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Integrating regional energy hubs with hydrogen: Pathways to understand and reduce decision-making uncertainties in the Netherlands

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HIGHLIGHTS

- Grid access, not technology, constrains hydrogen deployment in the Netherlands.
- Five uncertainties arise across four coordination requirements.
- Congestion, contracts, and coordination produce linked decision uncertainties.
- No single instrument is likely to secure financeability-related conditions.
- Four strategies and two pathways may reduce uncertainty at Cluster 6 nodes.

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ABSTRACT

Hydrogen integration at Dutch regional energy hubs appears to stall not because of technology but because no institutional arrangement adequately governs the conditions under which projects may operate on financeable terms. Grid access is the binding constraint: investment depends on how many hours a connection permits operation, what curtailment costs, and whether those hours coincide with renewable generation eligibility. At Cluster 6 nodes, outside reinforcement priority plans and lacking near-term access certainty, these interdependencies remain unresolved. This paper identifies five decision uncertainties arising at the boundaries between potential hub developers and network operators, across four coordination requirements: siting, access portfolio construction, curtailment and settlement design, and hub governance in Cluster 6-type contexts. In response, four coordination strategies are identified using existing Dutch regulatory instruments and configured into two lifecycle-sequenced integration pathways matched to observable hub conditions. The analysis indicates that no single instrument, on its own, is likely to secure the institutional conditions associated with financeability; rather, those conditions depend on how instruments are combined across the wider coordination arrangement.

1. Introduction

The viability of hydrogen as an industrial decarbonisation pathway depends not on technological readiness alone, but on whether electricity can be accessed at a specific grid connection point on terms that make investment financeable. Most planned hydrogen projects appear to stall not because the technology fails, but because project developers cannot secure grid access on financeable terms (Hasankhani et al., 2024, 2025). The question this paper addresses is therefore not whether hydrogen is strategically desirable, but whether the rules governing grid access can be made to enable hydrogen projects to operate on financeable terms.

The first problem is operational. Hydrogen electrolysers, unlike stable-demand industrial consumers, should run hard when electricity is cheap and curtail when it is not. Output depends directly on which hours the grid permits operation, and the hourly matching obligation under the Renewable Fuels of Non-Biological Origin (RFNBO) Delegated Regulation means the commercial case rests entirely on maximising the overlap between grid-available and renewable-eligible hours (Commission Delegated Regulation (EU) 2023; Hordvei et al., 2024).

The second problem is contractual. The bilateral connection and transport agreement (*aansluit-en transportovereenkomst*, CTA) governing large-consumer grid connections was designed for stable-demand

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consumers and specifies contracted capacity in megawatts, not useable hours (ACM, 2024). Network tariffs include a fixed capacity component charged regardless of actual delivery. This mismatch between contracted and delivered access is most acute in Cluster 6 mid-sized industrial sites, which sit outside the five major clusters, lack dedicated reinforcement programmes, and must commit capital without the backbone access or reinforcement priority available at higher-priority nodes.

Regional Energy Hubs (EHs) co-locating renewables, an electrolyser, and storage have been proposed as the structural response to these conditions (Haghi et al., 2018; Hasankhani, 2025; Mohammadi et al., 2017). By presenting the network operator (transmission system operators (TSOs) and distribution system operators (DSOs)) with a single accountable counterparty managing collective demand, a hub can secure better access terms than multiple individual developers negotiating separately (Simshauser, 2025). The EH does not escape the contractual problem described above; it inherits it while also adding substation-scale collective governance requirements that individual bilateral contracts cannot address.

The third problem is one of mutual decision-making dependency. Before committing capital, the developer needs to know which hours will be available, under what curtailment conditions, at what cost, and whether those hours will coincide with renewable generation. The network operator cannot produce that information without knowing the developer's intended operating profile. Neither party can resolve the key decision alone, and no institutional arrangement currently exists to structure that exchange (Williamson, 1985). This paper terms the resulting condition institutional decision-making uncertainties: uncertainties produced not by data absence but by the absence of a coordinated process through which the necessary information can be jointly established at the hub-network interface.

Existing pilots have explored hub-level coordination (Hasankhani et al., 2023) but systematic guidance on how roles, operating rules, and risk allocation at the hub-network interface should be designed to make configurations operable and to improve the institutional conditions relevant to financeability remains absent. The guiding research question is therefore: how can coordination arrangements between EH developers and network operators at congested nodes reduce institutional decision-making uncertainties and improve the institutional conditions relevant to hydrogen project financeability under persistent grid uncertainty? Two sub-questions follow. SQ1: which uncertainties recur at the boundaries between siting, access portfolio construction, curtailment and settlement design, and hub governance decisions at congested nodes, and what coordination requirements do they generate? SQ2: what coordination strategies and lifecycle-sequenced integration pathways can reduce these uncertainties in Cluster 6-type contexts?

The study identifies five decision uncertainties, four coordination strategies, and two lifecycle-sequenced integration pathways for Cluster 6-type nodes. Section 2 develops the background and problem structure; Section 3 describes the research design; Section 4 presents the results; Sections 5 and 6 offer discussion and conclusions.

2. Background and problem structure

2.1. The operational layer

The hub must accumulate hours satisfying both grid availability and renewable eligibility simultaneously. The RFNBO Delegated Regulation's hourly matching obligation independently bounds what is achievable: for wind-dominated PPAs, eligible operation is limited to approximately 2000 to 5000 full-load hours per year, with CE Delft modelling Dutch offshore wind-coupled electrolysers at approximately 4300 h under standard RFNBO hourly matching requirements (CE Delft, 2022, 2024; ISPT, 2020). At Cluster 6 inland nodes, where behind-the-meter price exemptions and high renewable share exemptions provide limited relief, the constraint binds in full.

Achieving that overlap requires coordination across three nested levels. At the internal hub level, batteries provide short-cycle buffering and hydrogen storage enables longer-cycle buffering; by adjusting electrolyser load and cycling storage in response to congestion signals and electricity prices, a hub can shift offtake away from constrained hours (Fig. 1). At the bilateral level, curtailment procedures, compensation terms, and dispatch rules must be agreed with the network operator before commissioning. At the substation scale, when multiple hubs simultaneously reduce withdrawal in response to the same congestion signal, the aggregate demand shift can produce outcomes no individual hub caused and no bilateral agreement anticipated (Hennig et al., 2023). These three coordination levels define what the operational layer requires but cannot establish on its own: the conditions under which flexibility reduces rather than compounds cash-flow volatility are determined by contractual and governance arrangements.

2.2. Contractual layer

Grid access for large consumers is governed by a CTA between the developer and the network operator. A system-level congestion management instrument sits above the CTA and operates independently of it: when the network operator anticipates congestion on a day-ahead basis, it activates a capacity limitation contract (CBC), restricting withdrawal rights for the duration of the event. CBC activations respond to grid conditions across multiple parties simultaneously (ACM, 2023; Dubbeling and Tindemans, 2025; Staten-Generaal, 2024).

Three CTA variants define the developer's structural position (Swarts et al., 2025). A firm CTA provides access at all contracted times and qualifies for curtailment compensation through a *beschikbaarheidsvergoeding* (availability payment) and *restrictievergoeding* (restriction payment) when a CBC restricts withdrawal and carries the highest tariff. A *tijdsduurgebonden transportrecht* (TDTR) provides access for at least 85% of annual hours, permits restrictions on one day's notice for the remaining 15%, and eliminates the contracted-kW tariff component yielding an approximately 50–65% tariff reduction while other tariff components remain. A non-firm agreement (NFA) provides no access guarantee, sets the contracted-kW component to zero, and carries the lowest tariff. Curtailment compensation methodology for NFA holders remains under active regulatory development, meaning the financial value of accepting non-firm terms cannot currently be modelled with confidence. In the Netherlands, national targets set a 3 to 4 GW ambition for electrolyser capacity by 2030 and 8 GW by 2032, yet realised capacity is projected at only 1.2 to 1.5 GW (Gasunie and TenneT, 2019; RVO, 2023), with the contracted-versus-delivered access gap a primary mechanism through which grid conditions undermine investment financeability: a developer contracted for 6000 useable hours who receives 3500 due to congestion still pays for 6000.

The tariff-risk trade-off this creates is not stable across locations. CE Delft (2024) quantifies the directional asymmetry: the TDTR imposes substantially lower restriction rates at coastal wind-landing locations, where electrolysers absorb excess offshore wind and have a net-positive grid impact, than at Cluster 6 inland nodes, which function as net demand-adders and face materially higher restriction exposure. Cluster 6 sites also fall outside Gasunie's national hydrogen backbone priority programme, with full backbone connectivity scheduled by 2033 (Gasunie and TenneT, 2019; RVO, 2023). They must therefore commit capital under persistent congestion without the reinforcement priority or backbone access available at higher-priority nodes.

2.3. Coordination requirements

Where the operational and contractual layers fail to align, four structural coordination problems emerge. Asset specificity: once an electrolyser is built at a specific node it cannot be moved, and the developer becomes entirely dependent on what the operator at that node decides (Williamson, 1985). Incomplete contracting: curtailment rules,

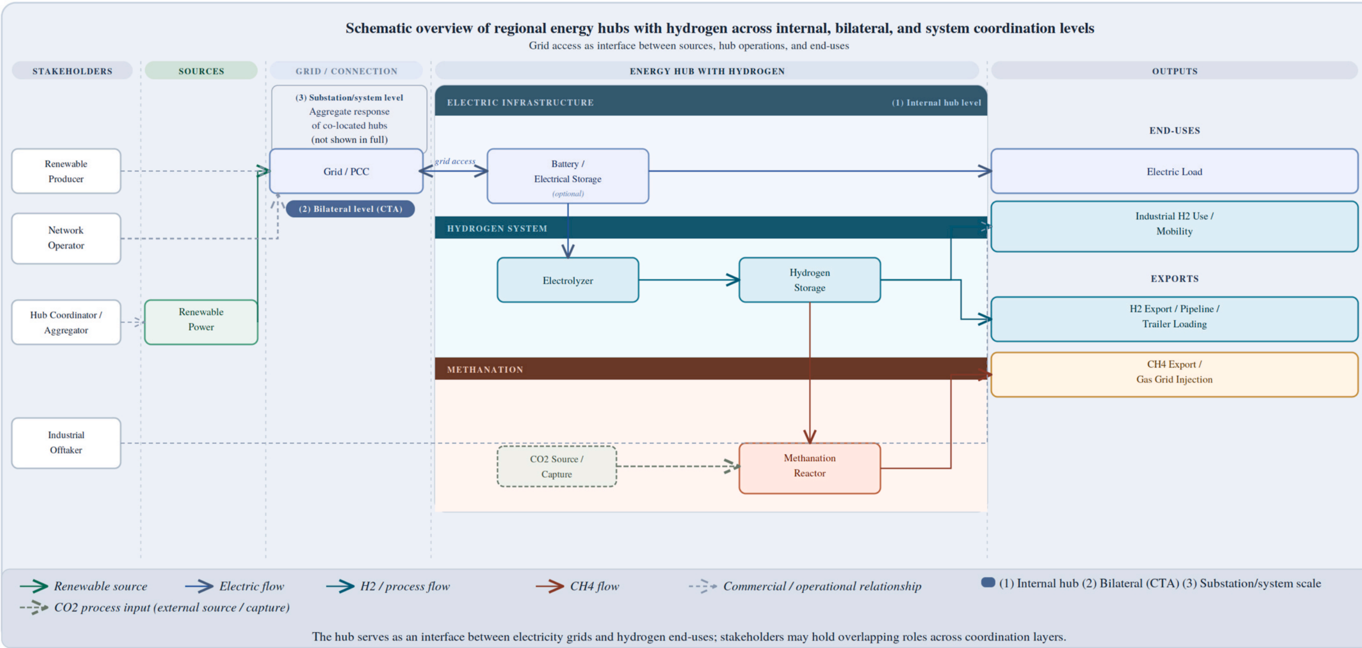

Fig. 1. Schematic overview of regional energy hubs with hydrogen across internal, bilateral, and system coordination levels.

compensation amounts, and settlement procedures depend on operator application and regulatory change, and no contract can fully specify these in advance. Bilateral governance failure: once investment is sunk, neither party can protect its position through renegotiation alone. Collective action failure: when multiple hubs respond simultaneously to identical congestion signals, their combined behaviour produces outcomes no individual hub caused and no bilateral contract can govern, because the problem emerges across parties who hold no contractual relationship with each other (Ostrom, 1990). Unbundling (Bampaou and Panopoulos, 2025; Veer et al., 2025) reinforces all four: preventing operators from coordinating hub assets, preventing hub developers from securing durable protections, and preventing any party from establishing the multilateral governance structure that collective action failure requires.

Four coordination requirements follow. Siting arises from asset specificity: evaluating grid capacity, congestion risk, and operator terms simultaneously requires integration that no single instrument currently provides, so hub developers commit capital at nodes whose full financeability they cannot assess in advance. Access portfolio construction arises from incomplete contracting: the developer must choose between CTA variants while satisfying two independent constraints simultaneously: enough hours for debt service, and hours coinciding with renewable generation eligibility under the RFNBO Delegated Regulation's hourly matching obligation. CE Delft (2024) estimates network tariff costs at approximately €2/kg under a firm CTA, falling to €1/kg under a TDTR, against a total production cost range of €6.5 to €12/kg. Curtailment and settlement design arises from bilateral governance failure: when the operator restricts withdrawal the developer loses revenue but retains fixed costs; infrastructure project finance requires contracted revenue floors, defined risk allocation, and cash-flow predictability before capital can be committed, and locally negotiated compensation arrangements cannot provide that stability. Hub governance arises from collective action failure: multiple hubs responding identically to the same congestion signal can collectively overload substation infrastructure in ways no bilateral contract can govern.

These requirements form a coupled sequence: siting determines which CTA variants are available; the access mix shapes curtailment risk; curtailment risk determines which settlement conditions must hold for financeability; and those conditions feed back into siting when they cannot be met. No single instrument addresses this loop, and no party can govern it unilaterally. The first two requirements arise before any stable contractual relationship is established; the third and fourth emerge once bilateral and substation-scale problems become binding. Fig. 2 maps this sequence across the four coordination requirements. The lifecycle phases through which these requirements become active are developed in Section 4.3. All four requirements are most acute in Cluster 6 contexts, where limited hosting capacity, extended reinforcement horizons, and the absence of near-term backbone access reduce available fallback options (Paul, 2024).

3. Research design and methods

This study examines why institutional decision-making uncertainties arise at Dutch regional energy hubs with integrated hydrogen, and which coordination arrangements could reduce them within existing institutional constraints. Because these uncertainties occur at the hub–developer–network-operator interface, they cannot be inferred from regulatory documents alone. The study proceeded in three sequential phases, each using the output of the previous phase as its direct input (Fig. 3). The design combines institutional diagnosis of coordination failure (Ostrom, 1990) with regulatory instrument synthesis and workshop-based pathway configuration. Three principles informed it: institutional decision-making uncertainties are most visible to actors who encounter them in practice, making qualitative inquiry necessary; any workable arrangement had to be acceptable across the hub–network interface, so the evidence base sought direct network-operator and project-development perspectives; and candidate strategies had to remain within existing Dutch regulatory authority.

Phase 1 — Analytical framing. The paper's central claim is that hydrogen integration at Dutch regional energy hubs is constrained less

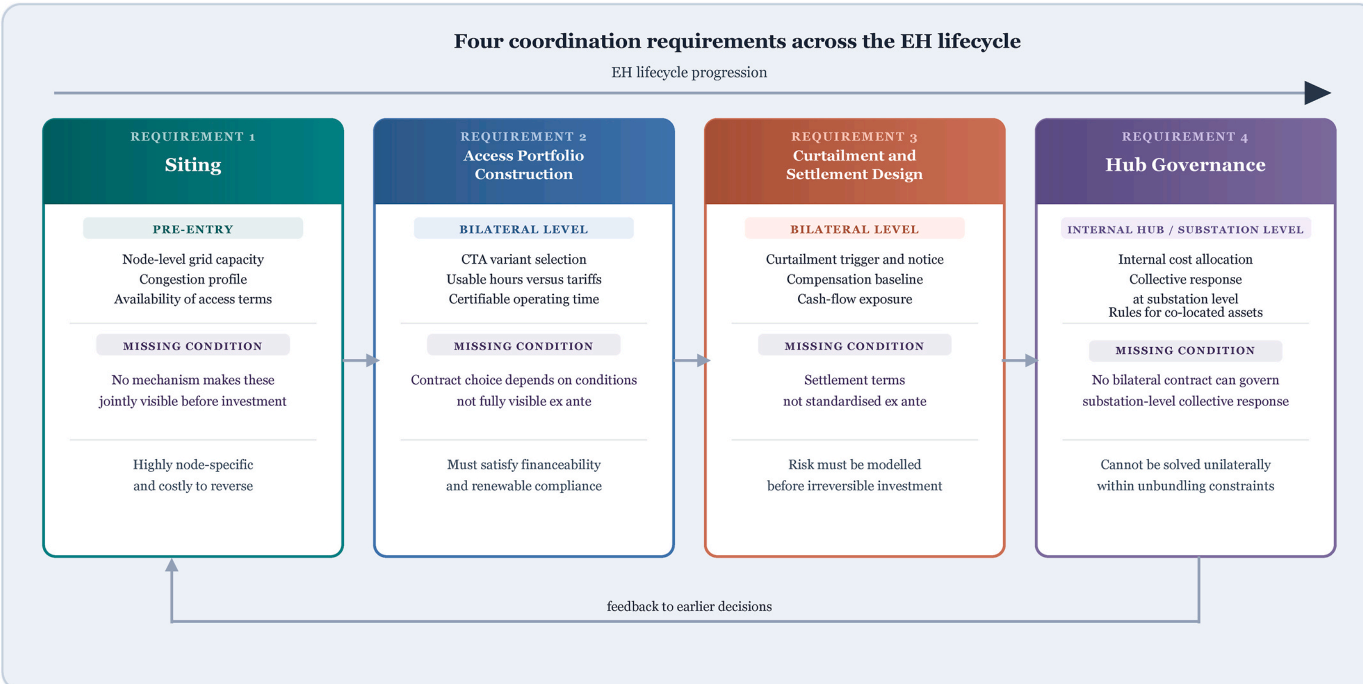

Fig. 2. Four coordination requirements across the EH lifecycle.

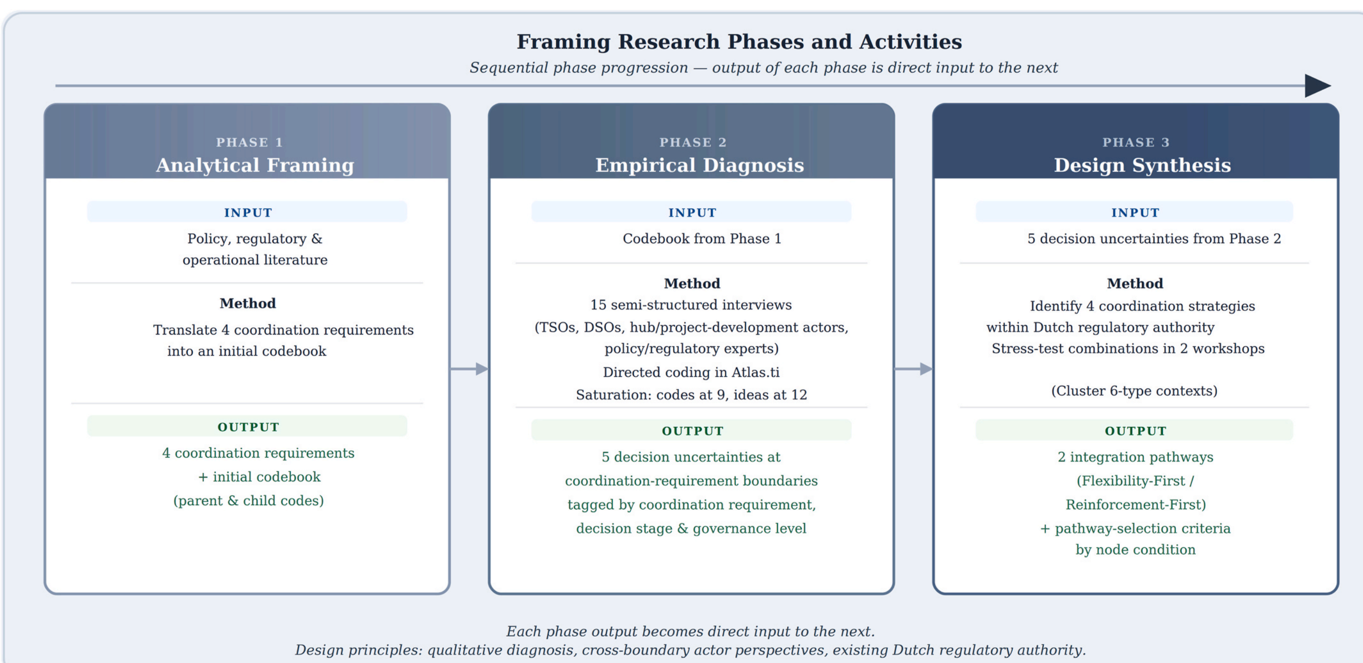

Fig. 3. Framing research phases and activities.

by technology than by unresolved institutional interdependencies that determine whether projects can operate on financeable terms. Four coordination requirements siting, access portfolio construction, curtailment and settlement design, and hub governance were used to structure the problem space and translated into an initial coding framework using directed content analysis (Hsieh and Shannon, 2005). These became the parent codes; child codes specified the more concrete institutional blockages expected in practice (informational gaps, commitment failures, settlement ambiguities, collective coordination problems), drawn from Dutch regulatory documents, network-operator publications, and the wider energy-governance literature. The full coding structure is provided in Appendix A, Table A3. The empirical task was therefore not unconstrained inductive discovery but theory-led diagnosis of where these coordination requirements became decision-relevant in practice. The five decision uncertainties reported later are higher-order analytical constructs, not initial codes, identified where differently worded passages referred to the same underlying decision dependence and missing institutional condition across multiple interviews. The codebook remained open primarily to revision at the child-code level and to new higher-order specifications; no interview material required replacement of the four parent codes.

Phase 2 — Empirical diagnosis. Fifteen semi-structured interviews were conducted with network operators (TSOs, DSOs), hub and project development actors, energy-service providers, and policy and regulatory experts (Appendix A, Table A1). Sampling was purposive (Patton, 2002), judged by positional coverage of the governance boundary rather than proportional stakeholder representation. Network-operator perspectives and project-development views (the latter captured more indirectly through advisory and infrastructure-development actors) were prioritised. Project financiers, hydrogen end-users, and smaller hub developers remained underrepresented, which limits claims concerning commercial bankability and downstream market uptake but does not invalidate the core diagnostic focus on the operator–developer boundary.

Interviews lasted 30–60 min, were conducted online or in person under informed consent and anonymisation procedures and were structured around the four coordination requirements. Each block covered the actor's experience of the relevant decision boundary, available instruments, and conditions under which those instruments had or had not functioned (Appendix A, Table A2).

Transcripts were analysed in Atlas.ti by two researchers. Both independently coded the first four transcripts to calibrate interpretation before dividing the remainder; disagreements were resolved against written code definitions. New codes required agreement from both researchers. Once application had stabilised, one researcher coded the remaining transcripts while the second independently reviewed every third. Coding stability, following Guest et al. (2006), was assessed by tracking whether new codes or substantively new ideas defined as previously unidentified actor behaviours, causal pathways, or instrument interactions emerged. No new codes appeared after interview 9 and no substantively new ideas after interview 12. Given the protocol's predetermined structure, this plateau reflects stability within the directed frame rather than exhaustion of the broader conceptual space. The final three interviews confirmed positional coverage and verified the plateau did not reflect incomplete role coverage.

A passage was classified as a decision uncertainty only when two conditions were met simultaneously: the uncertainty arose where coordination requirements became interdependent, and it made a key decision dependent on information, commitments, or operating rules that no actor under current institutional arrangements could reliably provide in advance. Five recurrent uncertainties met these conditions, with recurrence defined as appearance across multiple interviews and multiple participant roles under the same underlying decision dependence and missing condition. Each was tagged by coordination requirement affected, decision stage (pre-entry; portfolio design and contracting; operation and settlement; cross-cutting), and governance level (internal hub; bilateral hub–operator; substation-scale collective; cross-level), enabling a direct move from diagnosis to design.

Phase 3 — Design synthesis. Each of the five decision uncertainties was treated as a governance design problem in the sense of design-science research (Aken, 2004): diagnosis identifies what must be institutionally supplied for the affected decision to become actionable. A condition was treated as missing where a key decision depended on information, commitments, operating rules, or settlement terms that no actor could reliably provide ex ante. Candidate interventions were identified through a structured second-pass reading of interview material anchored in the Phase 2 codebook, re-examining coded passages for references to instruments, procedural adjustments, or governance mechanisms that addressed the missing condition and remained actionable within existing Dutch regulatory authority. Where network-operator participants and actors closer to project-development roles independently identified the same instrument, that convergence provided the evidential basis for a directly supported strategy; where compatible fragments were identified separately, they were assembled analytically into a composite strategy with explicitly lower evidential standing. This yielded four strategies: three directly supported by cross-role convergence and one analytically assembled from complementary fragments.

Knowing what conditions need to be supplied does not resolve how the four strategies should be combined, sequenced, or prioritised under different node circumstances. Two participatory workshops therefore tested whether specific strategy combinations could be configured into operationally coherent and legally feasible pathways and identified where proposed configurations failed and why. Their aim was not to generate new strategies or to ask participants whether they agreed with the research conclusions, but to stress-test configurations against defined operating conditions.

Each workshop lasted approximately 90–120 min and was conducted in Miro using pre-built boards structured around Cluster 6 node conditions, CTA variants, RFNBO hourly-matching requirements, curtailment-compensation parameters, storage assumptions, and the four EH lifecycle phases (Fig. 4; Appendix B). Because the boards were pre-structured around the Phase 2 framework, participants could refine and challenge configurations within that frame, but the workshop design did not provide a basis for independent disconfirmation of the underlying Phase 2 diagnosis. Workshop 1 included two network-operator participants and one researcher facilitator and focused on supply-side parameters: feasible access slices, ramping constraints, and realistic settlement envelopes at a Cluster 6 node. These outputs defined the operating envelope within which strategy configurations were subsequently tested in Workshop 2. Workshop 2 included one network-operator participant, one business-park infrastructure manager, and three researchers and focused on configuring the four strategies into full pathway form across the EH lifecycle.

Each workshop followed a three-stage procedure adapted to its focus. In Workshop 1: participants specified the operating envelope; mapped the four strategies against supply-side constraints; and confirmed realistic settlement envelope ranges at a Cluster 6 node. In Workshop 2: participants specified the operating envelope; arranged the four strategies into candidate pathway logics, deciding which function as necessary entry conditions and which as supporting arrangements; and stress-tested each configuration against three feasibility criteria: whether role allocations remained within existing Dutch regulatory authority; whether settlement assumptions were consistent with the CTA variant used; and whether operational rules avoided recreating synchronised ramping or equivalent collective congestion effects. Configurations failing one or more criteria were revised iteratively; where no revision could satisfy all three, the configuration was dropped.

Two revision examples illustrating what the feasibility testing produced are reported in Section 4.3, where they serve as evidence for the dependency structure of the final pathways. Workshop outputs were analysed by comparing retained configurations against the five Phase 2 uncertainties to identify coherent strategy combinations and sequencing dependencies. Reinforcement credibility and offtake signal strength were confirmed as the conditions most consistently determining which configurations survived and were therefore retained as the primary pathway-selection criteria; both conditions were treated as threshold phenomena in the workshop exercise rather than as continuous variables, as substantiated in Section 4.3.

Four limitations bound the evidential standing of these pathways. First, only four participants were involved across both workshops, skewed toward the operator side; developer-side constraints around offtaker and lender requirements were not directly tested. Second, the pre-structured boards mean the pathways cannot be read as independent corroboration of the Phase 2 diagnosis. Third, the absence of financiers means financeability remains indicative rather than confirmed: the pathways establish institutional feasibility within existing Dutch regulatory authority, not lender-validated bankability. Fourth, the iterative revision process involved researcher judgement in deciding when a revised configuration satisfied a criterion, introducing a degree of interpretation that cannot be fully eliminated.

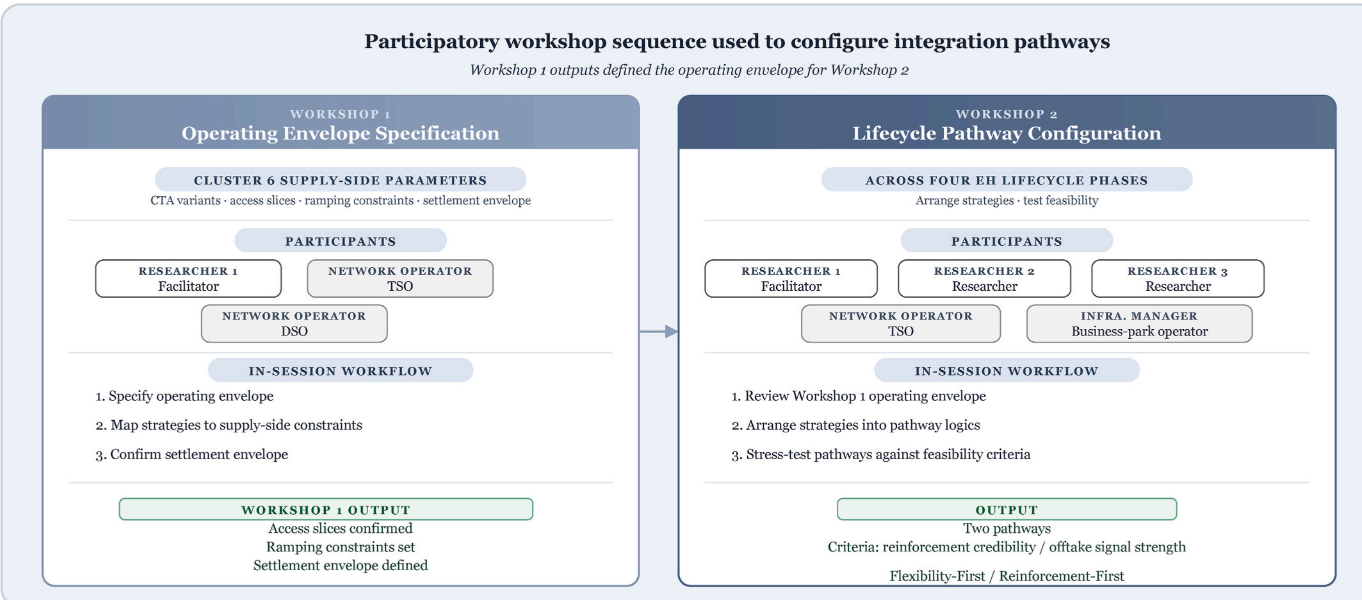

Fig. 4. Participatory workshop sequence used to configure integration pathways.

4. Results

4.1. Uncertainties and their interconnections

Five decision uncertainties were identified. They do not replace the four coordination requirements siting, access portfolio construction, curtailment and settlement design, and hub governance but specify the decision boundaries at which those requirements become persistently difficult to satisfy in Cluster 6-type contexts (Table 1). Consistent with the classification rule set out in Section 3, each uncertainty was identified where coordination requirements became interdependent and where a key decision depended on information, commitments, or operating rules that no actor could reliably provide in advance. Recurrence was assessed against the criterion defined in Section 3: appearance across multiple interviews and multiple participant roles under the same underlying decision dependence and missing condition.

U1: Capacity allocation asymmetry (siting and hub governance; pre-entry; cross-level). Operators cannot size infrastructure without knowing which projects will actually materialise, while hub developers cannot commit without knowing what access will cost and on what terms it will be available. No instrument currently allows contingent commitment or allocates idle-capacity costs between the party that builds and the party that does not materialise. U1 is classified as cross-level because it combines bilateral commitment uncertainty with a collective cost-allocation problem once hub-scale capacity must be sized before full participant commitment is secured. This pattern appeared across the majority of interviews and was identified by participants in both network-operator and advisory roles.

U2: Demand and offtake uncertainty (access portfolio construction and curtailment and settlement design; portfolio design and contracting;

Table 1
Five decision uncertainties.

Uncertainty	Coordination requirement(s) affected	Decision stage	Governance level	Missing condition	Core uncertainty	Illustrative quote
U1. Capacity allocation asymmetry	Siting; hub governance	Pre-entry	Cross-level	Credible contingent commitment and idle-capacity cost allocation	Commitment stalls because neither party is willing to proceed without credible assurance that the other will also commit.	“Size for 100, only 30 arrive — who pays?” (Network operator)
U2. Demand and offtake uncertainty	Access portfolio construction; curtailment and settlement design	Portfolio design and contracting	Bilateral hub–operator	An ex ante access structure and compensation envelope that can support offtake commitment	Firm access is difficult to finance without secure offtake, while offtake cannot be secured without sufficiently reliable access.	“We cannot fund without guaranteed load.” (Project-development actor)
U3. Curtailment compensation credibility	Curtailment and settlement design; access portfolio construction	Portfolio design and contracting	Bilateral hub–operator	Ex ante credible compensation methodology for triggers, baselines, and settlement	Compensation triggers, baselines, and settlement conditions vary across cases, making expected outcomes difficult to specify and model ex ante.	“If we are forced off, is that reimbursed?” (Project-development actor)
U4. Synchronised load response	Hub governance; access portfolio construction	Operation and settlement	Substation-scale collective	A collective response rule or recognised coordinating role for aggregate CBC response	Individual responses to the same CBC activation can, in aggregate, recreate the congestion they are intended to relieve.	“Add three 150 MW hubs ramping at 2 a.m. — back to square one.” (Network operator)
U5. Regulatory fluidity	All four coordination requirements	Cross-cutting	Cross-level	Stable regulatory reference points for tariffs, cost allocation, and compensation	Simultaneous revision of unbundling rules, tariff design, and cost-allocation arrangements weakens the predictability of present coordination choices.	*“We do not know who will pay for reinforcements yet.” (Network operator)*

bilateral hub–operator). Without confirmed offtake, hub developers cannot determine the access portfolio; without a defined access portfolio, compensation terms cannot be specified; and without specified compensation terms, offtake cannot be secured. The RFNBO Delegated Regulation intensifies this circularity because the minimum viable access volume must simultaneously provide sufficient hours for debt service and sufficient RFNBO-compliant hours for qualifying renewable hydrogen production. Market uncertainty compounds this further: anchor offtakers themselves face transition pressures that may weaken, delay, or dissolve agreements over the project lifetime. This circularity was identified across multiple interviews, with consistent formulations from both network-operator and project-development actors.

U3: Curtailment compensation credibility (curtailment and settlement design; access portfolio construction; portfolio design and contracting; bilateral hub–operator). Distinct from U2, this uncertainty concerns not the circularity of portfolio sizing but the instability of compensation terms during the structuring of access for contracting and finance. Lenders require stability across curtailment trigger definitions, notice windows, baseline calculations, and settlement verification before non-firm access can be modelled. Provincial variation in curtailment compensation availability means a framework confirmed elsewhere cannot be assumed to apply at a Cluster 6 node. This instability appeared across multiple interviews, primarily from network-operator participants, with corroborating references from advisory roles.

U4: Synchronised load response (hub governance and access portfolio construction; operation and settlement; substation-scale collective). When multiple EHs respond simultaneously to identical CBC activations, their combined withdrawal recreates the congestion that individual flexibility was intended to relieve. No bilateral contract can bind co-located parties or distribute aggregate CBC response, and no single counterparty has standing to govern the collective. This collective governance problem appeared across multiple interviews and was identified exclusively by network-operator participants, consistent with the stronger network-operator coverage of the sample.

U5: Regulatory fluidity (all four coordination requirements; cross-cutting; cross-level). Unbundling rules, tariff reform, cost-allocation principles, and NFA compensation methodology are under simultaneous revision, preventing either party from making confident long-term coordination decisions. Regulatory fluidity appeared as a cross-cutting pattern across the full interview sample and across network-operator and advisory/project-development-adjacent roles, consistent with its classification as affecting all four coordination requirements simultaneously.

The five uncertainties specify the coupled sequence developed in Section 2.3. Capacity allocation asymmetry shapes the access mix available at entry; that access mix then determines whether compensation terms must bear part of the burden of making the arrangement financeable and whether those terms can be modelled credibly ex ante. Where compensation credibility remains unresolved, the offtake circularity is reinforced rather than eased. Once projects proceed under those conditions, synchronised load response appears as a collective governance problem at substation scale. RFNBO compliance binds across the entire sequence, so failure at any point reduces both revenue and the volume of output that can qualify as renewable hydrogen. Regulatory fluidity weakens each link without being caused by any single one. Although U2 and U3 arise from different contracting gaps, together they form a single underwriting problem: lenders cannot model cash flows when both access volume and compensation terms remain unresolved. None of the final uncertainties operated solely at the internal-hub level. Because positional coverage was stronger on the operator side, the uncertainties are not equally evidenced across roles. This limitation matters most for U2 and U3, where claims concerning project-development and bankability implications are most sensitive, but it may also shape how U4 and U5 are perceived.

4.2. Coordination strategies

Four coordination strategies were developed to address the missing institutional conditions identified across the five decision uncertainties (Table 2). S1, S2, and S3 were independently supported across network-operator participants and actors closer to project-development roles. S4 was assembled analytically from compatible instrument fragments and therefore carries different evidential standing.

S1: Dynamic connection register (U1, U5; siting). A continuously updated register publishing queue positions, available capacity, congestion forecasts, and reinforcement timelines at feeder level lowers the threshold for conditional commitment without requiring either party to move first. Because it improves transparency rather than creating a new regulatory commitment, it is relatively robust to tariff reform and therefore also addresses U5 directly.

S2: Group transport agreement with collective CBC governance (U1 through hub governance, U4; hub governance). A GTO under the Energiewet (2024) allocates collective transport capacity to a hub group and establishes a designated authorised representative (the *gemachtigde*) who manages the relationship with the network operator on behalf of the group. Collective CBC response is governed through a complementary *Collectief Capaciteit Beperkend Contract* (C-CBC), which the GTO structure makes institutionally feasible by establishing the collective group and its coordinator. These two instruments supply the collective response rule and recognised coordinating role missing under U4. By consolidating individual CBCs into a single collective CBC managed at hub level, it converts the synchronised load-response problem into a question of internal governance. Internal allocation rules must preserve RFNBO-compliant operating hours.

S3: Standardised and ring-fenced compensation framework (U3, U2 partially; curtailment and settlement design). A standardised methodology funded through ring-fenced tariff allocations fixes trigger definitions, notice windows, baseline calculations, and settlement verification at national level. Ring-fencing is essential: without it, the congestion budget can be consumed before hub compensation is paid. By making compensation terms knowable before access terms are fixed, S3 removes one major variable from U2's circularity and directly addresses the missing ex ante credibility identified under U3.

Table 2
Four coordination strategies.

Strategy	Uncertainty addressed	Coordination requirement addressed	Institutional basis
S1. Dynamic connection register	U1; U5	Siting	Developed as an extension of the TenneT capacity map to provide more locationally specific and decision-relevant information on connection opportunities.
S2. Group transport agreement with collective CBC governance	U1 (through hub governance); U4	Hub governance	Established through a *groepstransportovereenkomst* (GTO) under the *Energiewet,* enabling coordinated collective response within the hub.
S3. Standardised and ring-fenced compensation framework	U3; U2 (partially)	Curtailment and settlement design	Designed as an extension of the existing curtailment-compensation framework to make compensation triggers, baseline definitions, and settlement terms more predictable ex ante.
S4. Staged access portfolio with hub-coordinated demand aggregation	U2	Access portfolio construction	Derived from staged connection approaches within existing network-operator competences and ACM authority to grant derogations from standard Netcode provisions.

S4: Staged access portfolio with hub-coordinated demand aggregation (U2; access portfolio construction). The GTO coordinator collects letters of intent through a structured open season, producing a demand forecast sufficient to size a preliminary connection offer. The operator then issues a staged TDTR tranche with a pre-agreed expansion option sized to cover both debt-service needs and RFNBO-compliant operating hours. S4 cannot function unless S3 is already in place: without S3's compensation framework already fixed, the staged tranche has no stable revenue floor and letters of intent cannot be anchored to financeable terms. S3 is therefore a precondition for S4's operationalisation, not a parallel arrangement. Even so, S4 depends on offtaker willingness to issue letters of intent before access terms are fixed, and on operator willingness to issue staged agreements against soft demand signals, conditions this study cannot confirm.

The four strategies form a dependency chain. S1 lowers the pre-entry commitment threshold by improving node-level visibility. S2 establishes the GTO coordinator role required for collective CBC governance and for the coordinated demand aggregation on which S4 relies. S3 stabilises the compensation terms that partially relieve U2's contracting circularity. S4 depends on both S2 and S3 to make a staged access portfolio institutionally plausible.

Their exposure to U5 is not uniform. S1 is the most robust, because feeder-level transparency does not depend on any specific tariff outcome or pending regulatory decision. S2 is also relatively robust: GTO constitution is established under the *Energiewet,* with the 1 January 2027 obligation date the main remaining source of uncertainty. S3 is more exposed because ring-fencing depends on ACM decisions still under revision and NFA compensation methodology remains unsettled; S4 inherits this exposure in full, since staged tranches cannot be anchored to financeable terms if S3's compensation baseline remains unresolved.

4.3. Developing two integration pathways

The workshop configuration exercise identified reinforcement credibility and offtake signal strength as the two primary criteria for pathway selection at Cluster 6-type congested nodes. In the workshops, both operated as threshold conditions rather than continuous variables: reinforcement was treated as credible only where a reinforcement project fell within the investment horizon, and offtake was treated as sufficiently strong only where demand could anchor an initial access structure on financeable terms. Configurations were compared against the five decision uncertainties identified in Section 4.1 and tested against the three feasibility criteria defined in Section 3: consistency with existing regulatory authority, compatibility with the CTA variant used, and avoidance of synchronised ramping or equivalent collective congestion effects. Only two of the four logical combinations yielded internally coherent generic configurations. Where both conditions were absent, a flexibility-first pathway was required. Where both were present, a reinforcement-first pathway was viable. Where only one condition held, no generic pathway satisfied all three feasibility criteria, and the coordination arrangement had to be configured case by case using S1-S4 as building blocks.

The two pathways do not introduce new strategies. Rather, they sequence the same four strategies differently and assign them different functions depending on the underlying node conditions. What changes between them is which strategies operate as entry conditions, and which serve mainly as supporting arrangements once a workable foundation already exists. Each pathway is organised around four phases reflecting EH project evolution: initialisation, operational execution, economic evaluation, and optimisation and feedback.

Pathway A—Flexibility-First (Coordinated Non-Firm Access) applies where reinforcement is distant and offtake remains uncertain. Under these conditions, all five uncertainties remain active, and the four strategies do not improve a workable arrangement already in place; they constitute the minimum coordination structure required for one to exist.

The dependency structure is strict. S1 and S2 must be established first: S1 lowers the pre-entry commitment threshold by improving feeder-level visibility, while S2 creates the GTO coordinator role required both for collective CBC governance and for the coordinated demand aggregation on which S4 relies. S3 must precede S4: without standardised compensation terms fixed ex ante, the staged tranche has no stable revenue floor and letters of intent cannot be anchored to financeable terms. S4 therefore depends on both S2 and S3 and is the last strategy activated. All four strategies function as entry conditions in this pathway (Fig. 5).

Workshop testing clarified this sequencing. An early configuration placed S4 before S2 and S3. This failed the settlement-consistency criterion because the staged tranche could not be specified on credible terms without an established compensation framework and a recognised coordinating role. A second configuration treated S2 as optional. This failed the congestion-avoidance criterion, since a CBC activation across co-located hubs without a coordinator could still recreate synchronised load response. S2 was therefore retained as necessary wherever co-location applies. Judging whether a revised configuration satisfied the relevant criterion required researcher judgement as well as participant input, consistent with the interpretive limitation noted in Section 3.

Initialisation. The operator provides feeder-level visibility through S1. Where co-location applies, a GTO coordinator role is established through S2, noting that grid operators are not obligated to offer GTO arrangements until 1 January 2027 (Energiewet, 2024). Compensation terms are then fixed ex ante through S3. Only on that basis does the GTO coordinator conduct a structured open season under S4, collecting letters of intent sufficient to size a preliminary demand forecast and initial connection offer. The developer secures a small firm CTA tranche for essential operations and contracts the remaining capacity through TDTR or NFA against that pre-established compensation framework.

Operational execution. The hub adjusts consumption in response to price signals, renewable availability, and congestion forecasts, using storage where relevant to smooth deliveries. The GTO coordinator manages collective CBC response and helps preserve RFNBO-compliant operating hours where possible. The operator issues day-ahead curtailment notices and settles compensation for verified curtailed MWh against the agreed baseline.

Economic evaluation. Financial performance depends on the interaction between curtailment exposure, compensation reliability, hydrogen price volatility, and the share of hours that remain RFNBO-compliant. If compensation budgets are exhausted before hub compensation is settled, the revenue floor on which non-firm access modelling depends is weakened or removed. Regulatory fluidity remains a cross-cutting risk throughout.

Optimisation and feedback. Operational data on curtailment events, compensation outcomes, hub behaviour, and RFNBO-compliant hour preservation feed back into system planning and later siting decisions. These data also strengthen the node-level evidence base published through S1.

Pathway B—Reinforcement-First (Predominantly Firm Access) applies where reinforcement is credible and offtake is stable. Under these conditions, the coordination problem changes. Grid upgrades reduce U1 directly, and confirmed offtake weakens U2 before the arrangement is assembled. Under these conditions, the strategies do not create the baseline arrangement; they support and stabilise one whose foundations are already in place.

The dependency structure differs from Pathway A in three respects. First, S1 shifts from an entry condition to a supporting arrangement: it improves node visibility but no longer enables commitment on its own. Second, S3 changes function: rather than making staged or non-firm access modellable, it operates mainly as a settlement procedure for infrequent curtailment events. Third, S4 is not required where access is predominantly firm and offtake is already anchored. The one element that remains necessary is S2: wherever co-location applies, a GTO coordinator is still required, because U4 persists regardless of access type and a CBC activation across co-located hubs without coordination

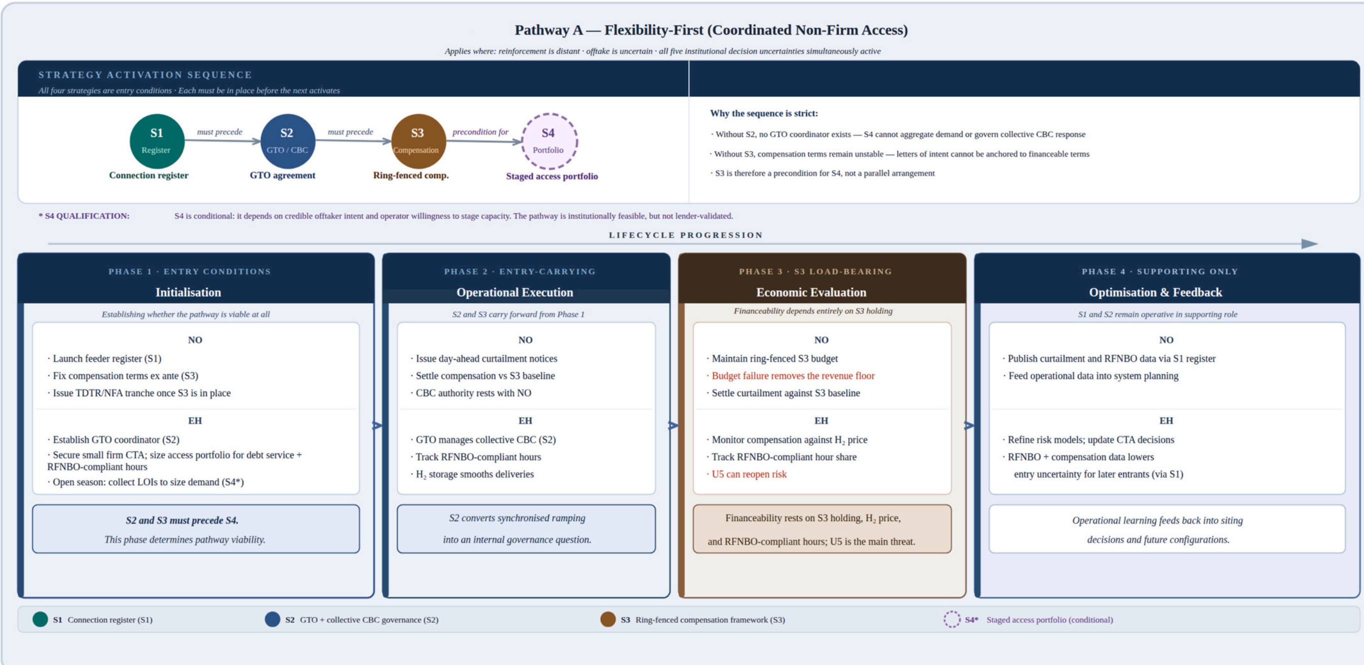

Fig. 5. Pathway A — Flexibility-First (Coordinated Non-Firm Access). EH = Energy Hub; NO = Network operator.

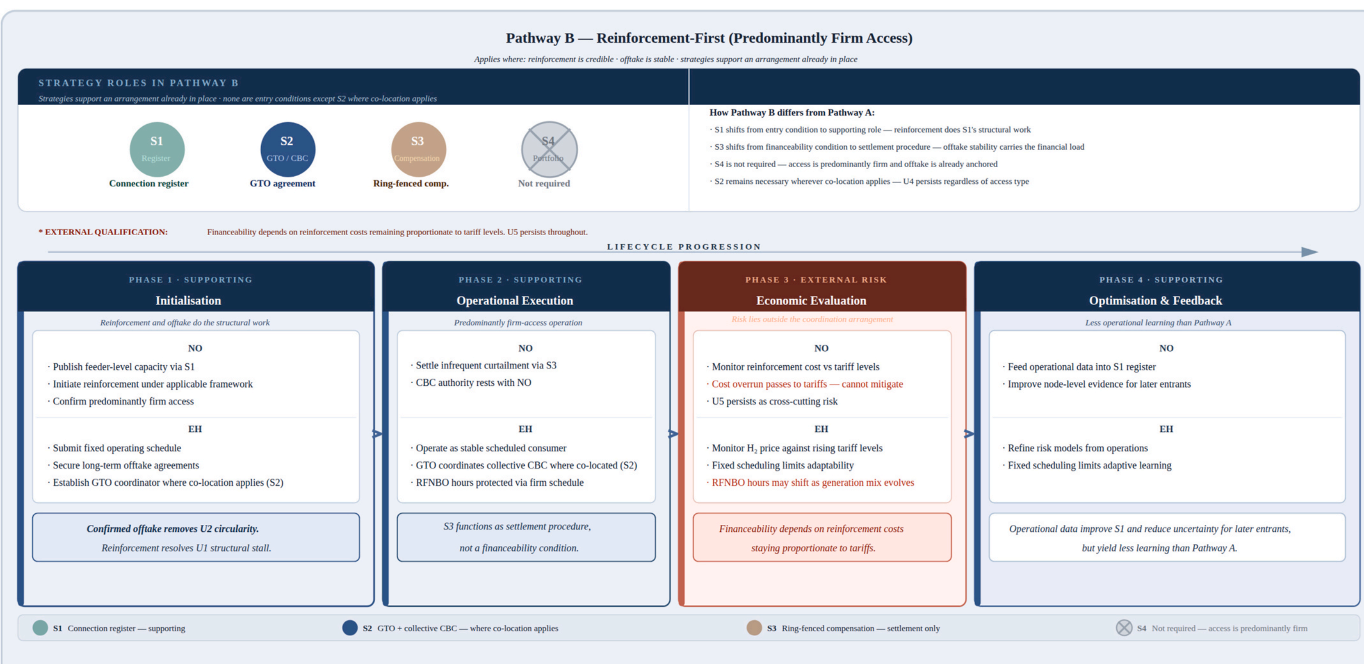

Fig. 6. Pathway B — Reinforcement-First (Predominantly Firm Access). EH = Energy Hub; NO = Network operator.

can still recreate synchronised load response (Fig. 6).

Initialisation. The operator publishes feeder-level information through S1 and initiates grid reinforcement under the applicable regulatory framework. The developer submits a fixed or predictable operating schedule and secures long-term offtake agreements. Where multiple hubs co-locate, S2 is established to provide the GTO coordinator role.

Operational execution. The hub operates as a relatively stable baseload or scheduled consumer. Curtailment events are expected to be infrequent and are settled through predefined arrangements under S3, which here functions mainly as a settlement procedure rather than as a financeability condition. Where co-location applies, S2 remains operative to coordinate collective CBC response.

Economic evaluation. The main risk is no longer the absence of a modellable access portfolio but the effect of reinforcement costs on tariffs and long-term competitiveness. Fixed scheduling may also reduce the hub's ability to adapt to evolving renewable generation patterns, with implications for RFNBO-compliant hour availability. Regulatory fluidity remains relevant, particularly where reinforcement cost allocation and tariff pass-through are still under revision.

Optimisation and feedback. Operational data feed back into the dynamic connection register and improve the evidence base available to later entrants. However, because this pathway relies more on reinforcement and stable scheduling than on adaptive coordination, it generates less operational learning than Pathway A.

The two pathways therefore deploy the same four strategies with different dependency structures. Table B1 in Appendix B summarises the comparison across the two pathways. In Pathway A, all four strategies act as entry conditions: S1 and S2 establish the institutional foundation, S3 makes non-firm access modellable, and S4 builds the staged access portfolio on that basis. In Pathway B, reinforcement credibility and offtake stability do much of the structural work: S1 remains useful but supportive, S2 remains necessary wherever co-location keeps U4 active, S3 shifts to a settlement role, and S4 is unnecessary.

The qualifications attached to the two pathways also differ. Pathway A carries an internal qualification. It depends on behavioural conditions linked to S4, especially offtaker willingness to commit before access terms are fixed and operator willingness to issue staged tranches against soft demand signals. This study cannot confirm either condition. Pathway B carries a more external qualification: its relevance to financeability depends on reinforcement costs remaining proportionate to tariff levels, a condition outside the coordination arrangement itself. In both pathways, the analysis identifies institutionally feasible configurations capable of reducing decision uncertainty under current Dutch conditions. Because financiers were absent from both workshops, neither pathway should be read as a lender-validated bankable model.

5. Discussion

The instruments governing grid access, curtailment compensation, and hub operation were designed separately, for different regulatory problems, and no institutional arrangement currently governs the interface between them. Improving one instrument relocates uncertainty rather than reducing it. Standardising compensation without establishing collective CBC governance leaves synchronised load response unresolved; improving feeder-level transparency without stabilising compensation terms leaves the offtake-access circularity similarly intact. The core problem is therefore not the weakness of any one instrument, but the absence of governance at the interface between instruments, which is precisely where investment decisions stall.

Transaction cost economics correctly diagnoses the problem but requires the remedy to be specified at a different level. Williamson (1985) identifies asset specificity, incomplete contracting, and bilateral governance failure as the conditions under which markets struggle to coordinate investment, and points to hierarchical or hybrid governance as a response. The findings confirm the diagnosis. The three conditions are present, but they are not independent: each blockage reinforces the others across the EH lifecycle. Addressing them sequentially through progressively more complete contracts does not close the loop; it shifts where the loop reopens. The relevant unit of analysis is therefore not the bilateral contract alone, but the coordination arrangement spanning the full lifecycle. The design question is not which instrument best addresses each condition separately, but which arrangement governs their interdependence. Even well-designed individual instruments a TDTR, a ring-fenced compensation framework, or a GTO remain insufficient unless their interaction is explicitly governed.

The substation-scale collective action problem identified in this paper is not a failure of bilateral contract design at larger scale it is a structurally different problem that Ostrom's framework was not designed to address. Ostrom (1990) addresses deliberate and repeated shared use by a bounded group whose members can recognise one another, monitor behaviour, and develop rules and sanctions over time. Hubs do not intentionally form a collective around load reduction; they become one indirectly when separate actors respond in similar ways to the same signal. Collective membership is not self-recognised in advance, and no actor automatically has standing to coordinate aggregate behaviour. This explains why the GTO coordinator role is important: it pre-constitutes the collective before the coordination problem becomes operational. Flexible-asset coordination at congested nodes therefore requires a more anticipatory form of institutional design than classic common-pool settings assume.

Hourly temporal correlation under the RFNBO Delegated Regulation has been analysed as a certification constraint; the findings show it also functions as a governance constraint, a dimension that has received limited attention in the literature. Because the minimum viable access portfolio must satisfy both the hours needed for debt service and the hours needed for RFNBO-compliant production, hourly matching creates a mutual dependency between the access structure, the curtailment-compensation framework, and the offtake agreement. None of these instruments is designed to be calibrated against the others. The certification framework and the grid-access framework were developed on separate regulatory tracks, and that separation has not been bridged at node level. The result is a coordination requirement aligning the access window with the eligibility window across interdependent instruments that currently lacks an institutional home. The challenge is not legislative clarification but institutional design at node level. The standardised compensation framework and staged access portfolio developed in this paper are a proposed response to that gap. Where Member States implement hourly correlation from 2030 without comparable coordination mechanisms, both revenue uncertainty and the institutional barriers to financeability are likely to increase. The underlying structural logic is not uniquely Dutch, though cross-jurisdictional empirical testing is required before this can be generalised.

Four scope conditions define precisely what the findings establish and where the evidence runs out. The pathways demonstrate institutional feasibility within existing Dutch regulatory authority; whether project-finance providers would regard either configuration as commercially bankable remains a separate question requiring direct research with lenders. The absence of financier perspectives from both workshops is the most important limitation in the evidence base. The staged access portfolio carries weaker evidential standing than the other three strategies not because the mechanism is implausible, but because it depends on prior commitments by offtakers and operators whose terms remain only partially specified. The Flexibility-First pathway inherits that qualification directly. The Reinforcement-First pathway's constraints are external rather than internal: its viability depends on reinforcement costs remaining proportionate to tariff levels, a condition outside the coordination arrangement. The underrepresentation of smaller hub developers and hydrogen end-users leaves open whether the proposed strategies are equally accessible to actors without direct leverage at the hub-network interface.

6. Conclusions

The practical significance of the two-pathway finding lies not only in what the pathways contain but in when the choice between them can be made. Reinforcement credibility and offtake signal strength the two conditions that determine which pathway applies are both observable before capital is committed. A developer entering the Flexibility-First pathway without the GTO coordinator arrangement and the ring-fenced compensation framework already in place does not reduce risk; it inherits all five uncertainties without the institutional structure required to govern them. For ACM, ring-fencing the compensation budget is not a refinement of the standardised compensation framework but its precondition. A standardised methodology that draws on the general congestion budget provides no stable revenue floor; hub developers cannot model against a floor that may be exhausted before their compensation is settled. For TSOs and DSOs, feeder-level queue transparency and GTO constitution at Cluster 6 nodes do not require legislative change and are achievable within existing authority. Grid operators are not obligated to offer GTO arrangements until 1 January 2027, so projects reaching co-location before then operate without the collective governance mechanism that makes the Flexibility-First pathway viable. For hub developers, identifying which pathway applies before committing capital is itself a governance act. The two conditions reinforcement credibility and offtake signal strength are observable at the point of decision, and mistaking a Flexibility-First situation for a Reinforcement-First one compounds rather than reduces risk. Dedicated research with project-finance providers to test whether either pathway is commercially bankable is the most important next step the paper cannot take on its own evidence. Whether the behavioural conditions the staged access portfolio requires hold at operating Cluster 6 nodes must be tested empirically before the Flexibility-First pathway can be recommended without qualification. Whether the four-requirement framework transfers to other Member States implementing hourly temporal correlation under congested-grid conditions must be tested in at least one non-Dutch context before the structural argument advanced here becomes a general claim.

CRediT authorship contribution statement

Mahshid Hasankhani: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jan-Carel Diehl:** Writing – review & editing, Validation, Methodology. **Sine Celik:** Visualization, Validation, Methodology. **Jo van Engelen:** Writing – review & editing, Writing – original draft, Validation, Methodology.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Claude, an AI assistant developed by Anthropic, to support the writing and editing process. All AI-assisted content was subsequently reviewed, revised, and verified by the authors, who retain full responsibility for the accuracy, integrity, and conclusions of the published work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices.

These appendices document the empirical materials supporting Phases 2 and 3 of the study. Appendix A presents the interview sample and the analytical framework used to structure data collection and coding, including the four coordination requirements that served as the parent codes of the initial codebook. Appendix B documents the participatory workshops through which the four coordination strategies were configured, stress-tested, and refined into two node-level integration pathways.

Appendix A. Interview Sample and Analytical Framework

Sampling was organised around positional coverage of the operator–developer governance boundary rather than proportional stakeholder representation. Because direct representation of project financiers, hydrogen end-users, and smaller hub developers remained limited, advisory and infrastructure-development actors were included where they participated in project development, coordination, or implementation at that boundary. This sampling logic and its implications for the evidential standing of the results are discussed in Section 3.

Table A1
Interview overview and positional coverage

Interview	Approx. duration	Interview type	Role/title	Organisation	Actor position in governance boundary
1	~30 min	Semi-structured	Hydrogen/Energy Specialist	Gasunie (TSO)	Network operator
2	~30 min	Semi-structured	Energy System Researcher	R&D/strategic advisory and infrastructure development partner	Advisory/intermediary
3	~30 min	Semi-structured	Energy System Researcher	R&D/strategic advisory and infrastructure development partner	Advisory/intermediary
4	~40 min	Semi-structured	System Strategy Lead	Stedin (DSO)	Network operator
5	~30 min	Semi-structured	Regulation & Strategy Adviser	Stedin (DSO)	Network operator
6	~35 min	Semi-structured	Project Leader, Hydrogen Transition	TenneT (TSO)	Network operator
7	~30 min	Semi-structured	Team Lead, Electricity Research	R&D/strategic advisory and infrastructure development partner	Advisory/intermediary
8	~30 min	Semi-structured	Team Leader, Energy & Fuels	Strategic advisory and infrastructure development partner	Advisory/intermediary
9	~30 min	Semi-structured	Hydrogen Project Lead	Alliander (DSO)	Network operator
10	~30 min	Semi-structured	Project Engineer	TenneT (TSO)	Network operator
11	~40 min	Semi-structured	Consultant/Project Expert	Strategic advisory and infrastructure development partner	Advisory/intermediary
12	~60 min	Semi-structured	Market Analyst	Stedin (DSO)	Network operator

(*continued on next page*)

Table A1 (*continued*)

Interview	Approx. duration	Interview type	Role/title	Organisation	Actor position in governance boundary
13	~60 min	Semi-structured	Project Engineer	Stedin (DSO)	Network operator
14	~45 min	Semi-structured	Consultant/Project Expert	Alliander (DSO)	Network operator
15	~40 min	Semi-structured	Consultant/Project Expert	Alliander (DSO)	Network operator

Table A2
Interview structure — analytical focus and illustrative questions per coordination requirement.
Each interview was structured around the four coordination requirements in sequence. For each requirement, questions covered three areas: the actor's experience of the relevant decision boundary; the instruments they regarded as available; and the conditions under which those instruments had or had not functioned.

Coordination requirement	Analytical focus	Illustrative questions
Siting	Node conditions and information availability before capital commitment	What information is currently missing or unreliable for siting decisions? What coordination would be needed for anticipatory or shared infrastructure planning?
Access portfolio construction	Choice of access mix under tariff, hour, and RFNBO constraints	Which elements of access choice remain uncertain before contracts are signed? How can demand and offtake uncertainty be incorporated into access design?
Curtailment and settlement design	Treatment of curtailment risk under constrained access conditions	Which settlement terms must be known in advance for access to be modellable? What compensation arrangements are seen as credible by hub developers and operators?
Hub governance	Collective response and cost allocation across co-located assets	Which decisions require commitments no single actor can currently make unilaterally? What governance arrangements are needed to manage overlapping peak use and aggregate CBC response?

Table A3
Initial coding framework — parent codes, child codes, definitions, and typical transcript indicators.
The four coordination requirements in Table A2 also served as the parent codes of the initial coding framework. Child codes specified the more concrete institutional blockages expected in practice, drawn from Dutch regulatory documents, network-operator publications, and the wider energy-governance literature. The codebook remained open to revision at the child-code level and to new higher-order specifications throughout the analysis; no interview material required replacement of the four parent codes. Passages meeting the classification rule were additionally tagged by decision stage (pre-entry; portfolio design and contracting; operation and settlement; cross-cutting) and governance level (internal hub; bilateral hub–operator; substation-scale collective; cross-level).

Parent code	Illustrative child codes	Definition	Typical transcript indicators
Siting	feeder-level capacity visibility; queue position; reinforcement timing; contingent commitment	Uncertainties affecting node choice before irreversible capital commitment	Missing or unreliable capacity information; inability to assess node risk before commitment; absence of a mechanism for conditional entry
Access portfolio construction	firm/TDTR/non-firm choice; useable hours; offtake dependence; RFNBO-compliant hours	Uncertainties affecting the selection and sizing of access arrangements	Circular dependency between access choice and offtake; difficulty sizing tranches without confirmed demand; constraints arising from RFNBO-compliant hour overlap
Curtailment and settlement design	compensation trigger; baseline calculation; notice window; settlement verification	Uncertainties affecting the valuation and treatment of curtailment risk	Unstable or locally negotiated compensation terms; inability to model curtailment cost ex ante; local variation in compensation availability
Hub governance	collective CBC response; synchronised ramping; coordinator role; cost allocation	Uncertainties affecting collective coordination across co-located assets	Aggregate ramping risk; absence of a recognised coordinating role; inability to bind co-located parties through bilateral contracts

Appendix B. Participatory Workshops — Design, Procedure, and Outputs

Aim. To test whether the four coordination strategies developed in the design-synthesis step on the basis of the five decision uncertainties identified in Phase 2 could be configured into operationally coherent and legally feasible integration pathways under defined node conditions, and to identify where proposed configurations failed and why. The workshops served a confirmatory and stress-testing function, not a generative one: strategies came from Phase 2 and were not open to replacement during the workshops.

Participants. Workshop 1 comprised one researcher and two network operators (TSO/DSO). Workshop 2 comprised one business-park infrastructure manager, one network operator, and three researchers.

Materials and boundary conditions. Sessions ran on Miro using pre-built boards structured around the Phase 2 analytical frame. Board parameters reflected: Cluster 6 node conditions (available capacity, queue position, reinforcement timeline); EH size 50–200 MW; RFNBO Delegated Regulation hourly matching obligation; CTA menu (firm/TDTR/non-firm); curtailment-compensation constructs (notice windows, baselines, settlement rules); storage buffering assumptions; and congestion profiles. Boards were organised around the four EH lifecycle phases used throughout the paper: Initialisation; Operational Execution; Economic Evaluation; Optimisation and Feedback. Because the boards were pre-structured around the Phase 2 framework, participants could refine and challenge configurations within that frame, but the workshop design did not provide a basis for independent disconfirmation of the underlying Phase 2 diagnosis. The workshops are therefore best understood as a structured elaboration of Phase 2 findings rather than independent validation of them.

Procedure (90–120 min each). Each session followed a fixed three-stage procedure consistent with the research design described in Section 3.

Stage 1: Node specification: participants agreed the operating envelope for the configuration exercise, including feasible capacity slices across firm/TDTR/non-firm, applicable ramping constraints, storage assumptions, and the CTA variant most appropriate to the node conditions.

Stage 2: Strategy arrangement: participants arranged the four strategies into candidate pathway logics, deciding which function as necessary entry conditions and which as supporting arrangements, and in what sequence across the four EH lifecycle phases.

Stage 3: Feasibility testing: each candidate configuration was tested against three criteria: (a) role allocations must not require either party to act outside its existing regulatory authority; (b) settlement assumptions must be consistent with the CTA variant used; and (c) operational rules must not recreate synchronised ramping or equivalent collective congestion effects at substation scale. Configurations failing one or more criteria were revised iteratively within the session. Where no revision could satisfy all three criteria, the configuration was dropped. Only configurations satisfying all three in their final form were retained.

Data. Annotated Miro boards, audio transcripts, facilitator notes, and parameter sheets covering connection type, capacity levels, curtailment rules, and cost-sharing logic.

Analysis. Workshop outputs were analysed by comparing retained configurations against the five decision uncertainties identified in Phase 2 to identify coherent strategy combinations and sequencing dependencies. Each retained configuration was checked against the three feasibility criteria before acceptance. Reinforcement credibility and offtake signal strength were confirmed as the conditions most consistently determining which configurations survived. For pathway selection, both were treated as binary conditions: either credibly present within the investment horizon or not, with no intermediate states requiring a distinct strategy configuration. This is reported and substantiated in Section 4.3.

Because financiers were absent from both workshops, financeability claims are indicative rather than confirmed throughout. The pathways establish institutional feasibility within existing Dutch regulatory authority; they do not establish lender-validated bankability.

Table B1
Comparison of Pathway A and Pathway B

Comparison dimension	Pathway A — Flexibility-First	Pathway B — Reinforcement-First
Entry conditions	Reinforcement is distant, offtake is uncertain, and all five uncertainties are active; S1–S4 are required as entry conditions.	Reinforcement is credible and offtake is stable; S1 supports visibility, S2 remains necessary where co-location applies, S3 operates mainly as settlement support, and S4 is not required for pathway viability.
Contract structure	Small firm CTA tranche combined with TDTR/NFA tranches; ring-fenced compensation under S3; S3 is a precondition for S4.	Predominantly firm access; fixed operating schedule; long-term offtake strengthens conditions relevant to financeability.
Curtailment role	Curtailment is priced and actively managed through day-ahead CBC notices; compensation is settled under S3, which functions as a financeability condition.	Curtailment becomes infrequent once primary congestion is relieved; it is settled under predefined compensation rules, with S3 functioning mainly as a settlement procedure.
Coordination mechanism	S1 remains active; a phased-capacity coordination platform is used; a GTO coordinator manages collective CBC response under S2.	S1 remains active; S2 is applied where hubs are co-located; otherwise, coordination relies on static schedules without an active dispatch platform.
RFNBO compliance	Internal allocation rules protect RFNBO-compliant hours; staged tranches are sized to cover both debt service and RFNBO-compliant operating hours.	Compliance is protected mainly through firm-access scheduling; internal allocation rules remain available where curtailment occurs.
Evidential standing	S1–S3 are supported across network-operator participants and actors closer to project-development roles; S4 is analytically assembled and therefore has weaker evidential standing.	S1–S3 are supported across network-operator participants and actors closer to project-development roles; S4 is not required for pathway viability.
Primary risk	Compensation-funding instability and offtaker reluctance to commit before access conditions are fixed.	Reinforcement cost overruns and tariff pass-through.
Financeability	Financeability is treated as a property of the coordination arrangement and remains indicative, with direct qualification from S4.	Financeability is jointly shaped by the coordination arrangement and external reinforcement and tariff conditions, and remains indicative.

Data availability

Data will be made available on request.

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