WESC-2026
The World Energy Storage Conference-2026
August 09-12, 2026
Istanbul, Türkiye

LIFECYCLE-DEPENDENT HYDROGEN UNITS: A MULTI-GRANULARITY BUSINESS FRAMEWORK FOR HYDROGEN DIGITAL PRODUCT PASSPORTS

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ABSTRACT

The Digital Product Passport (DPP) is emerging as a central instrument for product-level sustainability transparency, formalized in the European Union through the Ecodesign for Sustainable Products Regulation and already operationalized for batteries. Prevailing DPP models assume a stable, serialized product instance that persists from manufacture to end of life. Hydrogen violates this assumption: it is produced continuously, compressed, liquefied, stored, blended in shared tanks and pipelines, divided into consignments, converted into ammonia, methanol and other derivatives, and traded through overlapping physical, contractual and certificate transactions before final consumption. Across these operations the meaning of a hydrogen unit changes, and physical identity is frequently lost through mixing and transformation while sustainability claims must nonetheless be preserved. This paper proposes a lifecycle-aware, multi-granularity business framework for a Hydrogen DPP (H2DPP). Its core construct is the Lifecycle-Dependent Hydrogen Unit (LDHU), a digital business object whose identity and granularity are determined by physical state, containment, business process, custody, ownership, certification boundary, transformation state and required assurance. The framework separates four concerns into distinct but linked ledgers, namely physical quantity, custody, ownership and sustainability claim, and defines a seven-level granularity model spanning item, batch, consignment, flow, pool, mass-balance and book-and-claim representations together with auditable transition rules for aggregation, disaggregation, mixing, transformation, reconciliation and retirement. It integrates the chain-of-custody models of ISO 22095 and allows the model to change at controlled transition points rather than fixing one model for the entire lifecycle. A set of enforceable business invariants prevents double allocation, double retirement and over-certification, and a governance model assigns rights across data, custody, ownership and claim roles. We demonstrate the framework through an end-to-end renewable-hydrogen-to-ammonia scenario and evaluate it ex ante against single item-level, batch-level, pure mass-balance and certificate-only approaches, explaining why no single granularity is adequate for the complete hydrogen lifecycle. The contribution is positioned as a business-architecture and information-system design artifact rather than a specific software implementation.

Keywords: Hydrogen digital product passport, lifecycle traceability, sustainability claims

INTRODUCTION

Low-carbon hydrogen is increasingly considered a key option for decarbonizing hard-to-abate industries, heavy transport, and energy systems [1], [2]. Its market value, however, depends not only on the physical quantity delivered but also on attributes such as production method, energy source, greenhouse-gas intensity, and certification status. These attributes must remain verifiable, transferable, and protected against double counting throughout the value chain.

Digital Product Passports provide a promising basis for managing such information [3]. Existing DPP approaches, including the EU battery passport [4], are mainly designed for discrete products that retain a persistent identity throughout their lifecycle. Hydrogen does not follow this model. It may be produced continuously, stored or transported in shared infrastructure, mixed with hydrogen from different sources, divided into commercial quantities, and converted into derivatives such as ammonia, methanol, or synthetic fuels. Physical custody, legal ownership, and sustainability claims may also be transferred independently.

The main question addressed in this paper is how hydrogen units can be represented and traced when their quantity, form, ownership, custody, and aggregation level change across production, storage, transportation, conversion, trade, and consumption. We argue that an H2DPP cannot rely on a single identifier or a fixed traceability unit. Instead, it requires a lifecycle-aware and multi-granularity model.

For this purpose, we introduce the Lifecycle-Dependent Hydrogen Unit and a framework that defines traceability levels, controlled unit transitions, chain-of-custody rules, and attribute-allocation mechanisms. The proposed approach separates physical quantities, custody, ownership, commercial rights, and sustainability claims while preserving their relationships. It also supports aggregation, splitting, mixing, conversion, allocation, and retirement, and provides an auditable lineage from hydrogen production to final consumption.

BACKGROUND

Hydrogen can be produced through electrolysis, natural-gas reforming, biomass-based processes, or as an industrial by-product. It may then be compressed, liquefied, stored, transported through pipelines or mobile carriers, and either consumed directly or converted into derivatives. Its final greenhouse-gas intensity therefore depends on the complete lifecycle, including production, conditioning, storage, transport, and conversion.

The EU Digital Product Passport framework provides a structured and machine-readable mechanism for sharing lifecycle and sustainability data. However, current regulations, including the ESPR [5] and the Batteries Regulation [4], are designed mainly for durable and serialized products. Hydrogen requires a different approach because it is divisible, continuously produced, frequently mixed, and transformed across the value chain.

Renewable hydrogen in the EU is regulated under the RFNBO framework [6], [7], which defines renewable-electricity conditions [8] and lifecycle GHG requirements [9]. CertifHy [10], ISO standards [11], [12], [13], and IPHE methodologies [14] provide complementary rules for certification and emissions accounting. In parallel, ISO 22095 [15] defines chain-of-custody models ranging from identity preservation to book and claim, while GS1 EPCIS [16] provides an event-based structure for recording supply-chain activities. These standards form the basis of the proposed hydrogen traceability model.

RELATED WORK

This study draws on four related research areas. Digital Product Passport research focuses on product identifiers, lifecycle data, and cross-organizational information sharing, with the battery passport being the most mature example. Supply-chain traceability standards such as EPCIS provide event-based models for tracking custody, location, and transformation, mainly for serialized products and batches. Sustainability certification systems, including Guarantees of Origin, ISCC mass balance [17], and book-and-claim schemes, support the allocation and transfer of environmental attributes when physical flows are mixed. Hydrogen-specific frameworks such as CertifHy, RFNBO regulations, ISO/TS 19870, and IPHE methodologies define how hydrogen-related greenhouse-gas attributes are calculated and certified. However, these approaches do not provide a unified lifecycle model for tracing hydrogen across production, storage, transport, conversion, trade, and consumption.

PROBLEM DEFINITION

Existing approaches address only parts of the hydrogen traceability problem. DPP models are mainly designed for persistent products and do not adequately represent continuous production, mixing, or conversion [3]-[7]. Event-based traceability captures custody and location changes, but it does not by itself reconcile physical quantities with commercial claims [19]. Mass-balance and book-and-claim systems manage environmental attributes, yet they weaken or remove the link to physical lineage [18], [20], [21]. Hydrogen GHG methodologies define how sustainability attributes are calculated, but not how hydrogen units are represented, transferred, combined, divided, converted, and retired [2], [16], [17]. A hydrogen DPP must therefore support changing levels of granularity across production, storage, transportation, conversion, market exchange, and consumption. It must preserve lineage when quantities are aggregated, split, mixed, transferred, or transformed into derivatives such as ammonia or methanol. It must also distinguish physical custody, legal ownership, commercial entitlement, and environmental attributes while ensuring that these records remain consistent and auditable. The central research question is how a Hydrogen Digital Product Passport can represent, trace, and govern hydrogen units throughout their lifecycle. The proposed framework addresses this question by defining the appropriate traceability unit and chain-of-custody model for each stage, controlling transitions between physical and accounting-based representations, allocating attributes after mixing or conversion, and preventing double counting, over-allocation, and reuse of retired claims.

THE LIFECYCLE-DEPENDENT HYDROGEN UNIT (LDHU)

We define the Lifecycle-Dependent Hydrogen Unit (LDHU) as a digital business object representing a measurable quantity of hydrogen or a hydrogen-derived material at a specific lifecycle stage. Its granularity depends on the physical process, containment, custody, ownership, certification boundary, market transaction, and required assurance level. An LDHU may therefore represent a serialized container, a production batch, a metered flow, a commercial consignment, a share in a mixed pool, or an accounting-based quantity.

Each LDHU contains a stable identifier, quantity, physical and lifecycle state, granularity level, lineage links, supporting evidence, and references to custody, ownership, and sustainability claims. Although the identifier remains stable, the represented quantity and its state may change through controlled lifecycle events.

The framework separates four related records. The quantity ledger tracks physical quantities, losses, mixing, splitting, and reconciliation. The custody ledger records physical control, while the ownership ledger represents legal title and commercial entitlement. The claim ledger stores sustainability attributes, GHG intensity, and certification information. This separation allows physical material, ownership, custody, and environmental claims to move independently while

remaining auditable. The granularity levels in Table 1 adapt the chain-of-custody distinctions in ISO 22095, ISCC, and the RSB Book and Claim system to hydrogen-specific physical and accounting units [18], [20], [21].

Table 1. Granularity levels and their applicability.

Level	Definition	Typical unit	When to use	Assurance	Rel. cost
G0	Serialised, physically isolated item	Cylinder, sealed container, tanker compartment	Physical isolation exists and is maintained	Highest	High
G1	Homogeneous quantity handled together	Production/storage/conversion batch	Discrete measurable batches	High	Med-High
G2	Quantity grouped for a transaction/shipment	Delivery order, transport consignment	Commercial shipment or custody transfer	High	Medium
G3	Metered interval of a continuous process	Hourly output, pipeline injection/withdrawal	Continuous production or flow	Med-High	Medium
G4	Commingled multi-source inventory	Tank inventory, pipeline pool, terminal pool	Mixing in shared containment	Medium	Medium
G5	Attribute account after loss of identity	Facility mass-balance account, certified share	Identity lost but attributes preserved	Medium	Med-Low
G6	Attribute fully decoupled from delivery	Book-and-claim unit	Only where regulation/scheme permits	Lowest (physical link)	Lowest

RESULTS AND DISCUSSION

The framework is evaluated against four single-granularity baselines: an item-level DPP, a batch-level model, a pure mass-balance approach, and a certificate-only system. The latter two reflect the accounting logics formalized in chain-of-custody and book-and-claim schemes [18], [20], [21]. The comparison focuses on critical lifecycle points, including continuous production, commingled storage, separation of custody and ownership, conversion, and claim retirement. Table 2 summarizes the evaluation results. Each baseline addresses only part of the problem. Item-level models fail where no persistent physical item exists, while batch-level models require artificial segmentation of continuous flows and cannot adequately represent mixed pools. Mass-balance models handle mixing and conversion efficiently but lose the physical specificity required for dedicated consignments and proof of delivery. Certificate-only systems support attribute trading but cannot preserve physical lineage or identify losses and mis delivery.

The proposed framework selects the appropriate granularity at each lifecycle stage and changes representation through auditable events. Physical traceability is retained where a measurable unit exists, whereas proportional allocation or mass-balance accounting is used when identity is lost. Sustainability attributes are transferred to derivatives during conversion and retired from the input, preventing their repeated use. As shown in Table 2, the multi-granularity model provides greater lifecycle coverage, continuity, chain-of-custody flexibility, and regulatory adaptability than the four baselines. The main trade-off is between traceability precision and operational feasibility. Fine-grained representations offer stronger assurance but increase data volume, audit effort, and cost, whereas coarser representations improve scalability while weakening the link to specific material. The framework therefore resolves this trade-off separately at each lifecycle stage. Since no prototype is evaluated, the findings represent an analytical validation of the proposed design.

CONCLUSIONS

A Hydrogen Digital Product Passport cannot be designed as a static digital label attached to permanently identifiable hydrogen. Hydrogen is continuously produced, physically and commercially aggregated, split, mixed, transported, transformed, traded, consumed, and retired. The meaning of the traceable unit therefore changes across the lifecycle.

This paper introduced the Lifecycle-Dependent Hydrogen Unit and a Lifecycle-Aware Multi-Granularity Hydrogen Passport Framework. The framework combines G0 item-level, G1 batch, G2 consignment, G3 flow-event, G4 pool, G5 mass-balance, and G6 book-and-claim representations. It formalizes controlled transitions, separates physical and commercial rights, maintains quantity and claim balances, creates derivative lineage, and enforces conservation, no-double-allocation, conversion consistency, temporal consistency, and retirement invariants. The end-to-end ammonia scenario demonstrates how physical identity may be lost while business continuity and sustainability-claim integrity remain auditable.

The principal implication is architectural: the H2DPP should be a governed lifecycle system of units, events, balances, rights, evidence, and successor relationships. Its credibility depends less on permanent serialization than on choosing the appropriate granularity at each stage and controlling every transition between physical material and commercial claim.

Table 2. Comparison of the proposed framework with single-granularity approaches.

Criterion	Item-only	Batch-only	Mass-balance-only	Certificate-only	Proposed multi-granularity
Traceability completeness	Partial (fails continuous/mixed)	Partial	Partial (no item detail)	Low (no physical lineage)	High (stage-appropriate)
Accounting integrity	Medium	Medium	High	Medium	High
Double-count prevention	Weak across mixing	Weak across mixing	Strong within period	Depends on registry	Strong
Lifecycle continuity	Breaks at mixing/flow	Breaks at pools	Loses physical thread	Loses physical thread	Continuous via transitions
Multi-CoC support	No	No	Single model	Single model	Yes (controlled transitions)
Scalability	Low	Medium	High	High	High (coarsens where justified)
Transaction cost	High	Medium	Low	Low	Adaptive (finest justified)
Audit cost	High	Medium	Medium	Low-Med	Lower (machine-checkable trails)
Data-sharing burden	Very high	Medium	Low	Low	Proportionate to stage
Commercial usability	Low	Medium	Medium	High	High
Regulatory adaptability	Low	Medium	Medium (MB only)	Low (RFNBO)	High (per-stage rules)

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