Operationalizing a Lifecycle-Dependent Hydrogen Digital Product Passport against the 2026 European Digital Product Passport Standards

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Abstract— On 14 July 2026 Commission Implementing Decision (EU) 2026/1736 published the references of the first six harmonised Digital Product Passport (DPP) standards — EN 18216 and EN 18219 to EN 18223 — in the Official Journal of the European Union, giving the horizontal framework of the Ecodesign for Sustainable Products Regulation (ESPR) a concrete technical baseline. No ESPR delegated act covers hydrogen, yet renewable-hydrogen traceability, mass-balance accounting and certification impose demanding lifecycle requirements. This study asks to what extent a Hydrogen DPP (H2DPP) architecture built on the Lifecycle-Dependent Hydrogen Unit (LDHU) can be operationalized against that baseline. Twenty-one normative requirements were extracted from ESPR Articles 10–13 and the eight EN 182xx standards, classified into eight interoperability dimensions and mapped to architectural mechanisms with an explicit implementation status: five are implemented and evidenced, ten architecture-ready, five planned and one unsupported. An executable reference validator classified all eight LDHU transition cases correctly, and a 10 000-trial Monte-Carlo reconciliation of a commingled two-producer pipeline pool reduced over-certification from 49.96 % to 0.11 % under a coverage factor of three. The principal gap is that the model, batch and item identification levels of EN 18219 offer no counterpart for identity-destroying hydrogen events.

Keywords: hydrogen digital product passport, European DPP standards, EN 18219, chain of custody, mass balance

I. Introduction

Hydrogen is traded on attributes that cannot be observed in the delivered molecule: production route, electricity source, lifecycle greenhouse-gas intensity and certification status. These must remain verifiable and transferable while the material is compressed, stored in shared containment, blended, divided into consignments, converted into derivatives and consumed. The Digital Product Passport is the European instrument for making such information machine-readable and interoperable [1].

The normative situation changed materially in 2026. Commission Implementing Decision (EU) 2026/1736 published the references of six harmonised DPP standards in the Official Journal [2], and Commission Implementing Regulation (EU) 2026/1778 laid down the arrangements for the registry established under ESPR Article 13 [3]. A legally recognised baseline now exists against which a sector-specific architecture can be evaluated rather than merely proposed. That baseline is deliberately product-agnostic: it presumes a product carrying a persistent identifier on a physical data carrier and identified at model, batch or item level. Hydrogen satisfies none of these assumptions across its lifecycle.

Design principles for trusted hydrogen passports have been articulated conceptually [13] but not tested against such a baseline. Our previous work introduced the Lifecycle-Dependent Hydrogen Unit (LDHU), a digital business object whose granularity is determined by physical state, containment, custody, ownership and certification boundary, with a seven-level granularity model and auditable transition rules [4]; it was a business-architecture artifact, evaluated before the European DPP standards existed. This extended abstract therefore asks: to what extent can the H2DPP architecture and the LDHU model satisfy the horizontal interoperability requirements of the 2026 European DPP standards, and which hydrogen-specific requirements remain unaddressed?

II. Normative Baseline and Its Legal Status

The evaluation separates five strata, because conflating them produces overstated compliance claims. (i) Binding Union law. ESPR Article 10 requires connection through a data carrier to a persistent unique product identifier; data based on open standards, machine-readable, structured, searchable and transferable without vendor lock-in; and data referring to the model, batch or item. Article 11 adds technical, semantic and organisational interoperability, linkage of a new passport to the original passport or passports, availability over a defined period including after insolvency, restricted write rights, and assured data authentication, reliability and integrity. Articles 12 and 13 govern operator and facility identifiers and the registry [1], [3].

(ii) Harmonised standards. Six EN 182xx standards from CEN-CLC/JTC 24 under mandate M/604 are cited in the Official Journal [2], [5]; under Article 41(2) a passport

conforming to them is presumed to conform to Articles 10 and 11 to the extent covered. (iii) Standards not yet cited. EN 18239, on access rights, security and business confidentiality, and EN 18246, on data authentication, reliability and integrity, complete the series, but their references were not published in the Official Journal at the time of writing [2], [6], [7]. Publication of an EN standard and citation of its reference are distinct acts; only the latter triggers the presumption of conformity. Article 11(f)–(h) nevertheless applies directly, so an architecture must satisfy it by other demonstrable means.

(iv) Hydrogen-sector rules. Hydrogen is not among the product groups prioritised in the 2025–2030 ecodesign working plan, and no delegated act establishes a hydrogen DPP [8]. Hydrogen traceability is governed instead by the renewable-fuels regime: mass-balance chain of custody, the Union Database under Article 31a of Directive (EU) 2023/2413, and the RFNBO methodologies of Delegated Regulations (EU) 2023/1184 and (EU) 2023/1185 [9], supported by ISO 22095 [10] and voluntary schemes such as CertifHy. (v) Voluntary frameworks and architectural choices. The UN Transparency Protocol [11], GS1 identification and W3C Verifiable Credentials [12] are external frameworks, not components of the European DPP standards; decentralized identifiers, credential signing, dataspace connectors and hash chaining are architectural decisions of H2DPP, not obligations imposed by ESPR or the EN 182xx series. H2DPP is accordingly a research implementation against the horizontal requirements, and no conformity is claimed.

III. Method

The study is a standards-based architectural evaluation in the design-science tradition. Normative requirements were extracted from ESPR Articles 10–13 and from the scope of the eight EN 182xx standards, yielding 21 distinct requirements; these were classified into eight dimensions — identification, data carrier, data exchange, persistence, application programming interface, system interoperability, access control and integrity — and each was mapped to a named H2DPP mechanism. Every mapping received a status: implemented, meaning demonstrably present in the current schema, validator or simulation artifacts; architecture-ready, meaning an identified mechanism exists but is not fully built or validated; planned; or unsupported. Hydrogen lifecycle scenarios covering commingled storage, allocation and conversion were then executed against the artifacts. Architectural intent was never recorded as implementation.

IV. The H2DPP Architecture under Evaluation

The architecture places a canonical hydrogen domain at the centre and treats every external passport representation as a versioned adapter, so that external change cannot propagate into the domain model (Fig. 1). The LDHU is the unit of identity, carrying a URI-typed identifier, a monotonic version, a quantity with an explicit standard uncertainty, a granularity level from G0 to G6, a status, custodian and owner references, and a quality specification with compatible end uses. State changes occur only through the atomic transition events listed in Fig. 1, each mutating four separate ledgers for quantity, custody, ownership and claim. Every transition carries an idempotency key, an actor identifier, a regulatory context, at least one evidence reference with a SHA-256 digest, and the hashes of its predecessor events.

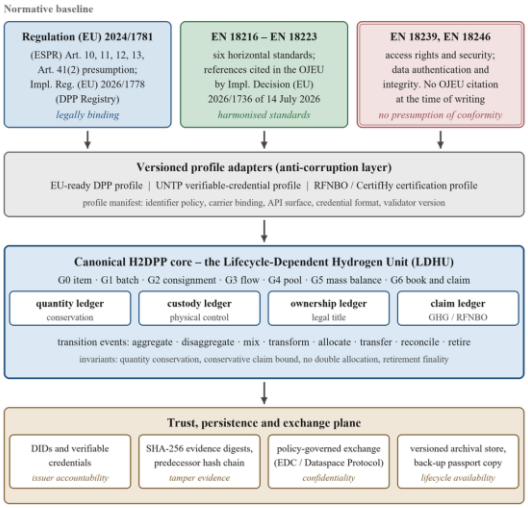


Fig. 1 Layered evaluation architecture: the normative baseline separated by legal status, versioned profile adapters isolating the canonical LDHU core, and the trust plane.

V. Results: Requirements Mapping

Table 1 maps each of the eight standards to the principal requirement it carries, the H2DPP mechanism intended to satisfy it, the status of that mechanism and the supporting evidence or residual gap. Across the 21 requirements, five are implemented and evidenced, ten are architecture-ready, five are planned and one is unsupported. Coverage is strongest for structured data and lineage, and weakest where a physical product surface or a long-lived custodial service is presumed.

TABLE 1. MAPPING OF THE EUROPEAN DPP STANDARDS TO H2DPP ARCHITECTURAL MECHANISMS.

Standard	Principal requirement (paraphrased)	H2DPP / LDHU mechanism	Status	Evidence or gap
EN 18216 (Art. 10(1)(d))	Open, machine-readable, structured and vendor-neutral data exchange.	Canonical transition document in JSON Schema 2020-12; substitutable dataspace and event ports.	Implemented (format); architecture-ready (protocol)	Schema artifact available; no conformance suite run.
EN 18219 (Art. 10(1)(a), (f); 12)	Persistent, globally unique product, operator and facility identifiers at model, batch or item level.	URI-typed unit, actor, custodian and owner identifiers with monotonic version; LDHU levels G0–G6.	Architecture-ready; unsupported (granularity)	Syntax fixed in the schema; G3–G6 have no counterpart (Table 2).
EN 18220 (Art. 10(1)(b), (c))	Data carrier physically present on the product, packaging or documentation, resolving to the passport.	Carrier bound to the containment or transaction artifact: asset tag (G0), batch record (G1), consignment document (G2).	Architecture-ready (G0–G2); planned (resolver)	No physical surface exists for pooled or accounting units (G4–G6).
EN 18221 (Art. 11(c), (e))	Storage, archiving and availability for the required period, including after insolvency.	Append-only event journal with projections; versioned archival store; back-up via a passport service provider.	Architecture-ready; planned (retention)	Append-only lineage in the schema; retention service not built.
EN 18222	Interfaces for passport creation, retrieval, update, lifecycle management and search.	Inbound ports for production, transformation, allocation and passport generation; idempotent writes.	Implemented (idempotency); architecture-ready (API)	Idempotency key and expected-version fields required by the schema; search endpoints planned.
EN 18223 (Art. 11(a), (d))	Technical, semantic and organisational interoperability; a new passport linked to its predecessors.	Canonical LDHU model behind versioned profile adapters (EU-ready, UNTP, certification); mandatory input and predecessor references.	Implemented (lineage); architecture-ready (mappings)	Predecessor linkage mandatory in the schema; mappings not conformance-tested.
EN 18239 not cited in the OJEU (Art. 11(b), (f), (h))	Access-rights management, information-system security and business confidentiality.	Per-transition actor and policy identifiers; ledger-scoped write authorisation; public, partner and auditor views.	Architecture-ready; planned (disclosure)	No presumption of conformity; selective disclosure not built.
EN 18246 not cited in the OJEU (Art. 11(g))	Data authentication, reliability and integrity.	SHA-256 evidence digests and predecessor hash chain; uncertainty-aware conservation with coverage factor k; DID-based signatures.	Implemented (integrity, reliability); planned (signatures)	8/8 invariant cases correct; over-certification 49.96 % → 0.11 %; signing not built.

Table 2 examines the most consequential mismatch. EN 18219 admits identification at model, batch or individual-item level. Only three of the seven LDHU levels align with it: G0 corresponds to an item, and G1 and G2 to a batch, the latter scoped to a transaction. The model level corresponds to a hydrogen product specification or quality grade rather than to a traceable quantity.

TABLE 2. LDHU GRANULARITY LEVELS AGAINST THE IDENTIFICATION MODEL OF EN 18219.

LDHU level	Typical hydrogen representation	EN 18219 level	Identity across transitions
G0	Sealed cylinder or tanker compartment	item	Preserved
G1	Production, storage or conversion batch	batch	Preserved
G2	Consignment or delivery order	batch (transaction-scoped)	Preserved
G3	Metered interval of a continuous flow	none	Created by metering convention
G4	Commingled tank or pipeline pool	none	Lost on mixing; share-based
G5	Mass-balance account after loss of identity	none	Accounting identity only
G6	Book-and-claim unit	none	Decoupled from delivery

VI. HYDROGEN-SPECIFIC EVALUATION

Two artifacts were executed to test whether the architecture enforces the invariants the mapping depends on. An executable reference validator was run over eight LDHU transition cases: it accepted the one legal transition and rejected the seven illegal ones, reporting the expected violation in each — quantity conservation, the conservative claim bound, retirement finality, book-and-claim issuance for an RFNBO-compliance purpose, quality incompatibility with the required end use, failure of hourly temporal correlation for post-2030 production, and duplicate claim inputs.

A second artifact reconciled a synthetic 24-hour commingled pipeline pool supplied by two producers, with 39 501 kg of eligible claim input, over 10 000 Monte-Carlo trials. The combined standard uncertainty of the balance was 142.45 kg. Exact-tolerance reconciliation raised a balance alert in 99.41 % of trials and is operationally unusable; two-sigma and three-sigma tolerances reduced this to 4.58 % and 0.33 %. More importantly, issuing claims against the nominal

balance over-certified the pool in 49.96 % of trials, whereas the validator's conservative bound, which deducts three times the standard uncertainty before issuance, over-certified in 0.11 %. Measurement uncertainty is therefore a first-class requirement of passport integrity, and it is invisible in an item-oriented DPP.

These results also show why hydrogen needs lifecycle-dependent semantics rather than a fixed granularity. Mixing destroys physical identity, splitting creates several successors from one predecessor, and conversion to ammonia or methanol changes the product itself. ESPR Article 11(d) requires a new passport to be linked to the original passport or passports, which is precisely the primitive these events need; H2DPP realises it by making input unit references and predecessor event hashes mandatory in every transition, so that lineage survives the loss of physical identity even where the identifier cannot.

VII. Gap Analysis

Four gaps follow. First, identification: persistent unique identification under EN 18219 is defined for entities that retain identity, which hydrogen at flow, pool, mass-balance and book-and-claim level does not. The required extension is a lifecycle-dependent identifier class whose persistence guarantee is declared per granularity level and whose identity-destroying transitions must carry predecessor linkage. Second, physical-to-digital binding: EN 18220 presumes a carrier on the product, its packaging or accompanying documentation, whereas for bulk fungible media the binding can attach only to a containment asset, a transport or transaction document, or a certificate; a normative notion of a carrier of record for bulk media is absent.

Third, the assurance stratum is incomplete: the two standards that would operationalise ESPR Article 11(f)–(h) were not cited in the Official Journal at the time of writing, so the access-control and integrity mechanisms of H2DPP are architectural commitments evaluated on their own evidence and cannot confer a presumption of conformity. Fourth, dual-registry reconciliation: the registry stores identifiers at model, batch or item level [3], whereas renewable-hydrogen claims are traced as mass-balance transactions in the Union Database [9], with no defined correspondence between the two. H2DPP carries a Union Database transaction reference in each transition as a provisional bridge; formalising that correspondence is the clearest item of future standardisation work.

VIII. Conclusions

A lifecycle- and granularity-aware hydrogen passport can be operationalized against the horizontal European DPP framework to a substantial but bounded degree. Of 21 requirements, 15 are implemented or architecture-ready, concentrated in data exchange, lineage, interoperability and integrity; binding bulk hydrogen to a physical carrier and preserving identifiers across identity-destroying events are not accommodated.

The contribution beyond our previous work is a change of layer. That work proposed the LDHU as a conceptual artifact evaluated ex ante against single-granularity baselines [4]. The present study evaluates the same construct against an external, legally recognised baseline that did not then exist, produces a systematic requirement-to-mechanism mapping with explicit implementation status, quantifies the reliability of the claim-issuance rule under measurement uncertainty, and identifies four interoperability gaps with the extensions they require. The result is a conformance-oriented architecture and a research agenda for hydrogen-specific extensions, not a claim of compliance.

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