. The entity preserves the confidentiality of its production data, the verifier processes cryptographic proof without ever seeing the original data, and the regulator receives the final certified result without needing to access the raw data of the audited party

Illustrative Scenario of Framework Application

To illustrate how the proposed framework operates, this section presents a scenario walkthrough using a hypothetical case representing current regulatory conditions. It should be emphasized that this scenario is illustrative-conceptual in nature, not the result of empirical testing on an implemented and executed prototype; the cost and time estimates presented are derived accordingly.

Scenario: A steel producer in Indonesia exports products to an importer in the European Union subject to CBAM obligations. Under the definitive regulation in effect since 1 January 2026, the importer is required to verify the embedded emissions of the product and report them in an annual declaration, with a penalty of €100 per ton of excess emissions for non-compliance.

Walkthrough of the proposed framework:

a. Data Collection Layer.
   The producer records actual production emissions data locally, without transmitting it to any external party, including the importer in the European Union.
b. Proof Generation Layer

The ZKP circuit processes this data and generates a proof demonstrating the statement "embedded product emissions ≤ reported threshold," without disclosing details of the production process. Based on benchmark estimates for circuits of comparable complexity, the proof generation process is expected to take on the order of seconds to tens of seconds on the prover's side depending on the number of circuit constraints while the resulting proof size is expected to remain compact (hundreds of bytes).

c. Smart Contract Verification Layer
The proof is submitted on-chain and verified by the smart contract verifier. Referring to the Groth16 gas cost formula (207,700 + 7,160 × number of public inputs), for a simple circuit with two public inputs, the verification cost is estimated at approximately 220,000 gas per transaction far more efficient than the STARK scheme, which can exceed one million gas per proof.

d. Interoperability Layer
The verification results are mapped into the CBAM declaration format, allowing the importer in the European Union to directly use these results as proof of compliance without needing to access the producer's raw production data from Indonesia. Estimated comparison with the manual audit process: the conventional carbon audit process through an accredited third party which is a mandatory obligation under the definitive phase of CBAM generally requires manual verification lasting weeks to months, with service costs far exceeding the on-chain gas costs described above

Techno-Economic Analysis

The analysis in this section is analytically estimative in nature, constructed from a combination of on-chain cost benchmarks and literature on conventional carbon audit cost structures as well as blockchain transaction economics.

a. Cost Estimation per Audit Transaction
Based on the illustrative scenario, the on-chain verification cost per audit transaction using the Groth16 scheme is estimated at approximately 220,000 gas. As a point of comparison, studies on gas cost patterns in Ethereum smart contract transactions show that gas costs are highly volatile and influenced by network congestion conditions, meaning that fiat-currency cost estimates should account for a range of gas price scenarios rather than a single figure (Paramitha & Tarigan, 2025). This volatility is further reinforced by economic studies on Ethereum gas fees, which highlight how the fee market mechanism affects transaction cost valuation over time (Meister & Price, 2024).

b. Comparison with Manual Audit Costs
Literature on conventional carbon Measurement, Reporting, and Verification (MRV) indicates that MRV costs can absorb a significant portion of a carbon project's total value, with third-party verification processes involving field visits, cross-checking of data, and manual methodology validation (Mercer & Burke, 2025). The duration of a conventional MRV cycle from reporting to certification issuance is reported to last a year or more. Compared with the estimated on-chain verification time on the order of seconds to minutes, the proposed framework has the potential to significantly reduce the time component of the audit cycle, although a comparison of absolute costs requires further validation, as the two measure different types of costs (on-chain computational costs versus labor and field-visit costs).

c. Automation vs. Adaptation Cost Trade-off
It is important to note that smart contract cost efficiency is not absolute. Research from a transaction cost economics perspective shows that although smart contracts can

reduce transaction costs related to deviations by contracting parties, they may also give rise to new transaction costs related to adapting to changing conditions given that smart contracts, by nature, restrict ex-post legal intervention (Vatiero, 2022). In the context of cross-border carbon audits, this is relevant because regulatory parameters (such as CBAM emissions thresholds) may change over time, meaning smart contracts must be designed with an upgradability mechanism that preserves verification integrity.

Conversely, large-scale empirical studies have found that smart contract adoption is associated with improved operational efficiency in firms, particularly in the context of automating agreement execution without intermediaries (Xiong et al., 2025). This finding supports the argument that the efficiency benefits from automated verification in the proposed framework are likely to outweigh the additional adaptation costs arising from regulatory changes, provided the circuit upgrade mechanism is adequately designed

d. Summary of Estimates

Overall, the estimates indicate that a ZKP- and smart-contract-based framework has the potential to offer cost and time efficiency compared to conventional manual audits, with the following caveats: (a) on-chain costs are volatile depending on network conditions, (b) upfront investment is required in circuit design and upgrade mechanisms to accommodate regulatory changes, and (c) a precise comparison of absolute costs requires further empirical validation.

Evaluation of the Five Metrics

Table 1. Evaluation Estimates of Five Techno-Economic Metrics for ZKP-Based Carbon Audit Framework

No	Metric	Estimation	Reference Source
1	On-chain verification gas cost	±220,000 gas for a two public input circuit (207,700+7,160 gas/input)	Guo et al. (2024)
2	Proof generation & verification time	Generation: order of seconds to tens of seconds (depending on the number of constraints); Verification: constant time, order of milliseconds	
3	Proof size	Hundreds of bytes (typical characteristic of Groth16)	

No	Metric	Estimation	Reference Source
4	Scalability projection	Verification cost increases linearly with the number of public inputs, not with the complexity of the proven data supporting high transaction volume scalability	
5	Comparison vs manual audit	Conventional manual audit cycle: ±1 year or more; On-chain verification: order of minutes. Manual MRV costs can absorb a significant portion of the project value	(Mercer & Burke, 2025).

Source: Data processed by the researcher (2026)

In terms of the gas cost and proof size metrics, Groth16's advantage is relatively consistent across the literature reviewed the "succinct" characteristic in its name (zk-SNARK: succinct non-interactive argument of knowledge) is directly reflected in the proof size remaining small regardless of the complexity of the statement being proven. Interestingly, Guo et al. (2024) also found that selecting a ZK-friendly hash function (such as Poseidon2) can further reduce on-chain costs by up to 73% on EVM-based chains compared to the baseline an additional optimization opportunity relevant for the future development of this framework. Regarding the time metric, there is an important asymmetry: proof generation (on the reporting entity's side) is computationally far more expensive than verification (on the smart contract's side). This is in fact consistent with the framework's design the heavy computational burden is incurred once by the party that holds the data, while verification, performed repeatedly by multiple parties (regulators across different countries), remains cheap and fast.

Regarding the scalability metric, the fact that verification cost increases based on the number of public inputs rather than the volume of data being proven constitutes a structural advantage for high-volume, cross-border use cases, since an increase in export-import transaction volume does not necessarily lead to a proportional increase in verification cost per transaction.Regarding the comparison-with-manual-audit metric, the difference in time order (years vs. minutes) is the most striking finding, yet it must be interpreted with caution: manual auditing encompasses activities that are not fully replaced by on-chain

verification, so this estimate represents the potential efficiency gain in the repeated verification component, rather than a complete replacement of the entire audit process.

The relevance of the proposed framework is further reinforced by recent research trends. Heiss et al. (2023) demonstrate that a verifiable computing approach to carbon accounting in supply chains enables the verification of emissions claims without requiring full trust in the reporting party, a principle consistent with the ZKP approach adopted in this study, albeit through a different cryptographic mechanism. Furthermore, recent developments in 2026 research also indicate growing academic interest in decentralized frameworks for blockchain-based carbon credit verification and exchange (Dalui et al., 2026), suggesting that the direction of this study's contribution aligns with current research trends in the field, while also underscoring the urgency of addressing the specific gap identified namely, the explicit integration of ZKP, smart contracts, and techno-economic analysis for the cross-border context.

Discussion of Interpretation

This study identifies three main gaps: (1) the lack of integration between ZKP–smart contract technical design and economic feasibility analysis, (2) the scarcity of frameworks that explicitly address cross-jurisdictional interoperability, and (3) the limited number of techno-economic studies that combine technical and institutional-economic aspects. The findings of this study respond to all three gaps: the layered architecture explicitly incorporates the cross-jurisdictional interoperability layer as a core component rather than an addition. In addition, the techno-economic estimates directly juxtapose technical parameters (gas cost, time, proof size) with their cost and economic feasibility implications; and comparison with recent research shows that, although academic interest in blockchain-based carbon verification continues to grow, the specific combination of ZKP + smart contract + techno-economic analysis + explicit cross-border context remains a contribution space that has not been extensively explored.

a. Implications for Regulators and Policymakers

For regulators such as the CBAM authority in the European Union, this framework offers a middle ground between two previously conflicting needs: transparency for cross-border oversight purposes, and the confidentiality of production data, which remains a key concern for business entities. The Perpetual Powers of Tau trusted setup scheme, which enables multi-party participation across countries, also opens up opportunities for new institutional design: regulators from various jurisdictions can directly participate in the setup process, rather than merely being recipients of verification results from a system whose trust they had no part in building. For Indonesia's context as an exporter with sectors falling under CBAM coverage (iron and steel, aluminum, fertilizer, cement), the estimated time and cost efficiencies serve as policy considerations: adopting an automated verification mechanism has the potential to reduce the administrative burden on exporters in fulfilling CBAM reporting obligations compared to conventional manual audit processes

b. Trade-offs

Although the estimates indicate potential efficiency gains, this study also identifies trade-offs that cannot be overlooked. First, the privacy vs. adaptability trade-off: Groth16 offers the best cost efficiency but requires a dedicated setup for each circuit

structure, meaning that major changes to compliance rules (for instance, if CBAM significantly alters its emissions calculation methodology) may require the setup process to be repeated although minor parameter changes, such as threshold values, do not require this.

Second, the automation vs. legal flexibility trade-off: as discussed earlier, a smart contract that restricts manual intervention also limits the possibility of ex-post adjustment by legal authorities when conditions not anticipated in the circuit design arise an institutional risk that needs to be balanced with clear governance and upgradability mechanisms.

Third, the trade-off between measured efficiency and empirical validity: all the efficiency figures presented are estimates derived from literature benchmarks across different domains (cryptography, blockchain economics, carbon MRV), rather than results from integrated measurements on an actually built system for the carbon audit use case. The interaction between components when all layers operate together in a real system may produce results that differ from the estimates of each individual component considered separately.

RESEARCH LIMITATIONS

Three main limitations should be reiterated in the context of the results: (1) there is no empirical validation through a prototype that has actually been built and tested; (2) the techno-economic estimates are drawn from studies in different domains (not specific to carbon auditing), so the transferability of these figures to real-world contexts requires further testing; and (3) the regulatory scenario refers to the CBAM framework, which is still undergoing continuous revision, meaning that circuit design elements dependent on specific CBAM methodology details may require adjustment as regulations evolve in the future.

CONCLUSION

This study proposes a decentralized framework integrating Zero-Knowledge Proofs and smart contracts to automate cross-border carbon audits, in order to address three gaps identified in the introduction: the lack of integration between ZKP–smart contract technical design and economic feasibility analysis, the limited number of frameworks that explicitly address cross-jurisdictional interoperability, and the scarcity of techno-economic studies that combine technical and institutional-economic aspects.

Based on the analysis presented, several conclusions can be drawn. First, the proposed four-layer architecture data collection, proof generation, smart contract verification, and cross-jurisdictional interoperability offers a structural solution to the fundamental tension between regulators' need for transparency and business entities' need for production data confidentiality, with the Groth16 scheme and the Perpetual Powers of Tau trusted setup mechanism being the most suitable choices given their verification cost efficiency and potential for cross-country trust distribution.

Second, the techno-economic estimates indicate that this framework has the potential to offer cost and time efficiency compared to conventional manual carbon audits, with on-chain verification costs estimated at approximately 220,000 gas per transaction and verification times on the order of seconds to minutes, compared to manual audit cycles that may last a year or more. Nevertheless, this efficiency comes with a number of trade-offs that must be consciously managed: the privacy versus circuit adaptability trade-off , the

automation versus legal flexibility trade-off, and the trade-off between estimated efficiency and as-yet-unproven empirical validity.

Third, this study affirms that its contribution is conceptual-analytical in nature, rather than empirical validation. The estimates presented are drawn from literature benchmarks across different domains cryptography, blockchain economics, and conventional carbon MRV such that the interaction between layers when implemented as a single integrated system may yield performance characteristics that differ from the estimates of each individual component considered separately.

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