Infrastructure Quality in the Energy Sector

Why Energy Infrastructure Must be Understood as a Whole

IQI IES1
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1. Introduction: Why the Energy Sector Reveals the Infrastructure Quality Problem

The energy sector reveals a basic reality about infrastructure: major failure, degradation, or loss of function may occur even when many individual components, activities, and documents conform to applicable requirements. The problem is often not one defective part. It is the behavior of many interacting elements within a defined infrastructure object over time.

Energy infrastructure is commonly governed through separate categories - components, facilities, projects, operating organizations, and regulatory domains. Production zones, processing facilities, pipelines, storage systems, power stations, transmission networks, and distribution systems are addressed by different standards, authorities, contracts, and technical disciplines. This specialization is necessary, but it does not by itself determine the quality of the assembled infrastructure object.

Energy supply depends on defined Infrastructure Quality Objects and their system-of-systems relationships. These objects are real operating configurations made of physical, functional, informational, environmental, human, and organizational elements connected through Interfaces. At this level, quality depends on Function Realization, interaction among subsystems, lifecycle conditions, operating variability, Evidence, Uncertainty, and the consequences of lost alignment.

Energy Infrastructure Quality Objects are not static. Their configuration, operating medium, responsibilities, Boundaries, Interfaces, Evidence basis, and Critical Infrastructure Conditions may change across Design, Construction, Commissioning, Operation, Maintenance, Repair/Modification, and Decommissioning/Transition. Small decisions made at different stages can accumulate until the object moves beyond the conditions for which its Quality State was previously supported.

The energy sector makes this reality especially visible because its objects are long-lived, interconnected, interface-intensive, and often high-consequence. It exposes the gap between quality understood as separate compliance results and quality understood as the evidence-supported state of a whole, bounded Infrastructure Quality Object.

This article explains why energy infrastructure must be interpreted through declared objects and system-of-systems relationships, why product-centric standards remain necessary but insufficient, and how the

IQI architecture connects object description, Structural Checkpoints, Core Quality Factors, Core Quality Indicators, Quality Outcome Criteria, Evidence, Critical Conditions, Quality State determination, and bounded claims.

The controlling document relationship is: WQI_VOC1 -> IQI_VOC1 -> IQC1 -> IQI Context Guides. WQI_VOC1 defines Root Concepts, IQI_VOC1 defines energy-infrastructure Applied Concepts, IQC1 establishes invariant Core requirements, and Context Guides interpret those requirements for bounded infrastructure contexts.

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2. From Components to Defined Infrastructure Quality Objects

Traditional engineering and technical standards appropriately focus on parts, materials, methods, and activities, such as:

- material and equipment specifications
- design calculations, margins, and technical requirements
- fabrication, construction, installation, and commissioning practices
- inspection, testing, conformity assessment, and acceptance methods
- operating, monitoring, maintenance, repair, and transition requirements

These standards are indispensable. They support correctness, conformity, safety, reliability, and traceability at the level for which they were written. Their results may become Evidence for a broader determination, but they do not automatically establish the Infrastructure Quality State of the assembled object.

When compliant components and activities are combined, system-level conditions emerge. They may include:

- integrated structural and functional integrity, containment, and isolation behavior
- operational stability, controllability, reliability, and recovery capability
- interaction among degradation, abnormal conditions, and external threats
- maintainability, inspectability, monitoring visibility, and information continuity
- interaction of Failure-Mode Families across subsystems and Interfaces
- propagation of consequences across organizational, environmental, community, and downstream Boundaries

These conditions cannot be guaranteed by component conformity alone. They become visible only when the declared object, its composition, functions, Interfaces, lifecycle and operating conditions, and supporting Evidence are interpreted together.

The key IQI unit of analysis is the Infrastructure Quality Object: a declared and bounded energy-infrastructure asset, facility, network, subsystem, zone, lifecycle program, Interface condition, asset population, or system-of-systems whose Infrastructure Quality State is being determined. The selected Scale controls what is included, what is excluded, and how far the resulting claim may extend.

3. Scale and System-of-Systems Relationships

As the Scale of a technical object changes, the relevant quality question also changes. Methods suitable for a manufactured product do not automatically address the behavior of a facility, network, production zone, asset population, or infrastructure system-of-systems.

At a component Scale, quality may be examined primarily through technical specifications, manufacturing controls, testing, and conformity. At broader Scales, quality depends increasingly on composition, interdependence, Interfaces, operating conditions, Uncertainty, lifecycle change, and consequence propagation.

The IQI distinction is therefore not between useful and useless standards, but between different levels of the quality question:

- product or component quality - conformity and performance of a defined part or product
- Infrastructure Quality - Function Realization and Quality State of a declared assembled object at its selected Scale

Component conformity, facility performance, or a favorable finding at one Scale may support a broader determination. It shall not be substituted for the Infrastructure Quality State of a different or larger object unless the Boundaries, Interfaces, criteria, and Evidence support that extension.

4. Lifecycle Reality, Structural Checkpoints, and the Work-Result-Outcome Relationship

Energy infrastructure quality forms through decisions and realized conditions across the principal IQI lifecycle sequence:

- Design
- Construction
- Commissioning
- Operation
- Maintenance
- Repair/Modification
- Decommissioning/Transition

Before detailed quality interpretation begins, the Infrastructure Quality Object Description should make the object sufficiently visible: its Scale, composition, Infrastructure Intended Functions and Infrastructure Intended Results, configuration, operating medium and conditions, Boundaries, Interfaces, responsibilities, Context, Assumptions, Uncertainty, and Evidence basis. Structural Checkpoints confirm this methodological completeness; they are not Quality Factors or a Quality State determination.

Lifecycle interpretation must also distinguish activity from realized effect. Infrastructure Work + Infrastructure Result = Infrastructure Outcome. Completed design, construction, inspection, maintenance, or modification Work does not by itself prove that the intended Result was achieved, and an observed Result does not by itself establish the Quality State of the broader object. IQC1 therefore does not prescribe universal scores or fixed Quality State categories; the determination must remain bounded by the declared object, conditions, criteria, and Evidence.

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5. Brownfield Systems and Loss of Alignment

Much of the energy infrastructure in service is brownfield infrastructure: existing objects that are repaired, modified, expanded, repurposed, or operated under legacy constraints and changing external conditions.

In brownfield environments:

- original assumptions, models, or design bases may no longer remain valid
- records and configuration information may be incomplete, fragmented, or inconsistent
- operating practices and actual conditions may drift from intended functions and results
- temporary restrictions, workarounds, or provisional Boundaries may become persistent
- Critical Infrastructure Conditions and Failure-Mode Families may change without adequate re-evaluation

Consider an onshore natural gas production zone undergoing incremental modification:

- legacy reservoir or collector information continues to govern later decisions without sufficient revalidation
- earlier integrity assumptions or corrosion allowances are reused after configuration or operating conditions change
- inspection, monitoring, or subsurface visibility remains limited by access or Evidence constraints
- temporary operating limits or transfer conditions become routine without an updated determination
- necessary repair, modification, or interface work is deferred under schedule, production, or budget pressure

No individual decision necessarily proves nonconformity or failure. Together, however, they may change well integrity, surface-system capacity, monitoring visibility, downstream transfer compatibility, environmental protection, or the demonstrated operating envelope.

The central issue is loss of alignment: the declared Infrastructure Quality Object, its intended functions and intended results, actual configuration, Boundaries, Interfaces, operating conditions, Assumptions, Evidence, Critical Conditions, and claim limits no longer describe the same reality. A responsible determination must then be revised, restricted, qualified, or withdrawn.

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6. Boundaries, Interfaces, and Operating Conditions

Energy infrastructure operates through networks of quality-relevant Interfaces, including:

- physical and functional Interfaces among subsystems and adjacent infrastructure objects
- responsibility, organizational, contractual, and contractor Interfaces
- regulatory, jurisdictional, and Reference Layer Interfaces
- commercial, custody-transfer, customer, and service Interfaces
- informational, monitoring, environmental, community, and emergency-response Interfaces

Many systemic failures originate not inside a single component but at an Interface where function, information, responsibility, operating conditions, or Evidence is incomplete or misaligned. IQI therefore treats Boundaries and Interfaces as intrinsic to the object description and to the resulting claim.

Infrastructure Quality may be determined for a narrow asset or for a broader system-of-systems, but the selected Scale must be explicit. External objects may remain critical Interfaces without being included inside the declared Boundary. A claim about one object shall not imply the Quality State of an adjacent object.

Boundaries and Interfaces may be physical, functional, operational, organizational, informational, lifecycle-based, environmental, transported-medium-based, stakeholder or community-based, evidence-based, or claim-based. Their condition may also change across normal, startup, shutdown, transient, abnormal, degraded, emergency, repair, and transition operating conditions.

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7. Uncertainty, Failure-Mode Families, and Critical Infrastructure Conditions

Energy infrastructure operates with inherent Uncertainty arising from conditions such as:

- geological, subsurface, environmental, and external-hazard variability
- configuration, boundary, interface, and operating-condition uncertainty
- aging, degradation, damage, and incomplete monitoring visibility
- human interaction, organizational responsibility, and contextual pressure
- changing demand, supply, downstream conditions, and system-of-systems behavior

Models, standards, and professional judgment are essential, but they cannot remove every unknown. IQI requires Assumptions, Uncertainty, and Unresolved Conditions to remain visible where they affect criteria, Evidence Sufficiency, lifecycle decisions, Critical Conditions, or claim validity.

Failure-Mode Families help connect the declared object and its intended functions to the invariant Core Quality Factors and Core Quality Indicators. Where failure, prohibition, unresolved status, insufficient Evidence, or loss of visibility would prevent a responsible positive determination, the condition is treated as a Critical Infrastructure Condition. Favorable findings elsewhere cannot compensate for it; this is the application of Non-Compensability and Infrastructure Non-Substitutability.

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8. The Reference Layer and the Limits of Existing Standards

Energy infrastructure is governed by extensive laws, regulations, engineering codes, technical standards, permits, contracts, procedures, scientific knowledge, and professional guidance. These sources are indispensable and may form the Reference Layer for a declared application.

The structural limitation is not that these sources are unimportant. It is that they were created for different objects, purposes, Scales, lifecycle stages, and jurisdictions and therefore do not automatically form one bounded Infrastructure Quality State determination.

Many existing sources are primarily:

- component-, product-, method-, or activity-specific rather than object-level
- phase- or jurisdiction-specific rather than lifecycle-integrated
- discipline- or organization-specific rather than Interface-centered
- compliance- or acceptance-oriented rather than a complete Quality State determination

System-level Infrastructure Quality may therefore remain fragmented or implicit even when each source performs its intended role.

IQI does not replace the Reference Layer. It provides the object-level architecture that connects applicable sources to Infrastructure Intended Functions and Infrastructure Intended Results, Quality Outcome Criteria, Evidence-Supported Findings, Critical Conditions, and a bounded Infrastructure Quality State determination.

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9. Determining the Infrastructure Quality State

Infrastructure Quality is the degree to which a defined Infrastructure Quality Object realizes its Infrastructure Intended Functions and Infrastructure Intended Results within declared Boundaries and Interfaces, as interpreted against applicable Quality Outcome Criteria and supported by sufficient Evidence.

The determination is object-relative, function-based, bounded, lifecycle-aware, context-dependent, and evidence-supported. It does not arise from one document, one inspection, one compliance statement, one score, or the absence of observed failure.

The updated IQI architecture shifts the focus:

from isolated compliance to the behavior and Function Realization of the declared object

- from a static design representation to the realized object across lifecycle and operating conditions
- from undocumented averaging to transparent Quality Factor Interpretation and Critical-Condition review

- Infrastructure Quality is not a property of records or procedures alone. It is the established state of a sufficiently described Infrastructure Quality Object under the conditions covered by the determination.

The principal dependency is: Infrastructure Quality Object and Description -> Structural Checkpoints -> Boundaries and Interfaces -> Intended Functions and Intended Results -> Failure-Mode Families -> Core Quality Factors -> Core Quality Indicators -> Context-Specific Quality Outcome Criteria -> Evidence-Supported Findings -> Quality Factor Interpretation -> Critical-Condition and Non-Compensability Review -> Infrastructure Quality State -> Infrastructure Quality Claim Statement.

This sequence preserves traceability from the quality question to the communicated claim. It also prevents a claim from becoming broader than the object, Scale, Boundary, conditions, criteria, or Evidence on which the determination depends.

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10. Evidence, Findings, and Bounded Claims

Infrastructure Quality State determination requires Evidence, but information becomes Evidence only when its relevance, credibility, Context, traceability, and relationship to the declared object, Core Quality Indicator, and applicable Quality Outcome Criterion are established.

Energy-infrastructure Evidence may include:

- object descriptions, functional and technical requirements, models, drawings, and configuration records
- construction, commissioning, inspection, testing, monitoring, and performance information
- operating, maintenance, repair, modification, incident, anomaly, and lifecycle-transition records
- conformity, compliance, environmental, worker, community, and interface information
- assumption, uncertainty, unresolved-condition, and decision-traceability records
- Evidence concerning Critical Infrastructure Conditions and conditions of continued validity

Evidence-Supported Findings are developed at the Indicator level and interpreted at the Quality Factor level. The determination then undergoes Critical-Condition and Non-Compensability Review before the Infrastructure Quality State is established.

Evidence in the energy sector is often fragmented across disciplines, organizations, systems, and lifecycle stages. IQI organizes it around the declared object and the determination dependency rather than treating document volume as proof of quality.

An Infrastructure Quality Claim Statement communicates the supporting determination and must identify what is assessed, the Scale, Boundaries and Interfaces, lifecycle and operating conditions, applicable criteria, Evidence basis and Evidence Sufficiency, Assumptions, Uncertainty, Unresolved Conditions, Critical Infrastructure Conditions, limitations, date or validity context, and conditions of continued validity. It is not an IQI certification, approval, audit result, endorsement, or regulatory decision.

11. The Role of This Article in the IQI Document Architecture

This Foundational Article explains why the energy sector requires an object-level and system-of-systems view of Infrastructure Quality. It prepares the conceptual ground for the controlled IQI document set:

- WQI_VOC1 - Whole Quality Root Vocabulary Standard, which defines Root Concepts that retain the same meaning across application domains; and IQI_VOC1 - Infrastructure Quality Applied Vocabulary Standard, which defines energy-infrastructure Applied Concepts.
- IQC1 - Infrastructure Quality Standard - Core, which establishes the invariant Core Intended Function architecture, the 14 Core Quality Factors, Core Quality Indicators, determination requirements, Critical-Condition and Non-Compensability rules, and the permissible Infrastructure Quality Claim structure.
- IQI Context Guides, which interpret IQC1 for defined infrastructure systems and real operating conditions. PZN1 - Onshore Natural Gas Production Zone Infrastructure is the first previously published guide aligned with the updated architecture. MNT1, LDN1, UGS1, LNG1, and the other controlled Context Guide drafts remain scheduled for coordinated update.

Together, these documents separate explanation, authoritative definitions, invariant requirements, and context-specific interpretation while preserving one coherent Whole Quality architecture for energy infrastructure.

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12. Conclusion

The energy sector illustrates a fundamental truth: technical excellence and conformity at the component level do not automatically establish the Quality State of an assembled Infrastructure Quality Object.

Infrastructure Quality forms through the interaction of components, functions, Boundaries, Interfaces, operating conditions, lifecycle decisions, Evidence, Uncertainty, and Critical Infrastructure Conditions. Existing standards and regulations remain essential, but they do not by themselves combine these elements into one bounded determination.

IQI addresses this gap through a shared architecture for describing the object, checking structural completeness, interpreting the invariant Core, developing Evidence-Supported Findings, reviewing Critical Conditions and Non-Compensability, determining the Infrastructure Quality State, and communicating only a bounded Infrastructure Quality Claim Statement.

The result is not a substitute for engineering, regulation, management systems, or professional judgment. It is a disciplined way to make the quality of energy infrastructure visible, understandable, evidence-supported, and responsibly bounded.

Figures and Image References

Conceptual Illustrations of Infrastructure Quality in the Energy Sector

The figures below illustrate energy infrastructure at different Scales and lifecycle conditions. They are not engineering specifications, complete Infrastructure Quality Object descriptions, or Quality State determinations. Their purpose is to help visualize system-of-systems relationships, object Boundaries, Interfaces, Uncertainty, lifecycle evolution, operating pressures, and the updated IQI determination architecture.

Set A - System-Level Energy-Flow Context

(Macro-Scale system-of-systems perspective)

Source: Lawrence Livermore National Laboratory (LLNL) energy flow charts.

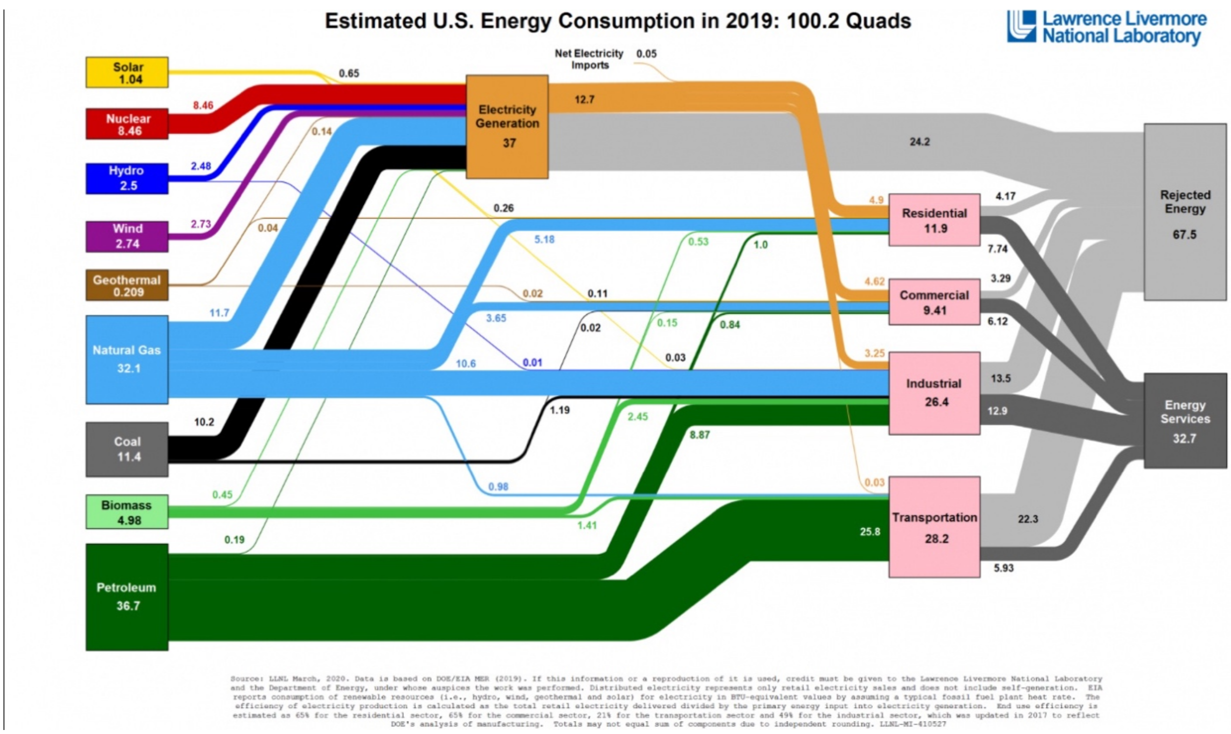

Figure A-1. U.S. Energy System Structure and Losses (LLNL, 2019)

This Sankey diagram presents the U.S. energy system as a macro-Scale system-of-systems. Primary energy sources pass through conversion and end-use sectors to produce delivered energy services and rejected energy.

In the IQI framework, the figure illustrates that:

- an Infrastructure Quality Object may be declared at a broad system-of-systems Scale when its purpose, composition, Boundaries, Interfaces, and Evidence basis are sufficiently defined;
- system-level results emerge from relationships among multiple infrastructure objects and conversion Interfaces;
- losses, constraints, risks, and consequences may accumulate across Interfaces and operating contexts.

The figure is a macro-Scale context illustration. It does not imply that one Quality State determination for an individual facility automatically determines the Quality State of the national energy system, or vice versa.

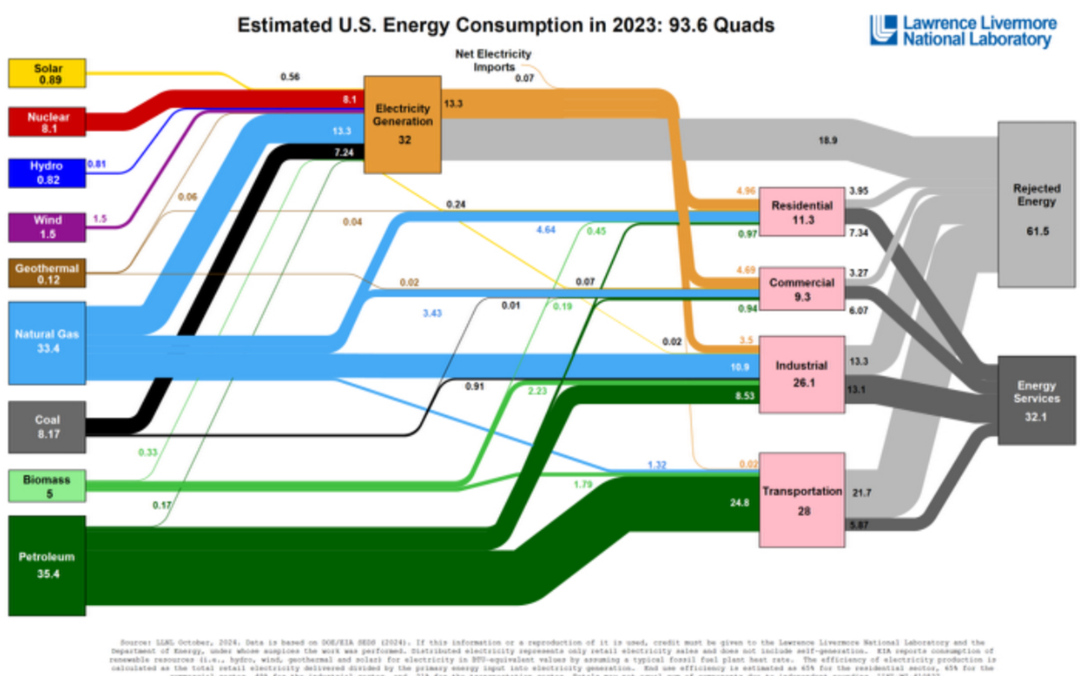

Figure A-2. U.S. Energy System Structure and Evolution (LLNL, 2023)

This later energy-flow chart enables comparison of the structure and context of the U.S. energy system across time.

In the IQI framework, comparison of Figures A-1 and A-2 illustrates:

- changes in system composition, operating context, and infrastructure relationships;
- changes in relevant Boundaries, Interfaces, conversion pathways, and external dependencies;
- changes that may alter Quality Outcome Criteria, Evidence needs, Critical Conditions, and claim validity.

The comparison reinforces that infrastructure context is dynamic. A prior Quality State determination does not remain valid automatically when the object, Scale, configuration, conditions, or Evidence basis materially changes.

Set B - Natural Gas Infrastructure as a System-of-Systems

(Functional topology, object Boundaries, and Interfaces)

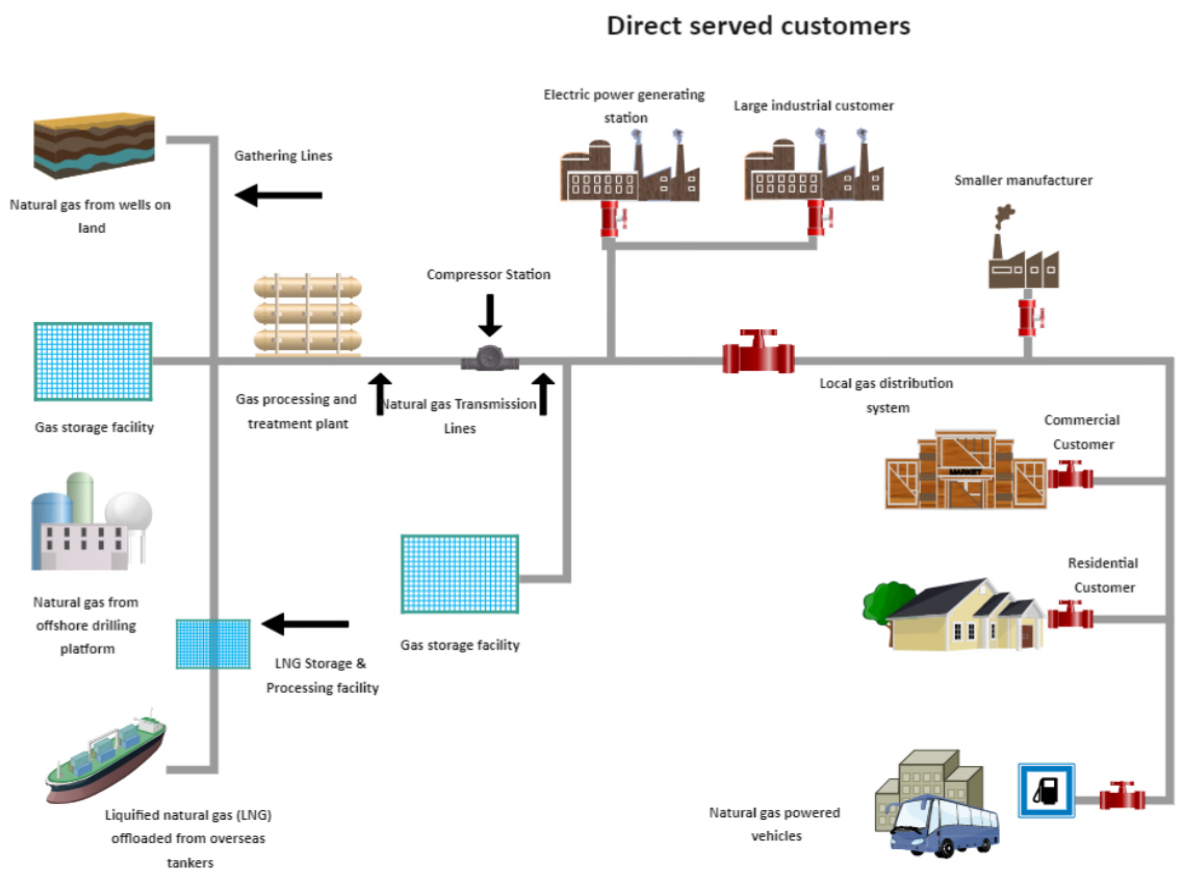

Figure B-1. Functional Delivery Chain of Natural Gas Infrastructure

This diagram presents a simplified functional chain connecting natural-gas production, processing, transportation, storage, distribution, and end use.

production -> processing -> transportation -> storage or conversion -> distribution or direct delivery -> end use.

In the IQI framework, the figure illustrates:

- a natural-gas chain may be interpreted as a system-of-systems composed of separately declared Infrastructure Quality Objects;
- quality-relevant Interfaces concentrate transfer conditions, responsibilities, information, custody, operating constraints, and Evidence;
- physical subsystems and functional roles must be distinguished when Boundaries and claims are established.

Infrastructure Quality may be determined for one bounded object or for a broader declared system-of-systems. The Scale and claim Boundary must be explicit, and a claim about one segment shall not imply the Quality State of adjacent segments.

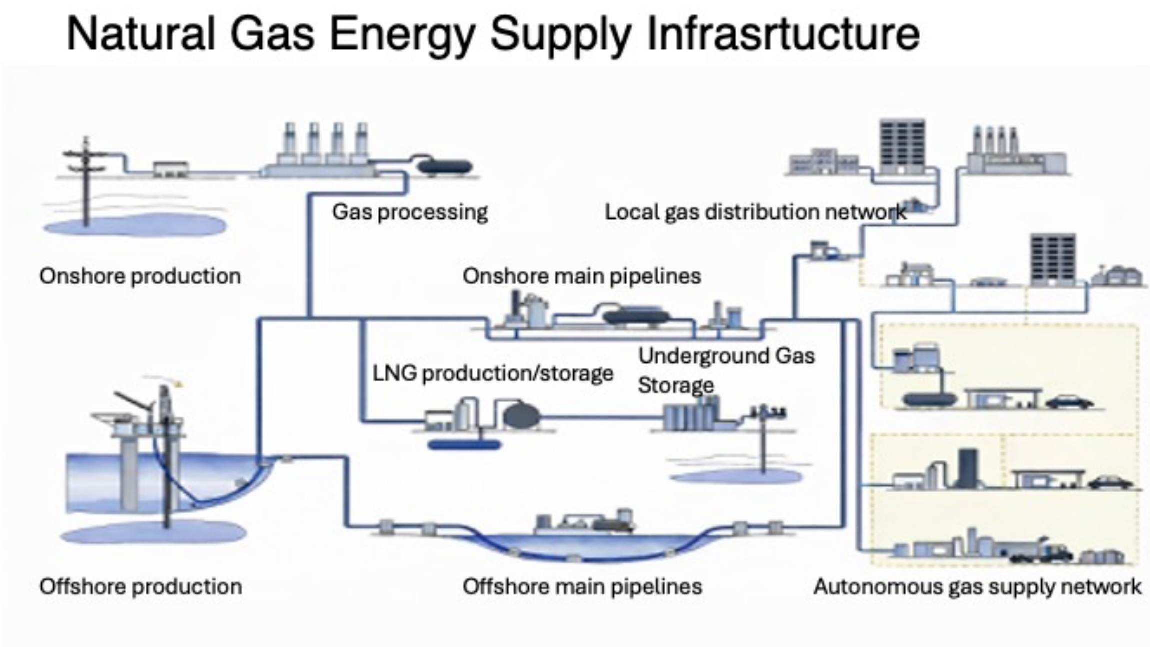

Figure B-2. Structural Topology of Natural Gas Infrastructure

This topology illustrates onshore and offshore production, natural gas processing, onshore and offshore main pipeline transportation, LNG, underground storage, local distribution, and autonomous supply as connected but separately bounded infrastructure contexts.

In the IQI framework, the topology illustrates:

- each infrastructure context requires its own declared object, Scale, Boundaries, Interfaces, operating conditions, and Evidence basis;
- the system-of-systems relationship does not erase the quality identity of each bounded object;
- responsibility and Quality Claim Boundaries must be visible across transfer Interfaces.

Infrastructure Boundaries are declared functional and methodological limits supported by physical, operational, informational, environmental, responsibility, Evidence, and claim conditions - not merely lines around equipment.

Context Guides apply the invariant IQC1 Core to different infrastructure contexts. PZN1 is aligned with the updated architecture; the other previously published natural-gas Context Guides remain scheduled for coordinated update.

Set C - Infrastructure Quality as a System Condition

(Scale, Uncertainty, and lifecycle interaction)

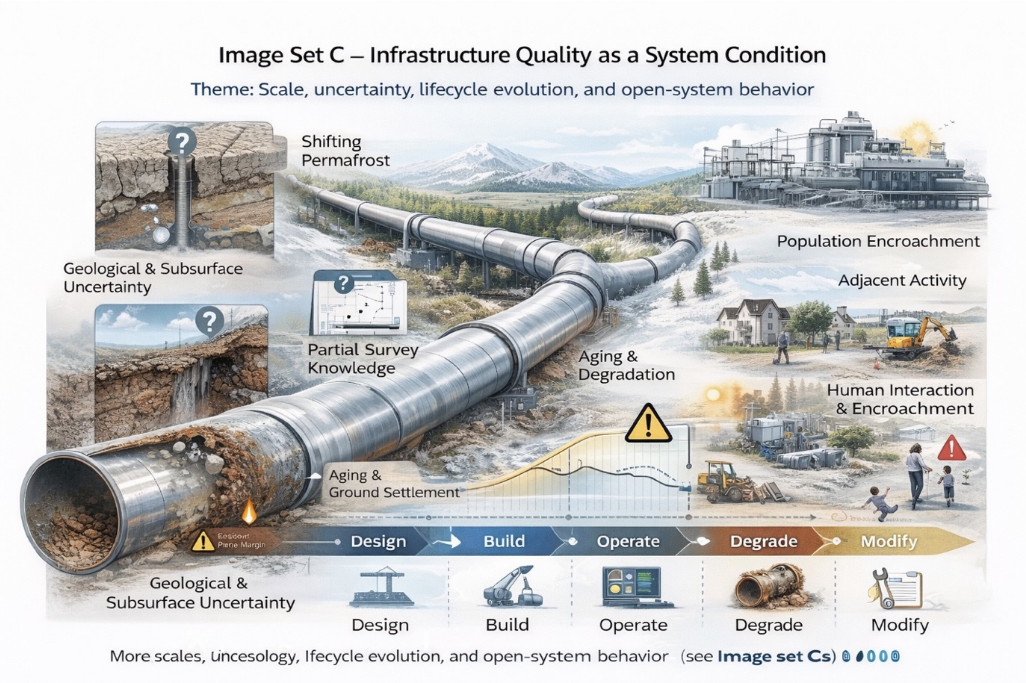

Figure C-1. Infrastructure Behavior Across Scale, Uncertainty, and Lifecycle

This conceptual illustration presents Infrastructure Quality as an object-level and system condition rather than a property of a single component.

It illustrates that the quality question changes with Scale:

- component Scale: technical specification, product behavior, and conformity of a defined part;
- facility, network, zone, or asset-population Scale: interaction among subsystems, functions, Boundaries, and Interfaces;
- system-of-systems Scale: interdependence, changing Context, Uncertainty, external interaction, and consequence propagation.

Key concepts illustrated include:

- partial knowledge and Uncertainty in geological, environmental, and operating conditions;
- cumulative degradation, aging, modification, and loss of alignment;
- propagation of local conditions through connected Interfaces and broader systems;

- interaction among infrastructure, workers, communities, environmental media, and adjacent activity.

The figure supports the distinction between product quality and Infrastructure Quality while emphasizing that any determination must begin with a declared Infrastructure Quality Object and Scale.

Set D - Market Pressure and Infrastructure Quality Reality

(Economic and schedule drivers versus Function Realization)

Figure D-1. Construction Under Schedule and Cost Pressure

This figure illustrates how schedule, cost, resource, and delivery pressures can influence Infrastructure Work and the realization of the intended object.

In the IQI framework, the figure demonstrates that:

- market and project pressures may change decisions without directly appearing as technical defects;
- completed Construction Work does not prove that the intended Infrastructure Result was realized;

- early trade-offs may reduce margins, create Unresolved Conditions, or establish later Critical Infrastructure Conditions.

Figure D-2. Brownfield Infrastructure Under Operational Pressure

This figure depicts a brownfield object operating under accumulated constraints, including:

- spatial congestion and complex physical Interfaces;
- limited access for inspection, monitoring, Maintenance, and Repair/Modification;
- legacy configuration, documentation, and design limitations;
- concentrated or interacting Failure-Mode Families and Critical Conditions.

In the IQI framework, the figure illustrates that:

- brownfield infrastructure is a principal energy-sector reality;
- degradation and loss of alignment may be incremental and difficult to observe;
- system-level risk may emerge from cumulative decisions rather than one isolated failure.

Set E - Lifecycle Quality

(Temporal realization and continued validity)

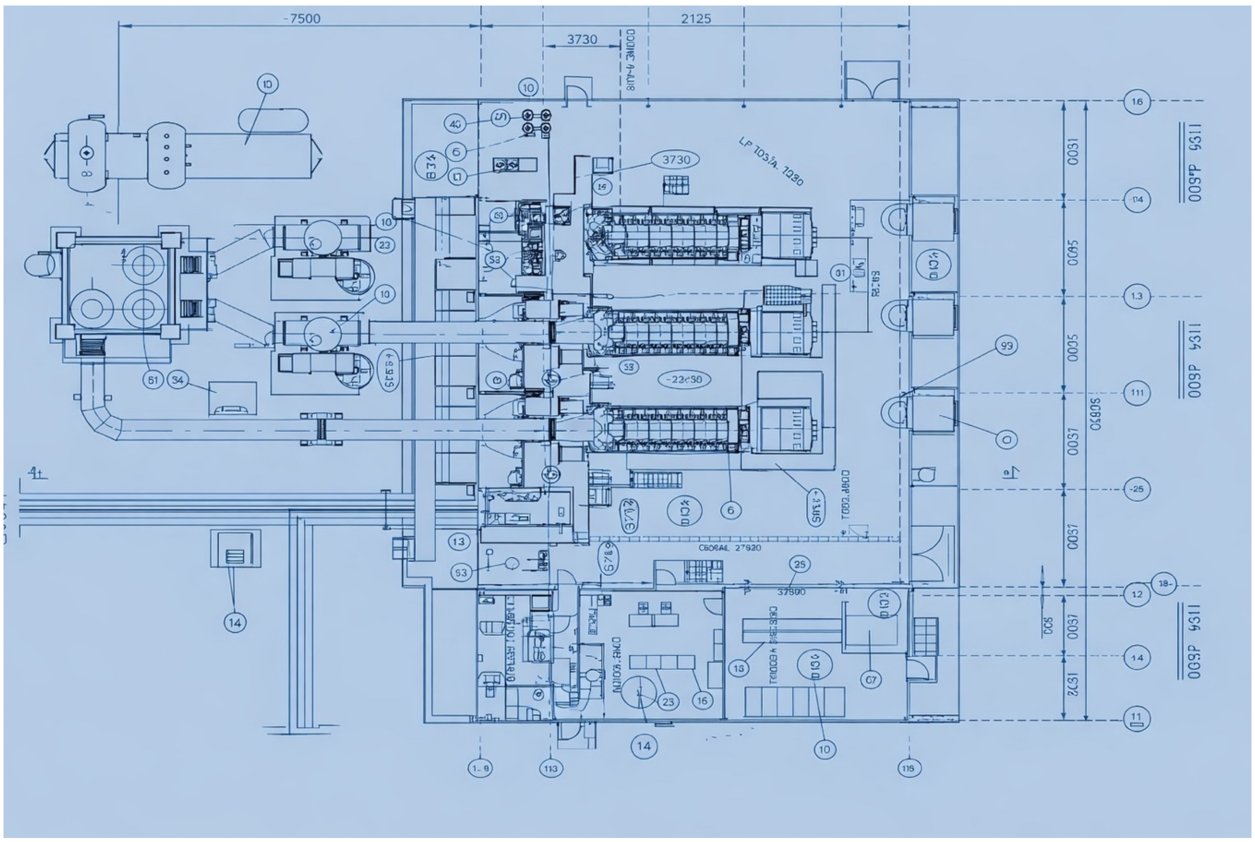

Figure E-1. Design Phase - Object Description and Intended Quality Boundaries

This figure represents Design as the stage in which the Infrastructure Quality Object, intended functions and intended results, configuration, assumptions, interfaces, criteria, and initial margins are described.

In the IQI framework, Design establishes an intended representation, not a demonstrated operating Quality State. Structural Checkpoints help test whether the object description is sufficiently complete before later interpretation.

Figure E-2. Construction Phase - Translation of Intent into the Realized Object

This figure illustrates Construction as Infrastructure Work through which intended requirements, Boundaries, Interfaces, and functions are translated into a physical and functional object.

The determination must distinguish completed Work from the actual Infrastructure Result. Construction records and conformity findings may provide Evidence, but they do not by themselves establish the Quality State of the commissioned or operating object.

Figure E-3. Operation and Modification - Lifecycle Change and Claim Validity

This figure depicts the long-term evolution of an Infrastructure Quality Object under Operation, aging, degradation, Maintenance, Repair/Modification, modernization, and adaptation.

Infrastructure Quality is not fixed at Commissioning. Material changes in configuration, operating conditions, Interfaces, Assumptions, Uncertainty, Critical Conditions, or Evidence may require the Infrastructure Quality State and the conditions of continued validity of its claim to be re-examined.

Set F - Shared Language and Determination Architecture

(Updated IQI object-level framework)

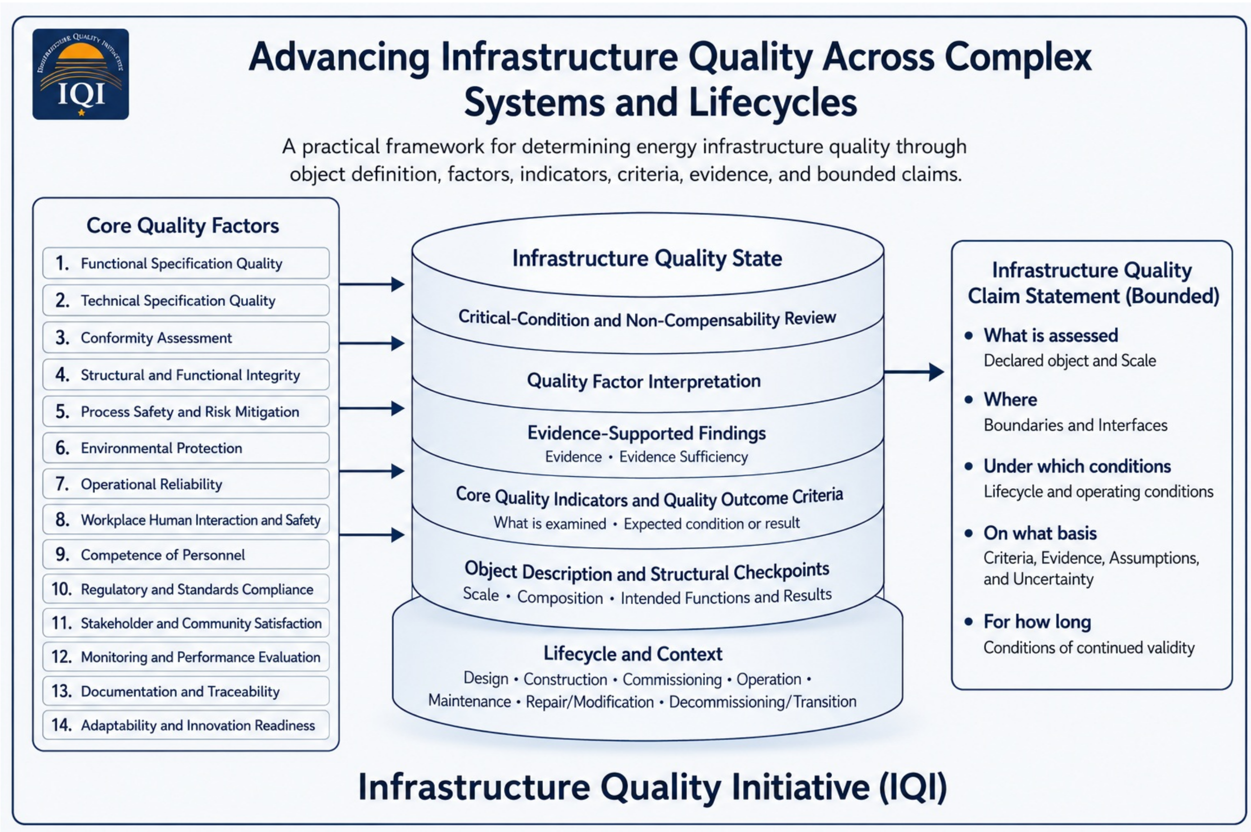

Figure F-1. Updated IQI Framework for Infrastructure Quality State Determination

The updated Master Diagram presents the principal IQI architecture, including:

- the 14 invariant Core Quality Factors;
- Core Quality Indicators and Quality Outcome Criteria;
- Object Description, Structural Checkpoints, lifecycle, and Context;
- Evidence-Supported Findings and Evidence Sufficiency;
- Quality Factor Interpretation and Critical-Condition and Non-Compensability Review;
- Infrastructure Quality State determination;
- a bounded Infrastructure Quality Claim Statement and its conditions of continued validity.

In the IQI framework, the figure demonstrates that:

- Infrastructure Quality requires a common vocabulary and a declared object rather than an unbounded assertion;
- technical, organizational, regulatory, worker, community, and other interested parties require shared reference points;
- IQI connects the Reference Layer and context-specific Evidence to one traceable determination architecture without replacing engineering standards, regulation, professional judgment, or organizational management systems.

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