Orient Academies


# Regulatory Grade Constraint Accounting for Concurrent Renewable Infrastructure Deployment and Operation

Nadir Bouziane[1], Samir Touati[2]

Abstract
Renewable energy portfolios are increasingly deployed as dense, heterogeneous infrastructures whose operational and societal constraints cannot be managed effectively through project-by-project approvals and periodic compliance reporting alone. As penetration rises, governance must accommodate time-varying grid limits, land-use and biodiversity constraints, community disturbance thresholds, and climate-driven hazards that alter both risks and acceptable operating envelopes. This paper proposes a constraint-budget ledger (CBL) as a regulatory-grade technical substrate that represents diverse obligations as consumable budgets and binds their use to verifiable lifecycle events. The core contribution is a portfolio-scale accounting architecture that treats constraints as scarce resources allocated across assets, time, and jurisdictions, enabling consistent decision-making under concurrency, delegation, and policy revision. The CBL unifies planning-stage reservations, construction-stage conversions, and operations-stage consumption into a single auditable record that supports adaptive updates while preserving historical interpretability. The design specifies typed budget instruments for physical capacity, reliability services, ecological exposure, and community externalities; transaction semantics for reservation, release, and reallocation; and verification workflows that reconcile telemetry, monitoring data, and administrative actions without forcing indiscriminate disclosure. The approach is intended to reduce administrative latency and dispute frequency by making trade-offs explicit, quantifying cumulative impacts continuously, and providing bounded transparency to stakeholders. The paper details the ledger object model, the policy compilation workflow, mechanisms to manage strategic behavior and intermediary involvement, and an evaluation methodology based on stress scenarios coupling policy change, climate hazards, and grid contingencies.

[1] University of Tindouf, Department of Environmental Economics and Climate Policy, Boulevard Emir Abdelkader 14, Tindouf 37000, Algeria
[2] University of Khenchela, Department of Sustainable Development and Resource Economics, Route de Batna 08, Khenchela 40000, Algeria

## Contents

1

1 Introduction 1
2 Portfolio Constraint Accounting Under Nonstationarity 3
3 Constraint-Budget Ledger Architecture 5
4 Policy Semantics, Evidence Binding, and Assurance Under Intermediation 8
5 Strategic Behavior, Regulatory Pitching, and Anti-Gaming Controls 10
6 Deployment: Interoperability, Privacy, and Intermediary Integration 12
7 Evaluation Methodology and Stress Scenarios 14
8 Conclusion 16
References 16

## 1. Introduction

Energy transitions at scale are no longer defined only by the physics of integrating variable resources; they are defined by the capacity of institutions and technical systems to manage cumulative constraints across thousands of decisions that must remain consistent over long lifetimes [1]. A modern renewable portfolio is a patchwork of assets, contracts, control systems, environmental commitments, and negotiated community conditions. Each element carries obligations that were often articulated at different times, by different authorities, using different evidentiary standards, and with different assumptions

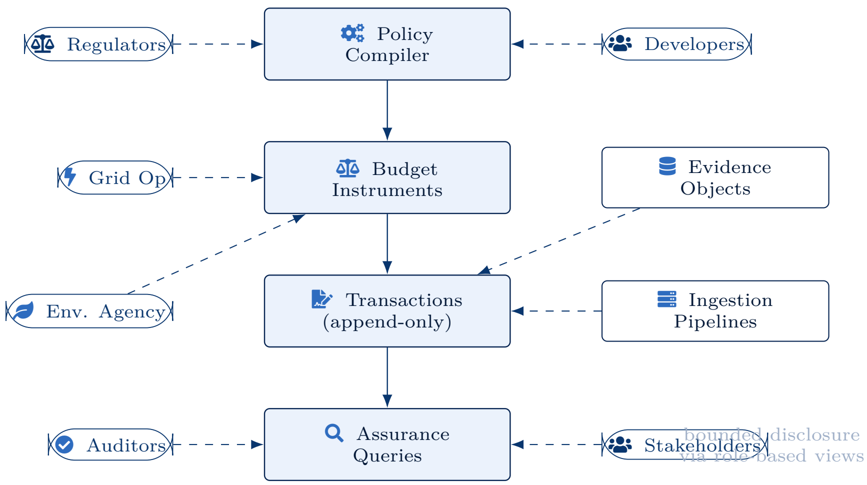


Figure 1. Constraint-Budget Ledger (CBL) portfolio governance stack: policy compilation mints typed budget instruments, transactions record reservations/allocations/consumption with integrity, and assurance queries expose portfolio state. Evidence objects and ingestion pipelines bind operational and administrative events to ledger updates under role-scoped visibility.

about how operation would unfold. When penetration is low, inconsistencies can be absorbed through ad hoc interpretation, conservative buffers, and local negotiation. When penetration is high, those workarounds become a dominant cost. Small semantic differences in a curtailment condition can multiply into large curtailment volumes [2]. A monitoring obligation that is interpreted differently across jurisdictions can trigger asymmetric enforcement and legal contestation. A siting mitigation that was plausible under one climate baseline can become ineffective under another, creating pressure for retrofits and renewed approvals.

The technical gap is not primarily a lack of data. Power systems already generate extensive telemetry, and environmental governance already produces extensive documentation. The gap is the absence of a unified, machine-actionable representation of constraints that can be tracked as cumulative resources under concurrency [3]. Grid constraints are inherently cumulative because multiple assets share network capacity and stability margins. Land-use and biodiversity constraints are cumulative because multiple projects draw from shared ecological carrying capacities and shared public tolerance for landscape change. Community externalities are cumulative because repeated local disruptions change perceptions of legitimacy and can cause escalating political responses. Climate hazards introduce an additional layer of cumulativity because correlated failures, such as heatwaves or wildfire events, can simultaneously reduce generation availability, increase demand, and constrain maintenance and emergency response.

This paper advances an independent thesis: scalable renewable governance requires continuous, portfolio-level accounting of constraints as budgets that can be reserved, consumed, released, and reallocated under explicit rules, with verifiable binding to evidence and operational events. Instead of treating each permit, interconnection agreement, and mitigation plan as a static artifact, the proposed approach treats them as sources of budget instruments that quantify allowable use of scarce resources [4]. The resulting constraint-budget ledger (CBL) is not a financial ledger, but it borrows ledger primitives to solve governance problems of concurrency, traceability, and cumulative impact management. The ledger provides a single technical locus where diverse constraints are represented in typed form, where their use is recorded in a time-ordered manner, and where the current portfolio assurance state can be computed from the ledger history under the policy version that was in force at any given time.

The CBL concept is motivated by a mismatch that is increasingly visible in climate policy: renewable energy is widely framed as mitigation infrastructure, while its role in adaptation and resilience is often treated as secondary, leaving deployment decisions insufficiently aligned with diversification and resilience needs [5]. When resilience objectives are not operationalized into enforceable constraints, they remain aspirational, and systems drift toward short-term mitigation metrics that can be counted easily. A ledger-based approach makes resilience-relevant constraints legible as budgets, such as geographic diversification targets, critical-load coverage budgets, or hazard-exposure ceilings that can be consumed by projects that concentrate risk.

The objective is not to mechanize normative choice [6]. Institutions still decide what budgets exist, what units they use, what evidence is acceptable, and what trade-offs are permissible. The objective is to provide a technical architecture that makes those choices implementable at scale, reduces ambiguity under delegation,

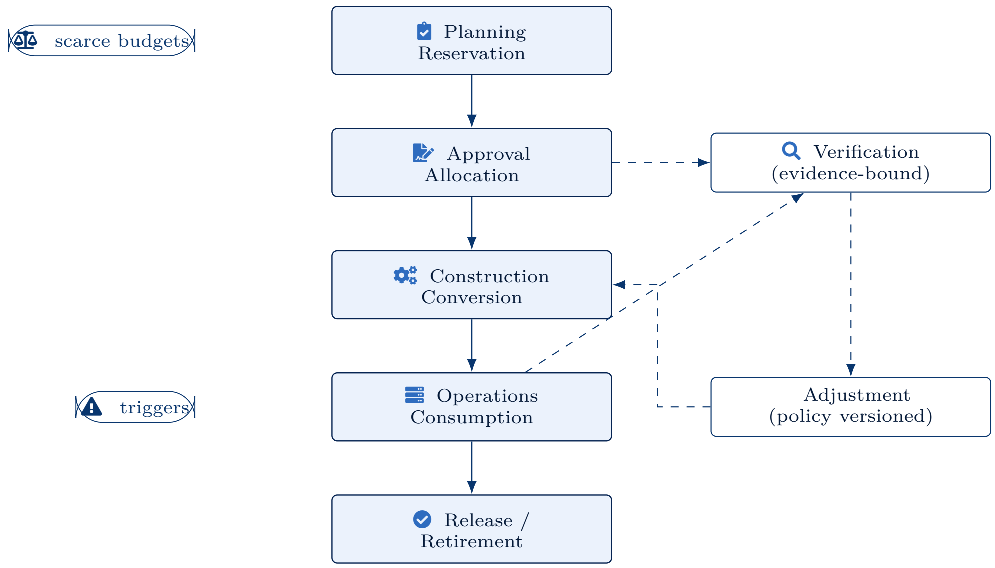


Figure 2. Budget lifecycle semantics across concurrent portfolio activity: planning reservations prevent over-commitment, approvals allocate instruments, construction converts obligations across phases, operations consume budgets via verifiable events, and releases retire or return unused capacity. Policy updates and interpretive revisions are recorded as adjustment transactions without rewriting history.

and supports adaptive updates without erasing history. The remainder of the paper formalizes the governance problem as portfolio constraint accounting, specifies the CBL architecture and transaction semantics, describes how policy and evidence bind to ledger entries, analyzes strategic behavior and intermediary roles, proposes implementation practices for interoperability and privacy, and outlines an evaluation methodology grounded in stress scenarios rather than idealized steady-state assumptions.

## 2. Portfolio Constraint Accounting Under Nonstationarity

A renewable portfolio operates across multiple constraint domains that differ in measurability, enforceability, and temporal structure. Grid-domain constraints include interconnection limits, thermal ratings, voltage and frequency envelopes, fault ride-through requirements, ramping limits, protection coordination constraints, and stability margins that depend on inertia, short-circuit strength, and control interactions [7]. These constraints often vary with topology, dispatch conditions, and contingency sets, and they can change as upgrades occur or as additional assets connect. Environmental-domain constraints include habitat protection buffers, avian risk mitigation commitments, seasonal operating windows, noise ceilings, shadow-flicker limits, runoff and erosion controls, and decommissioning and waste-handling obligations. Social-domain constraints include procedural obligations for engagement, community benefit agreements, visual impact mitigation, and locally negotiated operating conditions. Market-domain constraints include deliverability criteria, settlement rules, performance obligations for ancillary services, and penalties for deviations, which can indirectly shape physical operation and therefore affect environmental and community impacts.

Traditional governance treats these domains as separable workflows, each producing its own artifacts and approvals. In high-penetration systems, the separations fail because the constraints interact and because multiple projects compete for shared headroom in each domain [8]. A grid operator may prefer curtailment at a specific node during congestion, but that curtailment may conflict with an environmental requirement that restricts operational modulation during sensitive wildlife periods if modulation increases disturbance. Conversely, an environmental condition may require nighttime shutdowns that shift generation into daytime peaks, increasing local voltage excursions in distribution networks. A community agreement may require noise-limited operation that caps wind turbine speed, reducing expected output and altering deliverability assumptions in market contracts. When these interactions are managed through narrative conditions and informal coordination, the system becomes difficult to reason about and easy to contest.

Nonstationarity worsens the problem [9]. Climate hazards and socio-political baselines evolve in ways that invalidate earlier assumptions. Heatwaves can tighten thermal limits, reduce inverter capacity through derating, and increase demand, compressing reliability margins. Wildfire risks can induce planned shutoffs of lines, changing feasible power flows and interrupting telemetry

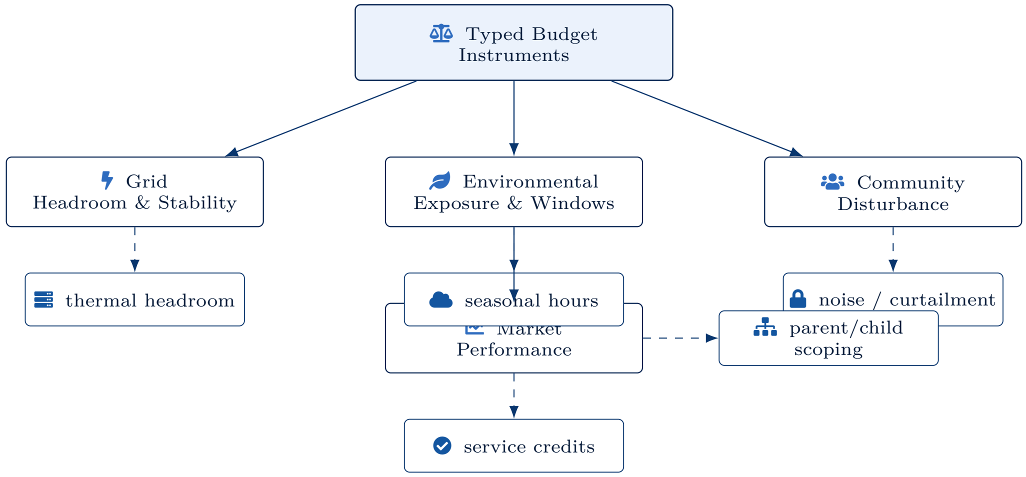


Figure 3. Budget instrument taxonomy for portfolio accounting: constraints are represented as typed instruments with explicit scope, units, and validity. Domain types (grid, environmental, community, market) admit different transaction semantics, while hierarchical scoping enables cumulative accounting across overlapping jurisdictions and sub-portfolios.

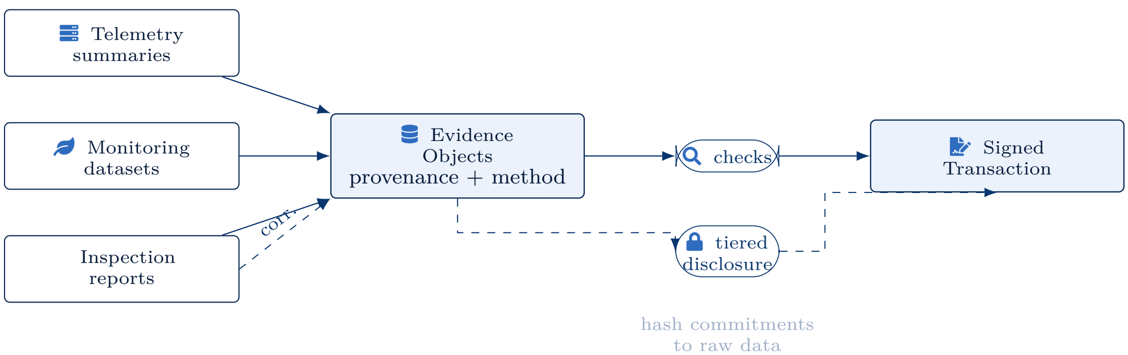


Figure 4. Evidence binding workflow: operational and administrative sources are normalized into evidence objects carrying methodology and provenance metadata, verified through lightweight checks, and then bound to signed ledger transactions. Confidentiality is preserved by tiered payload disclosure and cryptographic commitments enabling later audit without broad raw-data exposure.

and communications. Flood events can change land stability and access routes, affecting maintenance and emergency response. Environmental baselines shift as migration patterns change, vegetation changes, and cumulative development alters ecosystems, affecting the validity of earlier impact assessments and mitigation plans. Social baselines also shift as cumulative development changes local attitudes toward additional projects and as policy priorities change [10]. A governance system that relies on static approvals becomes brittle and prone to emergency exceptions, while a governance system that constantly reopens decisions becomes slow and politically unstable.

Portfolio constraint accounting reframes the problem by focusing on shared scarcity and cumulative effects. Instead of asking whether each project is compliant in isolation, the system asks whether the portfolio's cumulative consumption of constrained resources stays within acceptable budgets and whether deviations are detected early enough to trigger adaptive responses. The approach is analogous to capacity planning in compute systems, where multiple services share limited resources and where safe operation depends on reserving headroom for contingencies. In the renewable governance context, the shared resources are not only thermal capacity and reactive power margins but also ecological disturbance capacity, land conversion ceilings, and community tolerance thresholds that are socially negotiated [11].

A key difficulty is heterogeneity in measurability. Some constraints are direct and measurable, such as a feeder thermal limit or a noise level at a receptor point, while others are indirect, such as an obligation to maintain "minimal disturbance" or to support "public legitimacy." Portfolio accounting does not require all constraints to be equally quantifiable. It requires that each constraint domain provide a budget instrument whose semantics are explicit, including what it measures, what evidence supports its use, what uncertainty is acceptable, and what governance actions are triggered when it is close

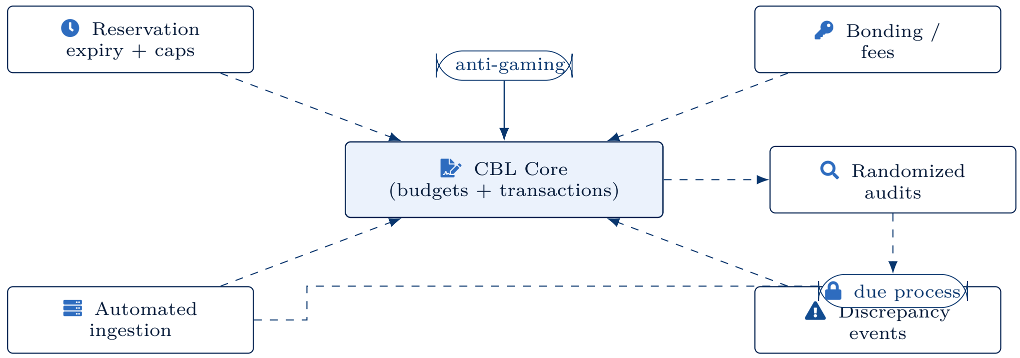


Figure 5. Strategic-behavior controls around scarce constraint budgets: reservation hoarding is limited through expiry and caps, speculative over-claims are discouraged through bonding/fees, consumption is hardened via automated ingestion, and discrepancies generate explicit events that feed targeted audits. The ledger's integrity and attributable signatures support contestation with procedural safeguards.

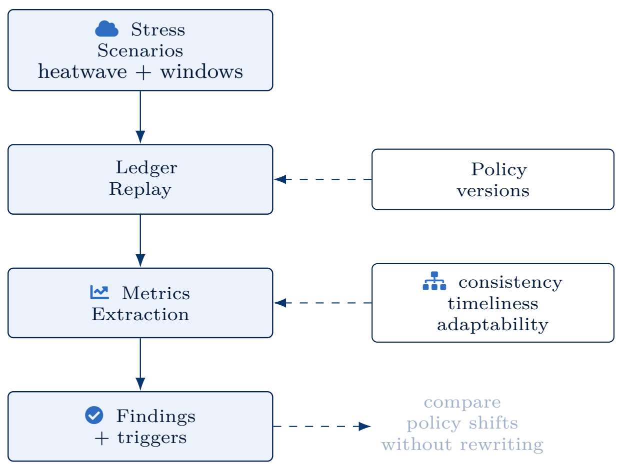


Figure 6. Evaluation loop using coupled stress scenarios: synthetic or historical events drive ledger replays under specific policy versions, metrics quantify determinism, latency, dispute tractability, and adaptation behavior, and outputs identify exhaustion proximity and governance trigger performance across interacting constraint domains.

to exhaustion. Where quantification is weak, the ledger can still represent budgets in coarse units, such as categorical risk credits tied to defined monitoring and review triggers. The ledger's value is then not numerical precision but the ability to make cumulative exposure visible, to reduce silent accumulation of untracked obligations, and to force explicit decisions when scarcity is reached [12].

The unit of analysis becomes the budget, not the document. A permit condition becomes a rule that mints an environmental budget, such as allowable seasonal operating hours under certain modes, and specifies how that budget is consumed by operations. An interconnection agreement becomes a rule that mints grid headroom budgets, such as ramp-rate envelopes or reactive capability obligations, and specifies how telemetry and tests consume or replenish them. A community agreement becomes a rule that mints disturbance budgets, such as allowable nighttime operation profiles, and specifies how measured outcomes consume those budgets. In this way, governance becomes a continuous, portfolio-scale control loop where the ledger is the state representation and where institutional actions correspond to budget adjustments rather than to ad hoc reinterpretations.

## 3. Constraint-Budget Ledger Architecture

The constraint-budget ledger (CBL) is defined as a versioned, append-only record of typed budget instruments and budget transactions [13]. The ledger is not inherently a blockchain; it can be implemented as a federated registry with cryptographic integrity, or as a centralized authoritative system with strong audit logging. The essential property is that ledger entries are immutable once committed, and that the current budget state can be derived deterministically from ledger history under a specified policy version. This property enables independent verification and dispute resolution, because stakeholders can replay the ledger and observe where budgets were minted, transferred, consumed, or released.

A budget instrument is a typed object that repre-

Table 1. Portfolio constraint domains and their cumulative characteristics

| Domain | Scope examples | Representative constraints | Cumulative drivers |
|---|---|---|---|
| Grid | Transmission and distribution networks, substations | Interconnection limits, thermal ratings, voltage and frequency envelopes, fault ride-through, ramp-rate limits | Multiple assets share headroom and stability margins; upgrades and new connections change feasible operating space |
| Environmental | Habitats, watersheds, migration corridors, protected zones | Habitat buffers, avian risk measures, seasonal operating windows, noise ceilings, shadow flicker limits, runoff controls | Projects draw from shared ecological carrying capacity and long-lived land-use changes |
| Social / Community | Host communities, municipalities, local institutions | Engagement duties, community benefit agreements, visual impact mitigation, negotiated operating profiles | Repeated disturbances affect legitimacy, tolerance thresholds, and political responses |
| Market / System Services | Energy and ancillary service markets, balancing areas | Deliverability rules, performance obligations, penalties, flexibility and reliability requirements | Contracted performance shapes physical operation and indirectly accumulates local impacts |

sents an allowance or obligation with measurable or reviewable semantics. Each instrument has a scope, such as a geographic boundary, asset set, or jurisdiction; a validity period; a unit definition; a minting authority; and a policy reference that defines the rules under which it exists [14]. Budget instruments can represent positive allowances, such as a permitted level of ecological disturbance, or negative obligations, such as a required amount of flexibility service provisioning. Instruments can also represent conditional allowances that are active only under certain states, such as seasonal windows or hazard modes. The instrument type determines which transaction types are valid. For example, a land conversion budget might be consumed by construction footprint events, while a reactive power capability budget might be consumed by periodic testing events and replenished by verified upgrades.

Budget transactions are the ledger events that modify the budget state [15]. The core transaction semantics are reservation, allocation, consumption, release, conversion, and adjustment. Reservation allows a project to tentatively claim a portion of a budget during planning, preventing overcommitment when multiple projects are proposed concurrently. Allocation converts a reservation into an active instrument bound to a project or asset set after approvals. Consumption records the use of a budget due to physical actions or operational behaviors, such as operating hours in a restricted window or use of congestion headroom during a contingency. Release returns unused reserved budget when a project is canceled or when a risk is retired through mitigation. Conversion maps a budget from one form to another, such as converting a planning-stage ecological risk budget into an operations-stage monitoring obligation budget after construction [16]. Adjustment modifies budgets due to policy updates, negotiated revisions, or new baseline information, but adjustments are modeled as new transactions rather than edits to existing entries, preserving history.

The ledger supports aggregation and decomposition to handle portfolios and sub-portfolios. A national authority may define a regional biodiversity disturbance budget, while a local authority defines a sub-budget for a sensitive corridor within the region. A grid operator may define a feeder headroom budget, while a transmission operator defines a system-level stability budget that interacts with inverter-based resource penetration. The ledger represents these relationships as parent-child constraints, where consumption at the child level is also consumption at the parent level, and where adjustments at the parent level propagate to children through explicit rules [17]. This structure allows cumulative impact man-

Table 2. Nonstationarity drivers affecting renewable portfolios

| Driver | Salient effects | Impacted domains | Governance challenge |
|---|---|---|---|
| Climate hazards | Heatwaves, wildfires, floods alter asset availability, line ratings, demand profiles and emergency access | Grid reliability, environmental risk, safety | Existing approvals embed outdated baselines; emergency exceptions become frequent |
| Ecological baseline shifts | Changing migration routes, vegetation and cumulative development alter impact pathways | Habitat disturbance, species risk, mitigation effectiveness | Earlier impact assessments become inaccurate; retrofits and renewed approvals are pressured |
| Social and political change | Evolving attitudes to infrastructure, equity concerns, and contestation arenas | Community tolerance, procedural norms, regulator stance | Informal workarounds lose legitimacy; scrutiny intensifies in specific regions or technologies |
| Infrastructure evolution | New assets, upgrades, market rules and control schemes reshape system behavior | Network constraints, service obligations, contract performance | Local decisions interact in opaque ways; cumulative headroom use is hard to track |
| Policy and standard updates | Revised environmental rules, grid codes, planning criteria | All domains through new obligations and measurement rules | Transitioning portfolios between versions without erasing history or creating ambiguity |

agement without requiring a single monolithic authority to define all constraints, while still enabling consistency across overlapping jurisdictions.

A design challenge is negotiation and institutional friction. Budgets are not merely technical; they are outcomes of bargaining among agencies, utilities, developers, and civil society. The CBL architecture treats negotiation as a first-class source of budget rules by allowing policy references to encode negotiated trade-off statements. Solar governance research in one national case has emphasized that deployment outcomes are shaped through interdependent negotiations across arenas such as state-utility relations, intra-state coordination, state-market interactions, and state-society contestation, rather than through a linear technocratic roll-out [18]. The ledger does not attempt to remove these dynamics; it attempts to make their consequences operational by encoding the negotiated result as budget instruments whose scarcity and consumption are visible. When a compromise allocates more land-use budget to utility-scale projects, the ledger makes the reduced remaining budget for other land uses explicit [19]. When a compromise tightens ecological disturbance limits, the ledger forces projects to reserve and compete for the tighter budget, revealing trade-offs early.

The CBL includes an identity and authority layer that binds transactions to authorized actors. Authorities can include regulators, grid operators, environmental agencies, accredited auditors, and delegated intermediaries. Each transaction is signed or otherwise attributable, and includes a justification reference that links to the policy and evidence basis for the transaction. This is crucial for disputes, because a consumption transaction can be contested not only on whether it occurred but on whether the policy semantics were interpreted correctly at the time [20]. By keeping policy references versioned, the ledger can distinguish between a transaction that was valid under an older policy and one that would be invalid under a newer one, enabling transition management without retrospective rewriting.

The ledger's outputs are portfolio assurance queries. Stakeholders can query remaining budgets, proximity to exhaustion, rate of consumption, and exposure concentration. They can also query the provenance of a budget state, reconstructing the sequence of transactions that led to it. These queries support operational

Table 3. Core objects in the constraint-budget ledger architecture

| Object | Role in CBL | Selected attributes |
|---|---|---|
| Budget instrument | Represents an allowance or obligation as a consumable budget | Type (grid, ecological, social, market), scope (geography, assets, jurisdiction), validity period, units, minting authority, policy reference |
| Budget transaction | Encodes state change to one or more instruments | Transaction kind (reservation, allocation, consumption, release, conversion, adjustment), timestamp, actor identity, affected instruments, linked evidence |
| Policy object | Captures versioned rules that define budgets and transaction semantics | Domain, version identifier, applicability conditions, measurement and verification rules, trigger thresholds, transition provisions |
| Evidence object | Supports or challenges a transaction or budget definition | Producer identity, methodology, time window, uncertainty declarations, data references, integrity metadata |
| Identity / authority record | Binds actors and institutions to permissions and signatures | Actor type (regulator, operator, intermediary), delegated powers, signing keys, accreditation status, revocation history |

decision-making, such as whether additional curtailment is permissible under community agreements, and planning decision-making, such as whether a region can accommodate additional projects without exceeding cumulative ecological exposure budgets [21]. Importantly, the ledger can support bounded transparency by exposing budget summaries and proofs without exposing raw underlying sensitive data, a property that is treated as a core deployment requirement rather than an optional add-on.

## 4. Policy Semantics, Evidence Binding, and Assurance Under Intermediation

A ledger only creates governance value if budget semantics are meaningful and if transactions are defensible. This requires a policy compilation workflow that translates legal and negotiated obligations into budget rules, and an evidence binding workflow that links transactions to the data and documentation that justify them. Policy compilation begins by identifying constraint sources and classifying them into domains and transaction types. A permit condition that restricts operating hours becomes a rule that defines a time-budget instrument and specifies that operational telemetry generates consumption transactions. A grid standard that requires reactive capability becomes a rule that defines a capability budget and specifies that test results and telemetry generate satisfaction or deficiency transactions [22]. A mitigation commitment that requires habitat restoration becomes a rule that defines a restoration obligation budget and specifies that verified restoration milestones generate consumption and completion transactions.

Evidence binding attaches structured evidence objects to transactions. Evidence objects can include telemetry summaries, monitoring datasets, inspection reports, third-party assessments, and administrative decisions. Each evidence object has provenance metadata, such as producer identity, methodology, time window, and declared limitations. The binding is not merely archival; it supports verification routines that check completeness, timeliness, and methodological consistency [23]. For instance, a consumption transaction that claims an asset operated within allowed noise limits can be bound to measured noise data with calibration references and to the policy rule that defines the receptor points and measurement methodology. If the measurement methodology changes, the ledger does not silently accept the new data as equivalent; it records a methodology change event and associates it with a policy version update or with an explicit interpretive adjustment transaction.

Intermediation complicates evidence. Many regulatory systems rely on third-party intermediaries to pro-

Table 4. Budget transaction semantics in the constraint-budget ledger

| Transaction | Functional meaning | Typical trigger | Risk if poorly governed |
|---|---|---|---|
| Reservation | Tentatively claims part of a budget to prevent over-commitment during planning | Project proposal, interconnection request, siting application | Speculative hoarding, blocking competitors, phantom portfolios |
| Allocation | Converts a reservation into an active budget bound to assets or projects | Final approval, contract execution, commissioning | Over-allocation when reservations and allocations are inconsistently reconciled |
| Consumption | Records use of budget through physical actions or operations | Telemetry ingestion, monitoring results, documented events | Untracked cumulative impacts, delayed recognition of scarcity |
| Release | Returns unused or retired budget to the pool | Project cancellation, decommissioning, mitigation completion | Locked-in scarcity if budgets are never released or are released opaquely |
| Conversion | Transforms one budget form into another under defined rules | Stage transitions (planning to operation), mitigation commitments | Double-counting or hidden debits if conversion ratios are unclear |
| Adjustment | Modifies budgets due to policy change, baseline update, or negotiated revision | New regulation, revised impact estimates, settlements | De facto rewriting of history if adjustments lack provenance or versioning |

duce assessments, especially for environmental impacts. In one empirical analysis of wind energy projects, environmental impact assessments performed through intermediaries were described as having high procedural effectiveness in meeting regulatory requirements, but lower substantive effectiveness for decision-makers, who frequently sought independent external consultants to validate or supplement the assessments [24]. This pattern matters for ledger design because a ledger that merely records that an assessment exists will not resolve credibility disputes [25]. The CBL therefore treats evidentiary sufficiency as a policy-defined attribute, allowing rules to specify when corroboration is required, when independence criteria apply, and when uncertainty declarations are mandatory.

Rather than encoding a single notion of truth, the ledger encodes claims and their support. A budget instrument can carry a confidence tier that reflects the evidentiary status of its underlying assumptions. For example, an ecological disturbance budget may initially be minted with conservative limits due to uncertainty, and later adjusted when monitoring reduces uncertainty. Conversely, a budget may be tightened when new evidence increases estimated risk. The key is that these adjustments are recorded transparently as transactions with evidence and policy references, enabling stakeholders to see not only the current limit but why it changed [26]. This reduces the likelihood that stakeholders interpret constraint changes as arbitrary or politically motivated, even when normative judgments are involved.

Assurance under policy change is handled through versioning. Policy objects are versioned, and each transaction references the policy version in force at the time of the transaction. When policy changes, new budget instruments may be minted, existing budgets may be adjusted, and new transaction semantics may become valid. The ledger does not retroactively reclassify past transactions [27]. Instead, it supports replay under new semantics for analysis purposes. This allows institutions to estimate transition impacts, such as how much additional ecological budget would have been consumed under tighter rules, without invalidating past authorizations that were granted under earlier rules. It also supports negotiated transition periods, where projects may be grandfathered under old budgets for a time while new projects must reserve under new budgets.

The ledger supports governance triggers. When a budget approaches exhaustion, the system can trigger review requirements, operational curtailment protocols, or negotiation reopeners. Triggers are policy-defined and can be tied to both absolute levels and rates of consumption [28]. For example, a rapid increase in consumption of a community disturbance budget may trigger enhanced engagement requirements, while a sustained high

Table 5. Illustrative budget archetypes across domains

| Budget type | Illustrative unit semantics | Primary domain | Evidence and verification examples |
|---|---|---|---|
| Grid headroom | MW of allowed injections on a feeder; Mvar capability range; ramp-rate envelopes | Network operation | SCADA telemetry, power flow models, commissioning tests, stability studies |
| Ecological disturbance | Area of habitat affected; hours of operation in sensitive periods; risk-weighted mortality units | Environmental | Field monitoring, remote sensing, impact assessments, species surveys |
| Community disturbance | Nighttime operating hours; noise or flicker credits at receptors; event frequency limits | Social / community | Noise meters, complaint logs, engagement records, operating schedules |
| Reliability services | Frequency response, inertia contribution, reserves, black-start capability | System services | Performance tests, market settlement data, event response reports |
| Hazard exposure / resilience | Concentration of critical assets in hazard zones; diversification scores; critical-load coverage | Cross-cutting resilience | Hazard maps, resilience studies, contingency simulations, scenario analyses |

consumption of a grid headroom budget may trigger network upgrade planning. Because triggers are encoded as rules, they can be executed consistently across projects, reducing claims of unequal treatment.

This section's core proposition is that the ledger shifts governance attention from document completion to claim maintenance. Budgets represent claims about allowable cumulative exposure and required cumulative provisioning. Transactions represent claim updates [29]. Evidence binding ensures those updates are defensible. Under high penetration, where both operational complexity and contestation are high, this shift provides a scalable way to maintain substantive confidence without expanding procedural bureaucracy indefinitely.

## 5. Strategic Behavior, Regulatory Pitching, and Anti-Gaming Controls

Any governance substrate that allocates scarce budgets creates incentives to manipulate allocation, timing, and interpretation. Strategic behavior can include over-reserving budgets to block competitors, delaying disclosure of consumption to avoid triggers, selectively presenting evidence that supports favorable interpretations, or framing projects in ways that influence how budgets are minted and sized. The CBL design therefore includes anti-gaming controls that are technical, procedural, and institutional [30].

Reservation anti-gaming is addressed through expiration and cost mechanisms. Reservations must expire unless converted into allocations within defined windows. Reservation sizes can be capped relative to project maturity, and reservation fees or bonding requirements can discourage speculative hoarding. The ledger can support priority rules, such as allocating scarce budgets based on readiness or on policy-defined portfolio diversity goals. These rules must be transparent because they are inherently normative. The ledger's role is to ensure that once rules exist, they are applied consistently and traceably [31].

Consumption anti-gaming is addressed through automated ingestion and cross-verification. For grid-domain budgets, telemetry ingestion can generate consumption transactions automatically, reducing the ability to delay reporting. For environmental-domain budgets, monitoring data can be ingested through accredited pipelines that enforce sampling and calibration requirements. Cross-verification can compare operator-reported consumption with independent measurements, such as network measurements or remote sensing proxies, within acceptable error bounds. When discrepancies exceed thresholds, the ledger can generate discrepancy events that trigger investigation protocols [32].

Interpretation anti-gaming is addressed through pol-

Table 6. Policy compilation and evidence binding in the ledger

| Step | Purpose | Key design elements |
|---|---|---|
| Constraint source identification | Map permits, codes, agreements, and negotiated conditions into constraint domains | Domain tagging, scope definition, linkage to assets and geographies, identification of interdependencies |
| Policy-to-budget compilation | Translate narrative obligations into budget instruments and transaction rules | Unit choice, uncertainty handling, activation conditions, trigger definitions, minting authority specification |
| Evidence schema definition | Standardize how evidence objects support transactions and budgets | Provenance metadata, methodology descriptors, time coverage, uncertainty descriptors, data access rules |
| Binding and verification | Attach evidence to transactions and execute checks | Automated completeness checks, corroboration rules, independence criteria, discrepancy events |
| Versioning and replay | Maintain traceable evolution of semantics and baselines | Policy version identifiers, transition windows, replay analyses under new rules, non-retroactive interpretation of past entries |

icy versioning and explicit interpretive transactions. When an actor claims that a consumption event does not count because of an interpretive nuance, that claim must be represented as an interpretive adjustment transaction with supporting rationale and authority signature. This prevents silent reinterpretation and creates an auditable record of how semantics evolve. It also allows institutions to detect patterns, such as repeated interpretive adjustments that systematically favor certain actors, which can indicate capture or poor rule design.

A particularly subtle strategic behavior involves influencing the rules themselves through persuasion and framing. In innovation governance, work on pitching to regulators has described pitching as a strategic effort to influence regulators by framing value, feasibility, and societal relevance in ways that reduce regulatory uncertainty, often through iterative engagement and adjustment rather than one-off communication [33]. In a budget-ledger context, pitching can influence how budgets are minted, such as whether a project is granted a larger ecological budget due to claimed mitigation effectiveness or whether a project is granted relaxed grid budgets due to claimed control sophistication [34]. The ledger cannot prevent pitching, and it should not, because persuasion is part of legitimate democratic and administrative processes. However, it can require that the outcomes of pitching be translated into explicit budget rules and evidence obligations. If a pitch claims that a control feature reduces avian risk, the resulting policy should define what evidence will be used to validate that claim over time, and how budgets will be adjusted if the claim is not borne out. This reduces the risk that persuasive claims become permanent privileges without accountability.

Delegation creates additional strategic surfaces [35]. Developers may outsource monitoring to intermediaries with aligned incentives. Aggregators may operate assets on behalf of owners and may have incentives to maximize revenue by pushing operational envelopes. Agencies may rely on consultants for capacity and may become dependent on particular firms. Anti-gaming under delegation is addressed by credentialing and separation requirements encoded as policy. The ledger can require that certain evidence objects be produced by accredited entities and that accreditation includes disclosure of conflicts [36]. It can require countersignatures or independent corroboration for high-impact transactions, such as large adjustments to ecological budgets or claims of exceptional operating modes. It can also require periodic randomized audits where ledger claims are checked against raw underlying records under confidentiality controls.

Another strategic challenge is scarcity politics. When budgets are tight, actors may lobby to expand budgets, arguing that constraints are overly conservative or that new technologies justify relaxation. Conversely, actors may lobby to tighten budgets to block development. The ledger does not adjudicate these arguments, but it im-

Table 7. Strategic behavior patterns and corresponding anti-gaming controls

| Strategic pattern | Ledger vulnerability | Control mechanism | Intended effect |
|---|---|---|---|
| Over-reservation of budgets | Blocking of scarce ecological or grid headroom without real intent to build | Reservation expiry, size caps tied to project maturity, fees or bonding requirements | Discourage speculative claims and free up unused capacity |
| Delayed or selective reporting | Understated consumption, late trigger activation | Automated telemetry ingestion, independent monitoring channels, discrepancy events | Reduce opportunity to hide overuse and align reporting with operations |
| Opportunistic reinterpretation | Claiming that impacts do not count under specific readings of rules | Explicit interpretive adjustment transactions, authority signatures, policy references | Make semantic changes visible and attributable, enabling scrutiny |
| Rule-shaping through persuasion | Budgets minted or relaxed on optimistic claims without follow-up | Evidence-linked commitments, review clauses, conditional budgets that tighten if claims fail | Tie persuasive claims to future verification and adaptive budget updates |
| Delegation without accountability | Intermediaries shaping evidence and monitoring with misaligned incentives | Accreditation, conflict disclosure, countersignatures, randomized audits | Preserve public authority while using external expertise under clear boundaries |

proves the quality of adjudication by making the empirical trajectory of budget consumption visible [37]. If a region's biodiversity budget is being exhausted rapidly, institutions can see whether the exhaustion is due to a few large projects, many small projects, or unexpected consumption rates. If a grid headroom budget is being consumed primarily during contingencies, institutions can see whether upgrades or operational changes would be more efficient. This evidence-based visibility can reduce reliance on rhetorical claims alone, even though normative decisions remain.

The core claim of this section is that a budget ledger is viable only if it anticipates strategic interaction. By treating rule changes, interpretive claims, and evidence sufficiency as explicit, attributable ledger events, the CBL makes strategic behavior more detectable and therefore more governable [38]. This does not eliminate conflict, but it changes conflict from opaque dispute over narratives to contestation over explicit budget states, transactions, and evidentiary obligations, which is a more scalable substrate for institutional resolution.

## 6. Deployment: Interoperability, Privacy, and Intermediary Integration

Deploying a CBL in real governance ecosystems requires accommodating legacy systems, fragmented authority, confidentiality constraints, and uneven institutional capacity. The deployment model assumed here is federated. Agencies and authorized entities publish budget instruments and transactions through standardized interfaces, while maintaining their own internal workflows. The ledger provides canonical identifiers for projects, assets, geographic scopes, and policy objects, enabling cross-domain joins without forcing a single database schema across all institutions [39].

Interoperability hinges on shared semantics for the minimal set of objects required for budget accounting. These include asset identifiers, geographic scope identifiers, time window conventions, and policy version identifiers. For grid budgets, interoperability also requires standardized representations of network locations, such as substation or feeder identifiers, and standardized representations of operational modes. For environmental budgets, interoperability requires standardized representations of protected zones and monitoring methodologies. The ledger does not require that all parties adopt the same monitoring tools; it requires that monitoring outputs be translatable into evidence objects with comparable metadata.

Privacy and confidentiality are addressed through tiered disclosure [40]. Many ledger transactions can be shared as aggregates. For example, a public stakeholder

Table 8. Deployment considerations for a federated constraint-budget ledger

| Aspect | Design choice | Supporting mechanisms | Deployment implication |
|---|---|---|---|
| Interoperability | Minimal shared semantics across agencies and domains | Common identifiers for assets, locations, policies; shared time conventions; domain adapters | Enables cross-domain queries without forcing a single database for all actors |
| Privacy and bounded transparency | Separation of integrity from content | Hash-linked transactions, role-based disclosure, aggregated public views, audit trails for data access | Allows portfolio visibility while protecting sensitive operational and commercial data |
| Security and integrity | Append-only, tamper-evident ledger with signed entries | Cryptographic chaining, key management, access control, integrity checks on evidence | Maintains trust that budget states and histories have not been altered |
| Intermediary integration | Use of external expertise without diluting authority | Proposal vs. authorization separation, accreditation rules, provenance tagging | Keeps the locus of decision-making accountable while scaling analytical capacity |
| Incremental adoption | Phased rollout across domains and regions | Coarse initial budgets, local pilots, versioned expansion, backwards-compatible interfaces | Reduces implementation risk and aligns with heterogeneous institutional capacity |

may be allowed to see that a region has consumed 62% of its land conversion budget without seeing the exact parcel-level footprints of each project. A grid operator may be allowed to see consumption of a feeder headroom budget without seeing proprietary setpoint trajectories beyond what is necessary for reliability analysis. An enforcement agency may have access to full transaction detail and evidence objects under legal authority. The ledger supports this by separating integrity from content: transaction hashes and signatures can be shared widely to prove that a transaction exists and is immutable, while transaction payload fields can be disclosed selectively based on role and purpose [41].

Security is treated as a governance requirement because a ledger that can be manipulated undermines trust and can create real safety risks. Transactions are signed, and the ledger is append-only with tamper-evident chaining. Evidence objects are similarly integrity-protected. Access to sensitive evidence is logged, and requests for additional disclosure are represented as ledger events, creating an auditable trail of who accessed what and why. This discourages fishing expeditions and supports due process in investigations.

Intermediary integration is unavoidable in many contexts because agencies and communities rely on external expertise for monitoring, modeling, and policy design [42]. Intermediaries can expand capacity but also create accountability concerns. An empirical case in environmental governance has described how a ministry leveraged a consulting firm to bridge technical gaps and support ambitious, measurable goal-setting while emphasizing that public authority remained intact and that clear benchmarks enabled accountability [43]. This dynamic motivates a design principle for the CBL: intermediaries can produce evidence and analytic inputs, but budget minting and authoritative adjustments should remain under accountable public signatures, or under tightly controlled delegated authority with clear boundaries.

In practice, this means that intermediaries can submit evidence objects and propose transactions, but the ledger can require that certain transaction types be countersigned by public authorities. For instance, an intermediary may submit monitoring evidence that suggests an ecological budget should be tightened, but the tightening adjustment transaction is executed by an environmental authority after review, preserving accountability.

Table 9. Evaluation dimensions and stress scenario classes for the CBL

| Dimension / scenario | Central question | Illustrative indicators | Representative coupled constraints |
|---|---|---|---|
| Consistency | Does the ledger prevent over-allocation under concurrency and support reproducible states? | Allocation errors, divergence between independent replays, frequency of conflicting claims | Multiple projects sharing feeder headroom and regional ecological budgets |
| Timeliness | Are budget consumption and triggers recorded quickly enough for operational response? | Ingestion latency, trigger delay, duration of untracked overuse | Heatwave-driven congestion combined with seasonal wildlife operating limits |
| Dispute tractability | Can stakeholders reconstruct provenance and evidence in a bounded time? | Time to answer audit queries, completeness of provenance, reliance on ad hoc searches | Challenges to claimed compliance with noise and ecological conditions during curtailment |
| Adaptability under policy change | Can new rules be implemented without erasing history or creating ambiguity? | Clarity of grandfathering, replay quality under new semantics, transition error rates | Tightening of disturbance budgets alongside new reactive capability standards |
| Social contestation and stance shifts | Does heightened scrutiny translate into explicit, manageable changes in budgets and triggers? | Transparency of adjustments, distributional summaries, trigger activation patterns | Local opposition leading to stricter environmental and community budgets in specific regions |

Conversely, an intermediary may submit evidence that a mitigation measure reduced impact, enabling budget relaxation, but the relaxation is similarly executed under public signature [44]. This structure allows agencies to harness expertise without relinquishing control, while still keeping the intermediary's role visible in provenance metadata.

Deployment also requires operational integration. For grid budgets, ledger consumption can be driven by telemetry and by event logs from control systems. For environmental budgets, consumption can be driven by monitoring schedules and by observed operations in sensitive windows. For community budgets, consumption can be driven by operational profiles and measured outcomes, such as exceedances of agreed disturbance thresholds [45]. The ledger must therefore provide ingestion pathways that can handle high volume without compromising integrity. A practical approach is to ingest high-frequency data into domain systems and produce ledger transactions at governance-relevant granularity, such as per interval summaries, exceedance events, or verified milestone events, with cryptographic commitments to underlying raw data for later audit if needed. This reduces storage burden and preserves confidentiality while maintaining auditability.

Finally, deployment must address institutional adoption constraints. Agencies may lack the capacity to define fine-grained budgets across all domains at once. The CBL supports incremental adoption by allowing coarse budgets initially, such as categorical risk credits with review triggers, and later refinement as monitoring and modeling improve [46]. It also supports localized pilots, such as implementing grid headroom budgets for a congested corridor or ecological budgets for a sensitive region, without requiring nationwide rollout. The key is to maintain consistent transaction semantics and versioning so that the ledger can scale horizontally across domains and jurisdictions over time.

## 7. Evaluation Methodology and Stress Scenarios

Evaluating a governance substrate requires metrics that reflect both technical performance and institutional usefulness. The CBL is evaluated along dimensions of consistency, timeliness, dispute tractability, and adaptability under change. Consistency refers to whether the ledger prevents over-allocation of scarce budgets under concurrency and whether derived budget states are deterministic and reproducible across verifiers [47]. Timeliness refers to whether consumption and trigger events are recorded with low enough latency to support operational responses and to prevent prolonged untracked overuse. Dispute tractability refers to whether stakeholders can reconstruct budget provenance and evidentiary support quickly enough to resolve contested claims without resorting to prolonged ad hoc investigations. Adaptability refers to whether policy updates, baseline shifts, and negotiated revisions can be implemented through versioned adjustments without erasing history or creating ambiguous transitional states.

Stress scenarios are designed to represent the coupled nature of constraints. One scenario class couples grid contingencies with environmental windows [48]. For example, a heatwave reduces thermal headroom, triggering congestion management, while a seasonal ecological constraint restricts operational modulation patterns. The evaluation examines whether the ledger can represent both constraints as budgets, whether consumption is recorded consistently when curtailment actions occur, and whether triggers fire when budgets approach exhaustion. It also examines whether operational actors can query remaining budgets in near real time to choose actions that remain within allowable envelopes, reducing the reliance on overly conservative default curtailment.

A second scenario class focuses on policy change under ongoing deployment. For instance, an environmental authority tightens disturbance budgets due to new baseline information, while a grid operator revises reactive capability requirements due to updated technical standards. The evaluation examines whether versioning prevents semantic confusion, whether existing reservations are treated under grandfathering rules as defined, and whether projects can transition through conversion transactions without losing traceability [49]. The evaluation also examines whether replay analysis supports impact assessment of the policy change, enabling institutions to anticipate administrative workload and operational implications.

A third scenario class focuses on social contestation and regulator stance shifts. Wind governance in one national setting has been described as involving strong local opposition that strategically aligns with environmental concerns, contributing to an environmental regulator adopting increasingly resolute opposition and heightened scrutiny, even while its formal authority is limited and its influence is exerted primarily through planning committees [50]. This kind of dynamic can be represented in CBL terms as a tightening of environmental and community budgets, increased corroboration requirements for evidence, and shorter trigger thresholds for review. The evaluation examines whether such tightening can be implemented as explicit budget adjustment transactions with clear authority and rationale, and whether the ledger reduces the administrative chaos that often accompanies heightened scrutiny by making new requirements immediately legible to all parties.

Institutional performance is evaluated through audit exercises [51]. Auditors are tasked with answering questions such as whether a portfolio exceeded a regional ecological budget during a period, which projects consumed the largest share, which evidence objects supported consumption claims, and which policy versions were in force. The time to produce a defensible answer and the completeness of the provenance trail are measured. This is compared to document-centric processes where answering the same questions often requires manual retrieval across multiple repositories, interpretation of heterogeneous conditions, and negotiation over which datasets are authoritative.

Another evaluation dimension is the reduction of silent cumulative impacts. In conventional governance, cumulative effects often emerge only when a threshold is exceeded, at which point conflict intensifies. The CBL is evaluated on whether it provides early warning signals, such as rising consumption rates or concentration of exposure in a corridor, and whether these signals can trigger adaptive actions like reallocating future reservations, tightening evidence requirements, or accelerating mitigation investments [52]. The evaluation also examines the risk of false alarms, which can occur if budget semantics are poorly defined or if evidence pipelines generate noisy consumption estimates. The ledger's role is not to guarantee perfect prediction but to ensure that uncertainty and noise are visible and managed through explicit policies rather than through silent drift.

The evaluation also considers equity and distributional visibility without prescribing outcomes. Because budgets can be scoped geographically and socially, the ledger can show whether burdens concentrate in particular communities or ecosystems. This visibility can inform policy adjustments, such as imposing stricter budgets in overburdened areas or requiring additional mitigation for projects that concentrate exposure [53]. The evaluation measures whether the ledger can produce these distributional summaries under privacy constraints, enabling public deliberation without exposing sensitive details.

A final evaluation dimension is operational overhead. A ledger that is too burdensome will be bypassed, and a ledger that is too permissive will be ineffective. The evaluation therefore measures transaction volumes, ingestion latency, and the cost of maintaining evidence bindings at scale. It also measures the effectiveness of hierarchical summarization strategies that reduce raw data disclosure while maintaining auditability, such as publishing interval-level consumption summaries with cryptographic commitments to underlying telemetry [54]. The objective is to show that portfolio-level constraint accounting can be achieved with bounded incremental overhead relative to existing telemetry and reporting practices, while delivering materially improved traceability and cumulative impact management.

## 8. Conclusion

High-penetration renewable systems create a governance problem of cumulative constraints under nonstationarity, delegation, and contestation. Project-by-project approvals and document-centric compliance mechanisms struggle to maintain consistency across interacting domains and to adapt to evolving climate hazards and socio-political baselines. This paper proposed a constraint-budget ledger (CBL) as a technical substrate for portfolio-scale governance. The CBL represents diverse obligations as typed budgets that can be reserved, consumed, released, converted, and adjusted through auditable transactions bound to versioned policy semantics and verifiable evidence objects. By shifting governance from static artifacts to continuous accounting, the ledger aims to reduce silent accumulation of cumulative impacts, improve concurrency control across competing projects, and provide bounded transparency for dispute resolution and public legitimacy [55].

The approach does not replace institutional judgment. Authorities still decide what budgets exist, how they are measured, how trade-offs are negotiated, and what triggers cause review or adaptation. The ledger's contribution is to make those decisions operational at scale, to preserve interpretability under policy change, and to reduce the ambiguity that enables both unintentional inconsistency and strategic manipulation. The design incorporates anti-gaming controls for reservation and consumption, explicit representation of interpretive adjustments, and provenance-aware integration of intermediaries so that expertise can be leveraged without dissolving accountability.

Limitations remain [56]. Budget semantics can be contentious and can embed normative assumptions that require democratic legitimacy. Some constraints resist quantification, requiring coarse units and review-based triggers rather than precise accounting. Interoperability requires sustained institutional coordination on identifiers and minimal schemas. Nonetheless, the CBL can be adopted incrementally, starting with domains where scarcity and cumulative effects are already acute, such as congested grid corridors or sensitive ecological regions, and expanding as institutions build capacity.

Future work can extend the ledger concept toward richer integration with resilience planning, including hazard-exposure budgeting and diversification budgets that align deployment with adaptation objectives, and toward improved methods for combining qualitative obligations with quantitative budgets without creating false precision. As renewable penetration continues to rise, governance systems that can represent cumulative constraints transparently and manage them adaptively will be central to maintaining both system reliability and public legitimacy [57].

## References

[1] N. Goyal, "Limited demand or unreliable supply? a bibliometric review and computational text analysis of research on energy policy in india," Sustainability, vol. 13, pp. 13421–13421, 12 2021.

[2] A. M. Maslove, How Ottawa Spends: 2018-2019. Carleton University, School of Public Policy and Administration, 11 2018.

[3] R. Leal-Arcas, A. Filis, and E. S. A. Gosh, List of tables. Edward Elgar Publishing, 11 2014.

[4] A. Asthana, "What determines access to subsidised food by the rural poor?: Evidence from india," International Development Planning Review, vol. 31, no. 3, pp. 263–279, 2009.

[5] A. Eitan, "Climate change adaptation through renewable energy: The cases of australia, canada, and the united kingdom," Environments, vol. 11, no. 9, p. 199, 2024.

[6] T. Rodon, L. Nachet, C. Krolik, and T. Palliser, "Building energy sovereignty through community-based projects in nunavik," Sustainability, vol. 13, pp. 9061–, 8 2021.

[7] B. Molo, "Zagraniczna polityka energetyczna niemiec: uwarunkowania - cele - instrumenty," Rocznik Polsko-Niemiecki, pp. 89–102, 9 2021.

[8] Y. Xiang, J. Zheng, and X. Tu, "The impact of intermediate goods imports on energy efficiency: Empirical evidence from chinese cities.," International journal of environmental research and public health, vol. 19, pp. 13007–13007, 10 2022.

[9] X. Li and Q. Tian, "New energy and national energy security strategy - based on geopolitical risk perspective," 1 2023.

[10] DSA2017 Conference Programme. NomadIT, 9 2017.

[11] I. Medina-Jiménez, F. J. R. Real, J. E. León-Vielma, and F. Calero-García, "Decarbonizing the tourism sector in the canary islands through the introduction of electric vehicles: An empirical analysis of stakeholder perspectives," 1 2024.

[12] L. C. P. da Silva, P. R. R. Meira, J. G. I. Cypriano, H. A. D. Azzini, and A. Q. Santos, "Software toolchain to enhance the management and integration of a sustainable campus model," Energy Informatics, vol. 4, pp. 1–11, 9 2021.

[13] O. Azurza-Zubizarreta, I. Basurko-PerezdeArenaza, E. Zelarain, E. Villamor, O. Akizu-Gardoki, U. Villena-Camarero, A. Campos-Celador, and I. Barcena-Hinojal, “Urban energy transitions in europe, towards low-socio-environmental impact cities,” Sustainability, vol. 13, pp. 11641–, 10 2021.

[14] N. D. Officer, “Everything but the building, project organisation, first light house, solar decathlon, 2011,” 1 2013.

[15] M. J. Burke, “Shared yet contested: Energy democracy counter-narratives,” Frontiers in Communication, vol. 3, 6 2018.

[16] Y. Sanusi, C. Ohadugha, V. Martins, and S. Olaide, “Analysis of energy governance in southern africa,” Polityka Energetyczna – Energy Policy Journal, vol. 25, pp. 73–94, 12 2022.

[17] P. Schroeder, “Leapfrogging in china’s renewable electricity development pathway? the roles of policy frameworks, innovation and international cooperation partnerships in fostering renewable electricity,” 1 2010.

[18] A. Eitan, “Negotiating the energy transition: Governance trade-offs in solar deployment,” Energy Strategy Reviews, vol. 61, p. 101854, 2025.

[19] X. Liu, B. Shen, L. Price, H. Lu, and A. Hasanbeigi, “What china can learn from international policy experiences to improve industrial energy efficiency and reduce co2 emissions,” 11 2016.

[20] Belt and Road Initiative, AIIB, and Global Energy Governance, pp. 25–39. Hong Kong University Press, 3 2023.

[21] Y. Li and X. Zhu, “The 2030 agenda for sustainable development and china’s belt and road initiative in latin america and the caribbean,” Sustainability, vol. 11, pp. 2297–, 4 2019.

[22] C. Demski and S. Becker, Energy security, pp. 93–104. Routledge, 9 2021.

[23] A. Schneiders, M. J. Fell, and C. Nolden, “Peer-to-peer energy trading and the sharing economy: Social, markets and regulatory perspectives,” 8 2020.

[24] A. Eitan and D. Levi-Faur, “Environmental impact assessments as a mechanism of regulatory intermediation: the case of israeli wind energy,” Policy and Society, vol. 44, no. 4, pp. 510–534, 2025.

[25] F. Proedrou, “Exploring eu energy governance and policy under a demoi-cratic lens: citizen participation, output legitimacy and democratic interdependence,” European Politics and Society, vol. 23, pp. 364–379, 1 2021.

[26] L. Fowler, T. T. Neaves, J. Terman, and A. G. Cosby, “Cultural penetration and punctuated policy change: Explaining the evolution of u.s. energy policy,” Review of Policy Research, vol. 34, pp. 559–577, 4 2017.

[27] J. Malinauskaite, H. Jouhara, B. Egilegor, F. Al-Mansour, L. Ahmad, and M. Pusnik, “Energy efficiency in the industrial sector in the eu, slovenia, and spain,” Energy (Oxford, England), vol. 208, pp. 118398–118398, 7 2020.

[28] C. Leong, “Response to “investigating ministry names for comparative policy analysis: Lessons from energy governance”,” Journal of Comparative Policy Analysis: Research and Practice, vol. 20, pp. 336–339, 5 2018.

[29] L. R. A. Gil, A glimpse into smart cities: opportunities for the development of energy cooperatives for citizens and businesses in Mexico, pp. 245–256. Routledge, 2 2022.

[30] A. Florini, “The international energy agency in global energy governance,” Global Policy, vol. 2, pp. 40–50, 9 2011.

[31] “Experiences,” 6 2016.

[32] M. K. Pasupuleti, “Energy innovations: Sustainable power solutions,” International Journal of Academic and Industrial Research Innovations(IJAIRI), vol. 4, pp. 1–14, 4 2024.

[33] A. Eitan and I. Fischhendler, “Shaping niche innovations in energy transitions: The role of pitching to regulators,” Energy Research & Social Science, vol. 126, p. 104170, 2025.

[34] B. Che, C. Shao, Z. Lu, B. Qian, and S. Chen, “Mineral requirements for china’s energy transition to 2060—focus on electricity and transportation,” Sustainability, vol. 15, pp. 585–585, 12 2022.

[35] Oil Wealth and Development in Uganda and Beyond. Leuven University Press, 12 2019.

[36] E. Eckert and O. Kovalevska, “Sustainability in the european union: Analyzing the discourse of the european green deal,” Journal of Risk and Financial Management, vol. 14, pp. 80–, 2 2021.

[37] K. Szulecki and D. H. Claes, “Towards decarbonization: Understanding eu energy governance,” Politics and Governance, vol. 7, pp. 1–5, 3 2019.

[38] M. Anggraini, “Renewable energy policy as indonesia’s energy security strategy,” Jurnal Mandala Jurnal Ilmu Hubungan Internasional, pp. 24–47, 6 2022.

[39] A. Balanzo, L. Garavito, H. Rojas, L. Sobotova, O. Pérez, D. Guaquetá, A. Mojica, J. Pavajeau, and S. Sanabria, “Typical challenges of governance for sustainable regional development in globalized latin america: A multidimensional literature review,” Sustainability, vol. 12, pp. 2702–, 3 2020.

[40] C. Pahl-Wostl, P. Gorris, N. W. Jager, L. Koch, L. Lebel, C. Stein, S. Venghaus, and S. S. Withanachchi, "Scale-related governance challenges in the water–energy–food nexus: toward a diagnostic approach," Sustainability Science, vol. 16, pp. 615–629, 12 2020.

[41] L. Gailing, A. Bues, K. Kern, and A. Röhring, "Socio-spatial dimensions in energy transitions: Applying the tpsn framework to case studies in germany:," Environment and Planning A: Economy and Space, vol. 52, pp. 1112–1130, 4 2019.

[42] B. Mao, X. Chang, Y. Xian, J. Chen, X. Li, and L. Wang, "Low-carbon economic scheduling optimization of distribution network with hydrogen storage system," 12 2023.

[43] A. Eitan, "Privatizing environmental governance: the evolving relationship between regulators and private entities," Journal of Environmental Policy & Planning, pp. 1–27, 2025.

[44] H. Ahn, "Republic of korea's energy security conundrum:the problems of energy mix and energy diplomacy deadlock," Handbook of Energy Politics, vol. 22, pp. 67–87, 5 2018.

[45] F. Karimi and M. Rodi, Energy transition in the Baltic Sea Region, pp. 3–16. Routledge, 1 2022.

[46] M. Deng, X. Lu, R. Tong, Y. Xue, S. Shi, and R. Guo, "The role of green finance in reshaping end-use energy consumption: insights from regional evidence in china," Frontiers in Environmental Science, vol. 13, 2 2025.

[47] K. Kleinschnitger, M. Knodt, M. Lortz, and A. K. Stöckl, Energy Relations in the EU Eastern Partnership, pp. 1–28. Springer International Publishing, 7 2022.

[48] S. D. Medici, "Italian architectural heritage and photovoltaic systems. matching style with sustainability," Sustainability, vol. 13, pp. 2108–, 2 2021.

[49] S. E. Cheren and L. A. Kumar, "Optimization techniques for improving the performance of solar photovoltaic system in conjunction with health informatics and the hospital energy management system," Journal of Medical Imaging and Health Informatics, vol. 11, pp. 3016–3023, 12 2021.

[50] A. Eitan, "Navigating sustainability trade-offs in wind energy governance: The role of environmental regulators," Energy Policy, vol. 203, p. 114645, 2025.

[51] N. Goyal and K. Iychettira, "Value change, value conflict, and policy innovation: Understanding the opposition to the market-based economic dispatch of electricity scheme in india using the multiple streams framework.," Science and engineering ethics, vol. 28, pp. 58–, 11 2022.

[52] X. Lu, E. Zhu, L. Campbell, M. Hafner, M. Noussan, and P. P. Raimondi, "Comparison between china, the eu and the us's climate and energy governance: How policies are made and implemented at different levels," SSRN Electronic Journal, 1 2021.

[53] D. D. Rodrigues and M. Grasso, "The resistance to solar energy expansion in italy: a systemic perspective," Sustainability Science, vol. 20, pp. 1329–1342, 4 2025.

[54] A. Asthana and D. Tavželj, "International business education through an intergovernmental organisation," Journal of International Business Education, vol. 17, pp. 247–266, 2022.

[55] "Eu energy governance: selected legal aspects," 11 2014.

[56] D. Wagemans, C. Scholl, and V. Vasseur, "Facilitating the energy transition—the governance role of local renewable energy cooperatives," Energies, vol. 12, pp. 4171–, 11 2019.

[57] E. İşeri and T. Uygurtürk, Energy Governance in Turkey, pp. 1217–1254. Springer International Publishing, 9 2022.