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Institutional Fragility and the Conditional Transferability of Green Hydrogen Strategy Across the Middle East and North Africa (MENA): Heterogeneous Burdens, Shared Mechanism

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Abstract

Green hydrogen strategies proliferate across developing economies, yet most assume the planning authority possesses the state capacity, regulatory autonomy, and investment conditions that conflict-affected and fragile economies lack. Whether a strategy logic derived in one such context transfers to others with different institutional capacity remains untested. This study develops a Conflict-Affected Energy Transitions (CAET) framework and empirically examines its barrier gradient and conditional transferability propositions, analyzing at the country level a regional expert survey—data that prior single-case work, including the authors' own, used only for binary external validation. A total of 137 energy experts across seventeen Arab states are grouped into three institutional clusters—conflict-affected/fragile, stable developing, and Gulf/high-capacity—and examined through cluster barrier and readiness profiles, a perceived-versus-predictive importance comparison, hierarchical clustering, and a Mode-A partial-least-squares path model with measurement invariance (MICOM) testing and permutation-based multi-group analysis. Energy justice and sovereignty are used as analytical and interpretive lenses, not as measured latent constructs in the structural model. Results show that barrier burdens follow a monotonic institutional fragility gradient: regulatory/institutional barriers rise from 3.02 (Gulf) through 3.52 (stable) to 4.06 (fragile), where they are the most severe constraint. Moreover, the perceived–predictive divergence—social barriers are rated least severe yet associate most strongly with sustainability—recurs across the region. In addition, the model satisfies compositional invariance across fragile and stable clusters while equality of regulatory means and variances fails as expected, and no structural path differs detectably between them at the current sample size. The adoption–governance–sustainability mechanism is therefore provisionally comparable rather than definitively invariant. We propose conditional transferability: the mechanism travels, provisionally, while priorities must be re-weighted by institutional context. Policy implications are differentiated—institutions-first, community-scale pathways for fragile states; finance and market formation for stable developing states; export-scale deployment for high-capacity states—and the CAET framework offers a generalizable alternative to techno-economic determinism for hydrogen strategy under constrained sovereignty. In practical terms, energy ministries in fragile states should sequence rule-making, permitting authority, and community-scale pilots before committing deployment capital; stable developing states should concentrate on de-risking finance and forming early offtake markets; and high-capacity states can proceed directly to export-scale projects and regional standard setting.

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1. Introduction

1.1. The Structural Blind Spot in Hydrogen Strategy

Green hydrogen has become a fixture of national decarbonization strategy across the Middle East and North Africa (MENA), and the global policy literature now offers a dense supply of templates for designing it [1,2]. Yet deployment in developing economies lags behind ambition, and the binding constraint is increasingly understood to be institutional rather than technological; in resource-rich but institutionally constrained settings, the obstacles are governance-, finance-, and acceptance-related [3–5], as a growing evidence base across African and MENA settings documents [6–12]. Most strategy frameworks, however, carry a hidden premise: that the planning authority possesses regulatory autonomy, fiscal space, and institutional integrity. For much of the Global South, and acutely for conflict-affected economies, that premise does not hold, and treating political constraint, regulatory voids, and capital scarcity as exogenous risks rather than constitutive design variables produces strategy that misallocates scarce resources. The stakes are concrete: since 2021, most MENA states have published national hydrogen strategies or signed export memoranda with European offtakers, so whether a single strategy template can serve institutionally heterogeneous MENA settings is now an urgent rather than hypothetical question.

A further problem is that strategies built solely on expert judgement may misallocate resources; the factors experts rate as most severe are not always those that best predict outcomes. If that divergence is systematic, strategy calibrated to perceived severity will under-fund the levers that matter. The present study takes up both problems at the regional scale using a resource that has been collected but not fully exploited: a regional expert survey spanning participating Arab states that is independent of the Palestine expert panel but part of the same research program. In prior work, this instrument served only as a binary external validator—a check of whether single-case propositions commanded regional agreement [13]. That use discarded almost all of the survey's information; however, the item-level, country-tagged responses contain cross-national variation in barrier severity, readiness, and the relationships among them that a yes/no validation cannot reveal. We analyze exactly that variation.

1.2. Relationship to, and Differentiation from, Prior Work

This study extends, and is clearly delimited from, the authors' recent single-case framework for Palestine [13], which developed an integrated barrier–adoption–sustainability framework for one conflict-affected economy and used the regional survey solely to confirm, in binary form, that its core propositions held across the MENA. The present manuscript analyzes the same survey as primary cross-national data, at the country and cluster level, to characterize how barrier burdens, readiness, and the mechanism linking them vary across institutional contexts, and to test whether that mechanism transfers. No barrier weight, structural coefficient, readiness score, or roadmap element from the prior article is re-reported here as a finding; the prior work is cited as the established point of departure (Table 1).

Table 1. Relationship to prior work and the incremental contribution of this manuscript.

Dimension	Prior Single-Case Article [13]	This Manuscript
Unit of analysis	One country (Palestine), an extreme case	Participating MENA states, grouped into institutional clusters
Use of the regional survey	Binary external validation of 18 propositions	Primary country- and cluster-level analysis of item responses
Core question	What is the strategy for a constrained-sovereignty case?	Does the mechanism transfer, and how must priorities be re-weighted?
Barrier evidence	AHP/PLS weights for Palestine	Cross-national fragility gradient in barrier severity
Dissociation	Documented within one case	Tested for cross-national recurrence
Structural test	Single-group PLS-SEM	Multi-group MICOM + permutation analysis across clusters
New theory	Single-case readiness and prioritization instruments (VISTA-H_2, SPIDER)	Conflict-Affected Energy Transitions (CAET) and conditional transferability

1.3. Research Questions and Contribution

Three questions organize the analysis: RQ1: Do green hydrogen barrier burdens and their ordering vary systematically across MENA states grouped by institutional capacity? RQ2: Does the divergence between perceived and predictive barrier importance recur across the region? RQ3: Is the structural mechanism linking barriers, adoption, governance, and sustainability comparable across state types or does it differ? The contribution is threefold: Theoretically, the Conflict-Affected Energy Transitions (CAET) framework and the conditional transferability proposition treat institutional fragility as a constitutive design variable rather than an exogenous risk. Empirically, cross-national MENA evidence documents barrier heterogeneity and an institutional fragility gradient that single-case work could only assert. Methodologically, a perceived-versus-predictive comparison is combined with MICOM and permutation-based multi-group analysis to test whether the mechanism is comparable across institutional contexts. Section 2 develops the framing; Section 3 describes the data and methods; Section 4 reports the results; Sections 5–7 discuss, draw policy implications, and conclude. To our knowledge this is among the first multi-country, structural—rather than descriptive—tests of strategy transferability for hydrogen, or any low-carbon technology, across fragile and stable institutional settings. Stated compactly, this study makes three contributions: (1) the first country-level comparative analysis, to our knowledge, of green hydrogen barriers across an institutional fragility gradient, moving beyond single-case evidence; (2) a transferability testing protocol with pre-specified decision criteria—compositional invariance, mean-and-variance equality, and permutation-based path comparison—that renders the transferability verdict falsifiable; and (3) the Conflict-Affected Energy Transitions framework and its conditional transferability proposition—the mechanism travels while priorities re-weight—as a generalizable alternative to techno-economic determinism for hydrogen strategy under constrained sovereignty.

2. Theoretical Framing: Conflict-Affected Energy Transitions

2.1. Why Barrier Configurations Vary by Institutional Context

Three established lenses predict that green hydrogen barrier configurations will differ across institutional contexts rather than form a single universal ordering: The technology–organization–environment perspective identifies regulation and market structure as environmental conditions shaping adoption [14]. Institutional theory adds that, amid institu-

tional voids, governance quality becomes a structural determinant of outcomes rather than a peripheral risk [15,16]. The technological innovation systems literature links diffusion to system functions—market formation, resource mobilization, legitimacy—whose weakness helps explain why mature technologies remain undeployed in fragile states [17,18]. Together, these lenses motivate a fragility gradient in institutional barriers, which Section 4 tests directly.

2.2. The CAET Framework: Fragility and Constrained Sovereignty as Design Variables

We organize these strands into a Conflict-Affected Energy Transitions (CAET) framework. Its premise is that, in fragile and constrained-sovereignty settings, four conditions cease to be background risks and become defining features of the design problem: limited control over land, resources, and borders; physical and institutional infrastructure disruption; donor dependence that can distort local priorities; and institutional fragmentation that weakens coordination and enforcement. Under these conditions, permitting regimes, technical standards, and grid rules can express contested political authority; in the CAET framework, this is a theoretical proposition rather than a directly measured construct in the survey. The CAET framework therefore predicts that strategy in such contexts should be modular, community-scaled, governance-gated, and justice-oriented rather than a scaled-down copy of high-capacity export models. In transitions terms, it extends the multi-level perspective [19] by specifying how regime-level institutional fragility, rather than niche-level technological readiness, can become the binding constraint, and by elevating justice and sovereignty from contextual background to analytical dimensions. The framework is more than a synthesis label: relative to the technology–organization–environment view, it treats institutional fragility as a structural determinant rather than one environmental condition among several; relative to technological innovation systems, it adds sovereignty, donor dependence, and conflict disruption to generic system function weakness; relative to public-sector strategic planning, it treats institutional capacity as a design constraint rather than a downstream implementation issue [20]; and, relative to energy justice scholarship, it treats justice as a condition of pathway viability while using it as an interpretive lens rather than a measured construct [21–25].

Stated as propositions, the CAET framework holds that, (P1) in fragile contexts, institutional capacity is a binding design parameter, not a background condition; (P2) regulatory barriers reflect contested authority, not merely missing policy; (P3) justice affects pathway viability, not only normative evaluation; and (P4) transferability operates at the mechanism level, not the priority-ranking level. Table 2 situates the framework against adjacent perspectives.

Table 2. How the CAET framework differs from adjacent perspectives.

Perspective	Typical Treatment	CAET Framework's Departure
Technology–organization–environment	Institutional context is one environmental condition	Treats institutional fragility as a structural, binding design parameter
Technological innovation systems	Generic system function weakness	Adds sovereignty, donor dependence, and conflict disruption
Multi-level perspective	Regime/niche dynamics, state capacity assumed	Specifies regime-level fragility as the binding constraint
Energy justice	Justice as normative evaluation	Treats justice as a condition of pathway viability (interpretive lens here, not a modeled construct)

2.3. Energy Justice as a Constitutive Parameter

Because hydrogen is resource-intensive and increasingly export-oriented, its deployment carries a distributive and procedural charge that is sharper where sovereignty is constrained [21–23]. The hydrogen-specific justice literature extends the classical tenets: Mueller et al. [24] propose six dimensions—procedural, distributive, restorative, relational, recognitional, and epistemic—that foreground water–energy trade-offs in arid regions and the risk of North–South value chain asymmetry; a complementary socio-political and techno-economic evaluation gives the same warning, finding that resource-intensive export projects threaten distributive, procedural, and recognitional justice through neocolonial extraction, water scarcity, and land disputes [25]; a parallel critique warns of green colonialism, in which export-led renewable mega-projects reproduce extractive patterns of land and water appropriation with limited local benefit [26]. For the CAET framework, these are not ethical addenda but determinants of which pathway is viable; in fragile states, community-scale and locally governed deployment is both a justice choice and a resilience strategy, a point we return to in Sections 5 and 6. Read through the six dimensions, the three clusters imply differentiated justice exposures: fragile states face a procedural and recognitional deficit, as weak institutions limit participation; high-capacity exporters face a distributive question about where value accrues; and all of them face a relational, water-related risk in arid settings.. The present survey does not measure these justice dimensions directly; the justice lens is applied interpretively to read the cluster results and frame a research agenda, and no justice effect is statistically tested in the structural model.

2.4. From Transferability to Conditional Transferability

The framing yields the study's central proposition. If the structural relationships linking barriers, adoption, governance, and sustainability are anchored in general behavioral and institutional regularities, they may transfer across contexts, but the weight that strategy should assign to each barrier domain depends on the local configuration of fragility. We therefore distinguish the mechanism (which may be comparable across states) from the priority structure (which should vary) and propose conditional transferability: the logic travels, the ranking does not. RQ1–RQ3 operationalize this proposition empirically and yield four testable hypotheses: H1: Regulatory/institutional barrier severity increases with institutional fragility (fragile > stable developing > Gulf). H2: Within each cluster, the perceived rank of barrier severity diverges from the predictive rank, with social barriers being systematically under-weighted relative to their association with sustainability. H3a: The adoption–governance–sustainability mechanism is measurement-comparable across clusters. H3b: No structural path differs detectably between fragile and stable contexts. H1 and H2 are descriptive-inferential; H3a and H3b are tested by MICOM and permutation analysis, subject to the power limitation set out in Section 3.5.

2.5. Positioning Against Existing Comparative and Readiness Work

This contribution is adjacent to, but distinct from, three recent strands: Reviews of MENA hydrogen transitions compare regional pathways through policy, economic, infrastructure, value chain, and scalability conditions [27]; our typology is instead survey-derived and barrier-based, and is paired with a structural test. Country-level readiness assessments—such as SWOT-based evaluations of single Gulf states—characterize one jurisdiction at a time; ours is multi-country and quantitative. Multi-criteria analyses of hydrogen barriers in Africa rank obstacles within a setting [28], and analytical frameworks for developing regions weigh risks and trade-offs qualitatively [29]; ours adds a cross-national invariance test of the mechanism linking those barriers to outcomes.

Naming these neighbors clarifies the increment: it is not another ranking, but a test of whether the strategy logic itself is portable. A cross-regional parallel reinforces the logic: varying hydrogen ambitions in Chile and Peru are explained by the interaction of state capacity and business positioning [30], of which our institutional fragility gradient is the MENA analog, derived from expert data and paired with a structural test. Figure 1 summarizes the resulting CAET framework.

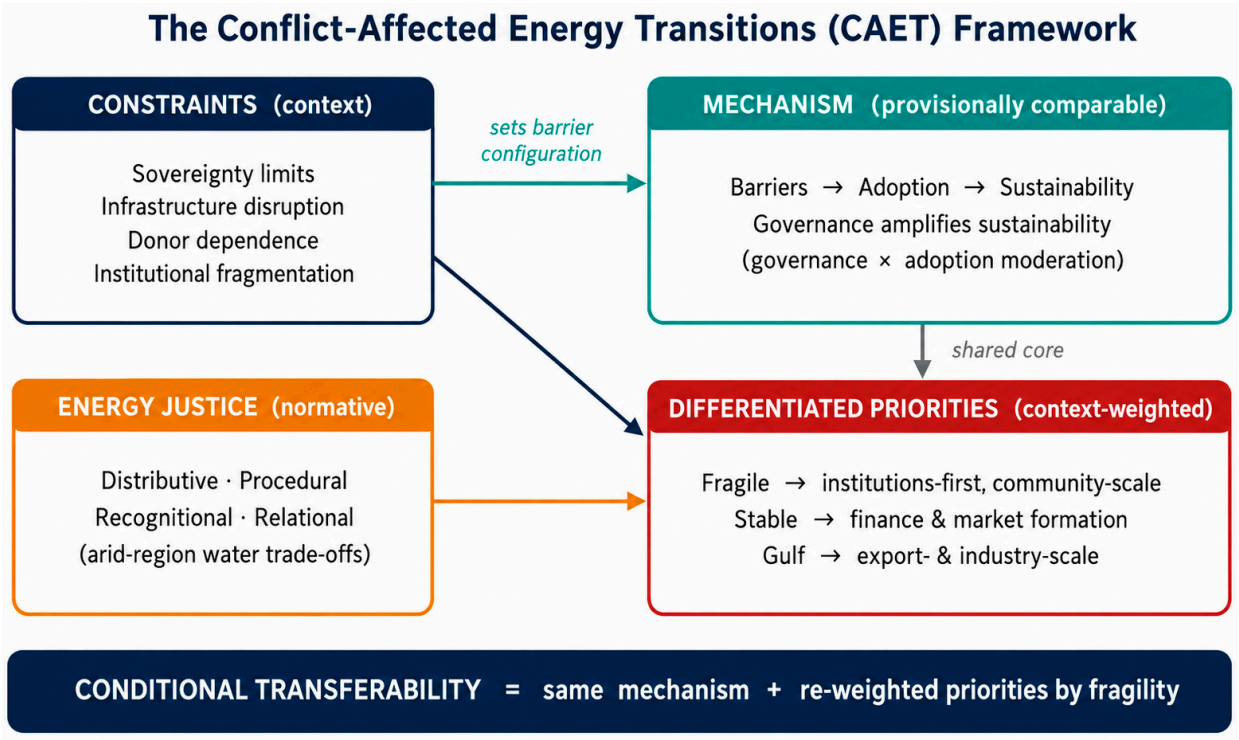


Figure 1. The Conflict-Affected Energy Transitions (CAET) framework: contextual constraints set the barrier configuration, the adoption–governance–sustainability mechanism is shown as a provisionally comparable candidate core, and justice and sovereignty serve as interpretive lenses that re-weight priorities by cluster; they are not modeled latent constructs in the survey. The governance × adoption link in the diagram is a theoretical proposition and is not statistically established here (between-group permutation $p = 0.08$).

3. Data and Methods

3.1. Data Provenance and Sample Construction

The data are responses to a structured expert survey on green hydrogen adoption and sustainability administered in Arabic across the MENA region. The instrument captures, on five-point scales, the perceived severity of technical, economic, social, and regulatory/institutional barriers, the perceived sustainability impact of adoption, the importance of supporting policies, adoption attitudes, and national readiness factors, alongside professional demographics and two priority questions. To avoid ambiguity about overlap with prior work, we state the provenance explicitly. The survey returned 158 raw responses. The companion single-case study [13] drew on a subset of this panel for one purpose only: a binary check of whether eighteen propositions met an agreement threshold. The present study instead uses retained item-level responses. Following experience and country identification screening and the item-level missing-data procedure described in Section 3.3, the analytic sample is 137 experts across seventeen states. No item-level estimates or cross-national cluster models from this regional panel were reported in the companion study. The two analyses thus share an instrument but not an inferential object: binary proposition testing there, country- and cluster-level modeling here. Responses were col-

lected through a single Arabic online instrument between 23 March and 4 June 2026. Of the 21 excluded records, 17 reported less than one year of relevant experience and 4 provided no identifiable country; the two categories are mutually exclusive, and no record required item-level deletion. Experts were recruited through purposive sampling supplemented by snowball referral via regional professional energy networks—the standard strategy for a specialized, hard-to-reach expert population. The minimum sample was fixed a priori from $n = Z^2P(1 - P)/d^2$ (95% confidence, P = 0.50, d = 0.10), giving $n \geq 96$, which the analytic sample of 137 exceeds. The instrument was identical in wording and item sequence to the 84-item Arabic questionnaire of the companion study [13]; the companion study analyzed an earlier snapshot of the same survey (N = 120), whereas the present study analyzes the full closed dataset.

3.2. Institutional Clusters and Constructs

Countries are grouped into three institutional clusters that are proxies for state capacity and fragility, with cluster membership informed by external fragility classifications rather than by the survey itself [31]: conflict-affected/fragile (Palestine, Lebanon, Iraq, Libya, Syria, Yemen, Somalia; n = 36), stable developing (Jordan, Egypt, Morocco, Tunisia, Algeria; n = 85), and Gulf/high-capacity (UAE, Saudi Arabia, Kuwait, Qatar, Oman; n = 16). The World Bank's 'Fragile and Conflict-Affected Situations' list classifies economies by institutional and policy weakness and by the presence and intensity of violent conflict; our fragile group corresponds to its institutionally weak and conflict-affected cases. Although the survey does not name or directly measure the CAET dimensions, each is linked post hoc to an observed indicator family: limited sovereignty and institutional fragmentation to regulatory/institutional barrier severity and governance; infrastructure disruption to technical barrier severity and readiness; and donor dependence to economic barrier severity and the importance attached to external policy support. These are interpretive correspondences, not a validated CAET measurement model. The fragility gradient and multi-group tests evaluate selected propositions of the framework; Table 3 sets out the mapping explicitly. Each barrier domain and the readiness, sustainability, policy, and adoption constructs are computed as the respondent mean of their items on the original one-to-five scale, with higher barrier values denoting greater perceived severity. Several countries present hybrid profiles—Lebanon combines severe institutional stress with legacy administrative capacity, and Algeria combines hydrocarbon-state features with developing-economy constraints—so the trichotomy is an analytic simplification; it is corroborated externally by the continuous Fragile States Index (Section 4.2) and probed directly by the boundary exclusion sensitivity reported in Section 4.1 and Supplementary Table S7.

Table 3. Operationalization of the CAET dimensions in the survey.

CAET Dimension	Interpretive Survey Proxy	Observed Survey Indication
Limited sovereignty	Regulatory/institutional barriers	Items on legislation, permitting, institutional coordination
Infrastructure disruption	Technical barriers and readiness	Items on technical expertise, infrastructure, resource availability
Donor dependence	Economic barriers and policy importance	Items on financing, investment risk, external support
Institutional fragmentation	Governance construct	Items on coordination, commitment, enforcement capacity

3.3. Measures and Reliability

Each construct is measured by between three and eight five-point items, listed in full as Supplementary Material. Pooled reliability and validity are generally acceptable: Cronbach's α ranges from 0.73 to 0.93 and composite reliability (ρc) from 0.83 to 0.94 across the seven constructs; average variance extracted is at or above 0.51 for every construct except the technical construct (0.49, marginally below the 0.50 convention). The technical construct is retained because composite reliability is adequate ($\rho c = 0.83$) and its indicators provide necessary content coverage, but its convergent validity is interpreted cautiously. Discriminant validity holds, with the maximum heterotrait–monotrait ratio being 0.76, below the 0.85 threshold; item collinearity is acceptable, with all variance inflation factors below 5.0. Reliability is also acceptable to excellent within each cluster (α = 0.64–0.95; per-cluster coefficients in Supplementary Table S3). Missing data were handled by listwise deletion at the item level within the screened records. The final analytic sample was $N = 137$, as described in Section 3.1.

The full item list, per-cluster reliabilities, validity coefficients, and MICOM details are provided as Supplementary Material for replication. Table 4 reports the pooled constructs, their representative items, and summary measurement properties (α, AVE, ρc). Table 5 maps each variable family to its analytic role—barrier constructs, the readiness composite, and the adoption, governance, and sustainability latents used in the structural model.

Table 4. Constructs, representative items, and measurement properties (pooled, $N = 137$).

Construct	Items	Representative Item (Gloss)	α	AVE	ρc
Technical	5	Technology not yet mature; limited technical expertise	0.74	0.49	0.83
Economic	5	High capital and production costs; financing risk	0.76	0.51	0.84
Social	4	Low public awareness and social acceptance	0.84	0.67	0.89
Regulatory	4	Absence of hydrogen-specific legislation and permitting	0.91	0.78	0.93
Adoption	3	Intention to support green hydrogen adoption	0.73	0.66	0.85
Governance	7	Strength of government policy, incentives, and commitment	0.93	0.71	0.94
Sustainability	8	Expected environmental and socio-economic benefits	0.93	0.68	0.94

Table 5. Measurement map: variable families and their roles.

Variable Family	Used in	Role	Items; Reliability
Technical, Economic, Social, Regulatory	Barrier profiles; structural model	Barrier constructs (reflective)	4–5 items each; α 0.74–0.91
Readiness	Cluster profiles, atlas, typology	Descriptive composite (not in the SEM)	7 items; α 0.93–0.95
Adoption	Structural model	Latent construct, distinct from readiness	3 items; α 0.73
Governance	Structural model	Latent construct, distinct from policy/readiness	7 items; α 0.93
Sustainability	Structural model (outcome)	Latent outcome construct	8 items; α 0.93

3.4. Analytical Strategy

Four analyses follow. Cluster profiles compare mean barrier, readiness, and sustainability scores and within-group barrier orderings. A perceived-versus-predictive comparison contrasts, for each cluster, the rank of barrier domains by direct severity rating against their rank by association with the sustainability outcome. Predictive rank is computed from the

absolute value of each barrier domain's bivariate correlation with the sustainability construct within each cluster, ties broken by mean rank (domains ordered by the magnitude of their correlation with sustainability, rank 1 = largest); a robustness check uses standardized regression coefficients from regressing sustainability on all four barrier domains jointly. The two methods agree exactly in the stable cluster and place social barriers among the two strongest predictors in every cluster, but diverge on the precise top rank in the smaller fragile and Gulf clusters, where the barrier domains are intercorrelated and per-cluster coefficients are unstable, as detailed in Section 4.3. An importance–performance map then displays each barrier domain's outcome-associated importance against its perceived severity, to identify domains that are under-resourced relative to their association with outcomes. A data-driven typology is obtained by Ward hierarchical clustering of countries with $n \geq 3$ on standardized barrier and readiness profiles, with a principal component projection used as a robustness check. This lower threshold is used only for exploratory typology construction; country-level descriptive and inferential claims elsewhere retain the $n \geq 4$ threshold. Finally, a multi-group structural model estimates, in each cluster, a Mode-A partial-least-squares path model, with barrier domains predicting adoption, and adoption, governance, and their interaction predicting sustainability. Cross-group comparability is assessed through the measurement invariance of composite models (MICOM) procedure—configural invariance by identical specification, compositional invariance via the correlation of group-specific and pooled composite scores, and equality of composite means and variances by permutation—after which, a permutation-based multi-group analysis (2000 permutations) compares the fragile and stable clusters path by path [32–35].

3.5. Sampling Design and Inferential Caution

Three features of the design bound the inferences and are stated up front rather than deferred: First, the panel is a purposive expert sample, not a probability sample, and country sub-samples are unequal (from $n = 45$ for Jordan to $n \approx 3$–5 for several fragile states); we therefore report country-level estimates only for countries with $n \geq 4$ and treat them as indicative, reserving confirmatory weight for the cluster level. Second, the adoption attitude measure exhibits a ceiling effect that weakens the barrier-to-adoption paths; the sustainability sub-model, which carries the structural argument, is more informative. Third, the data are cross-sectional self-reports, so associations are interpreted as predictive rather than causal. The Mode-A weighting approximates variance-based structural equation modeling; replication with alternative estimators (for example, consistent PLS) would be a useful robustness check. A post hoc power consideration bounds the multi-group comparison. With fragile ($n = 36$) and stable ($n = 85$) clusters, the analysis has 80% power at $\alpha = 0.05$ to detect only large between-cluster differences in standardized paths—of the order of Cohen's $q \approx 0.58$ in Fisher-z units. For example, a path of $r = 0.50$ in one cluster would be distinguishable only from $r \leq 0.0$ or $r \geq 0.80$ in the other. Modest differences would go undetected, and a finding of no detectable difference is interpreted in that light throughout. Finally, because all constructs derive from a single expert survey, common-method bias is a concern. A full collinearity diagnostic returned construct-level variance inflation factors at or below 2.45, below the proposed 3.3 threshold [36], and Harman's single-factor diagnostic attributed 29.1% of variance to the first unrotated factor. These diagnostics found no strong indication of severe common-method bias, but neither rules it out; the single-source design remains a limitation. More broadly, all constructs are expert-elicited perceptions—the appropriate evidence base for ex ante assessment of a pre-deployment technology; beyond the diagnostics above, subjectivity is bounded by the eligibility screen, by an internal consistency reliability of $\alpha = 0.739$–0.931 across constructs, and by external corroboration of the central gradient against the independently produced

Fragile States Index (Section 4.2). A further caveat concerns cross-cultural response styles: country comparisons of Likert-type ratings can confound substantive differences with acquiescent or extreme responding. Three features of the design bound this threat: the central gradient is corroborated against the Fragile States Index, an external anchor independent of respondents' scale use; the perceived-versus-predictive divergence rests on within-respondent rank comparisons, which are insensitive to uniform scale shifts; and MICOM establishes that indicator weighting is compositionally comparable across clusters. Response-style-adjusted replication (for example, with anchoring vignettes) remains a worthwhile refinement.

Estimation proceeds as follows: Indicators are standardized; each latent score is a Mode-A composite, with standardized indicators weighted by their correlation with the unit-weighted composite, chosen because the constructs are reflective measures of perceived barriers, adoption attitudes, governance, and sustainability. Path coefficients are ordinary-least-squares estimates on the latent scores; the moderation term is the standardized product of adoption and governance. Path significance and 95% confidence intervals use 2000 bootstrap resamples; between-group path differences use a 2000-permutation multi-group analysis; MICOM follows the three-step Henseler procedure. The formal multi-group comparison is the fragile-versus-stable test: the Gulf/high-capacity cluster (n = 16) is too small for stable multi-group estimation and is reported descriptively only, not entered into the permutation comparison. Exact software, package versions, and random seeds must be reported before submission so that the deposited code and results are exactly reproducible. All computations were implemented in SmartPLS 4 (SmartPLS GmbH, Oststeinbek, Germany), which performed the Mode-A composite scoring, structural path estimation, the 2000-resample bootstrap, MICOM testing, and the 2000-permutation multi-group analysis. The transferability verdict follows pre-specified decision criteria: Step 1 requires full compositional invariance (MICOM correlation c within its 5% one-sided permutation quantile for every construct); Step 2 assesses equality of composite means and variances against 95% permutation intervals, with inequality on the regulatory construct expected under the barrier gradient proposition; Step 3 tests each structural path for cross-cluster difference by two-tailed permutation testing (α = 0.05, 2000 permutations). "Provisionally transferable" requires Step 1 to pass and Step 3 to detect no difference; "definitively invariant" would additionally require Step 2 to pass in full and adequate power for small effects, which the present sample does not afford.

Relationship to the prior single-case study. The present article does not re-use any country-specific barrier weights, structural coefficients, analytic hierarchy priorities, roadmap elements, or Palestine-specific model estimates from the study of Dwaikat et al. [13]. The only shared element is the regional survey instrument; the prior article used regional responses solely to classify agreement with single-case propositions, whereas this article uses item-level, country-tagged responses as the primary dataset for cross-national modeling. No item-level estimates or cross-national cluster models from the regional panel appeared in the prior article. The inferential object differs accordingly: binary proposition validation there, comparative structural modeling here.

4. Results

4.1. Barrier Heterogeneity and the Institutional Fragility Gradient

Barrier burdens differ across the three clusters, and the difference is a re-ordering rather than a uniform shift (Figure 2; Table 6). In fragile states, regulatory/institutional barriers are the most severe constraint (4.06), above every other domain and well above the same domain in the Gulf (3.02). Fragile states also carry the highest burden on every other domain. In stable developing and Gulf states, economic barriers lead and institutional

barriers recede. The clearest single pattern is a monotonic institutional fragility gradient: regulatory severity rises from 3.02 (Gulf) to 3.52 (stable) to 4.06 (fragile) as state capacity falls (Figure 3). This trend is statistically supported, not merely descriptive. The ordered increase is significant according to the Jonckheere–Terpstra trend test ($z = 3.87$, $p < 0.001$) and by a Spearman rank correlation between fragility level and regulatory severity ($\rho = 0.34$, $p < 0.001$), with non-overlapping confidence intervals for the Gulf (3.02, 95% CI [2.55, 3.48]) and fragile (4.06, 95% CI [3.85, 4.27]) means. The step effect sizes are medium to large (Cohen's d = 0.54 Gulf–stable, 0.62 stable–fragile, 1.40 Gulf–fragile). The gradient is not a composition artifact; country-equal weighting reproduces it almost exactly (2.97, 3.51, 4.07), and it remains monotonic under leave-one-country-out removal of Palestine, Jordan, or Egypt. Excluding Jordan ($n = 45$) entirely, the stable developing mean falls to 3.37 and the ordering 3.02 < 3.37 < 4.06 is preserved; excluding the two boundary classification countries (Lebanon and Algeria) strengthens the gradient to 3.02, 3.51, 4.11. The country-level Fragile States Index association is likewise unchanged without Jordan (r = 0.67 vs. 0.66) (Supplementary Table S7). This is cross-national evidence for a proposition that single-case work could only assert, and it situates the Palestine case within a regional regularity rather than treating it as an anomaly. The 1.04-point regulatory gap between the Gulf (3.02) and fragile states (4.06) is substantively large; on a five-point scale, it is roughly the distance between rating regulatory obstacles as a moderate constraint and rating them as a severe one. It captures the cumulative effect of contested sovereignty, fragmented permitting, and the absence of hydrogen-specific legislation—conditions that technical assistance alone cannot resolve. The ordering also persists when respondents are aggregated to country means (Gulf 3.06 < stable 3.44 < fragile 3.87; Spearman rho = 0.56 across the eight countries with $n \geq 4$, not significant given the small number of country units), which indicates that the gradient is not an artifact of unequal within-country sample sizes.

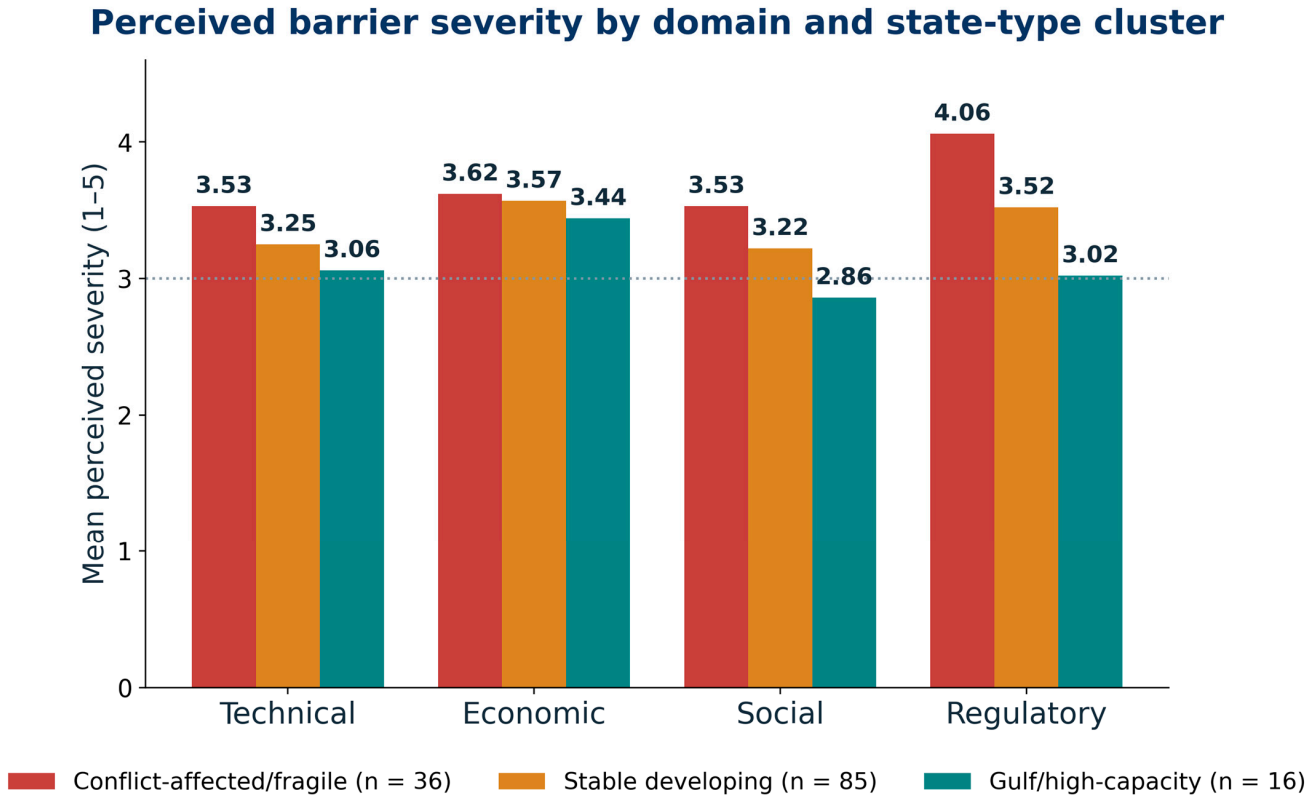


Figure 2. Mean perceived barrier severity by domain and state-type cluster. Barrier severity re-orders across clusters; regulatory barriers are most severe in fragile states.

Table 6. Barrier, readiness, and sustainability profiles by cluster (mean, 1–5).

Cluster (*n*)	Tech	Econ	Social	Regul.	Readiness	Sustain.
Conflict-affected/fragile (36)	3.53	3.62	3.54	4.06	3.93	4.15
Stable developing (85)	3.25	3.57	3.22	3.52	3.98	3.96
Gulf/high-capacity (16)	3.06	3.44	2.86	3.02	4.12	3.96

Note: Higher barrier values = greater perceived severity. Regulatory severity follows a monotonic fragility gradient (3.02 → 3.52 → 4.06).

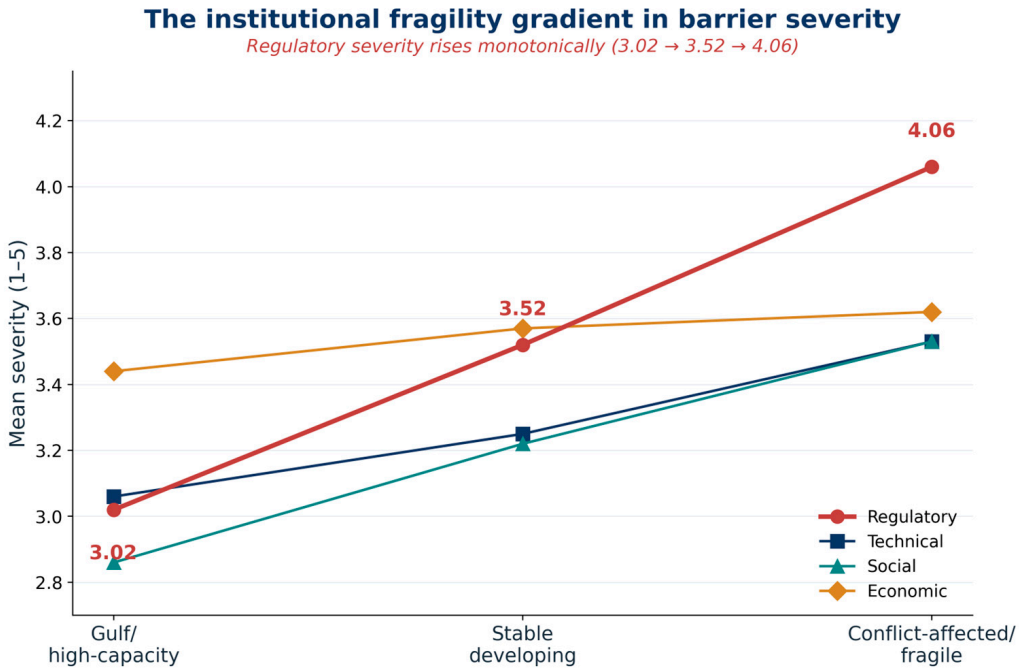


Figure 3. The institutional fragility gradient. Regulatory barrier severity rises monotonically as state capacity falls; other domains are flatter.

This regional regularity is also compared with an external, independently produced benchmark. Plotting each country's mean regulatory barrier severity against its 2024 Fragile States Index score—a composite produced by the Fund for Peace [37], separate from the World Bank classification used to form the clusters—shows the expected positive association (Figure 4): regulatory severity rises with external fragility (Pearson r = 0.66, R^2 = 0.43; slope +0.14 per ten index points). With only eight country units, the association is borderline (p = 0.08), so we read it as corroborative rather than confirmatory, but it is notable that the two domains this study foregrounds—regulatory (r = 0.66) and social (r = 0.69)—track the external index most closely, while economic (r = 0.52) and technical (r = 0.29) barriers track it weakly. Because the index is not the variable used to define the clusters, this helps address the concern that the gradient could be an artifact of the grouping criterion.

Viewed across all six domains at once, the clusters trace distinct profiles (Figure 5). The fragile cluster sits outward on every barrier axis—technical, economic, social, and especially regulatory—while reporting readiness and sustainability expectations close to the others. This juxtaposition captures the CAET premise that fragile states perceive comparable promise but face uniformly heavier constraints. The Gulf profile is the mirror image, lowest on barriers and highest on readiness, with the stable cluster between the two.

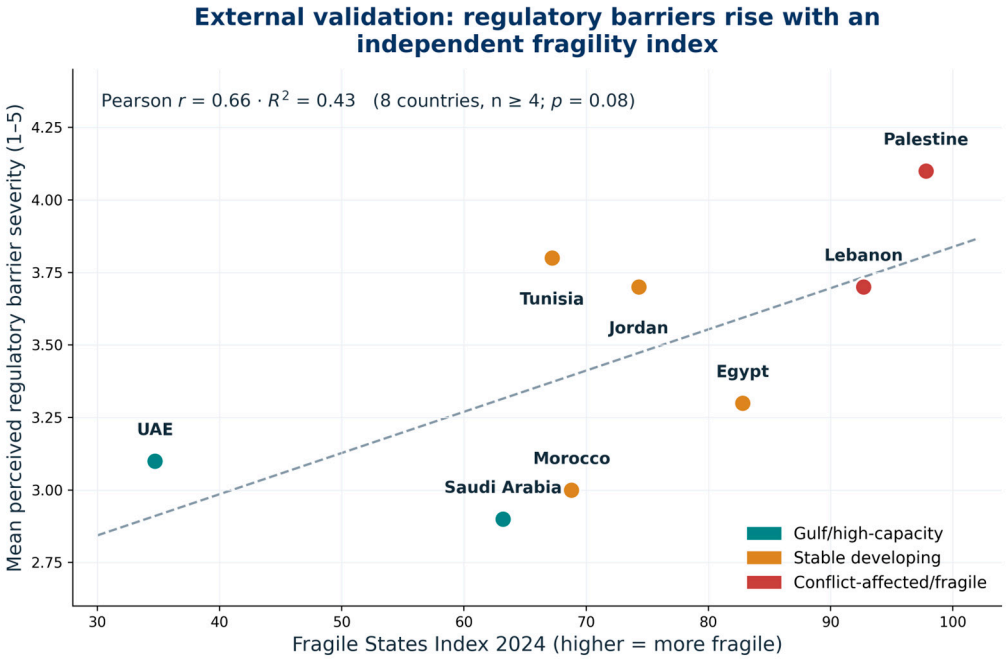


Figure 4. External corroboration of the fragility gradient. Country mean regulatory barrier severity against the Fund for Peace Fragile States Index 2024 (eight countries with $n \geq 4$). Higher index = more fragile. The association is exploratory ($p = 0.08$).

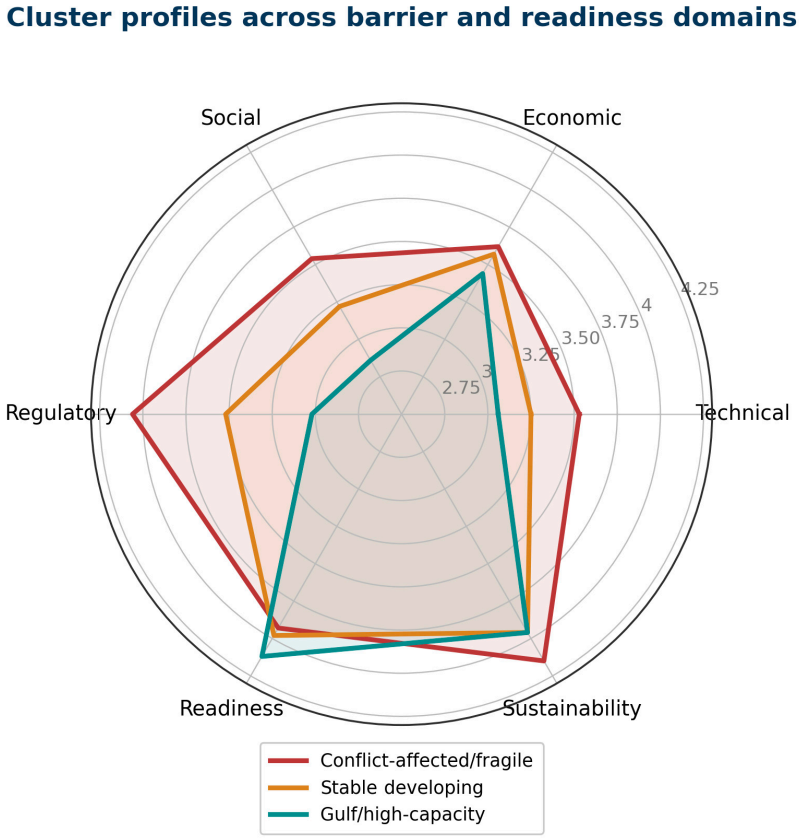


Figure 5. Cluster profiles across barrier and readiness domains. The three clusters compared on six domains (1–5); a larger reach on a barrier axis denotes greater perceived severity.

4.2. A Cross-National Barrier and Readiness Atlas

Disaggregating to countries with at least four respondents (Figure 6) shows Palestine to be carrying the region's heaviest regulatory and overall barrier load, Lebanon emerging as a

distinct low-readiness, high-stress case with the lowest readiness and sustainability ratings, and the Gulf states together with Tunisia rating highest on readiness. The atlas makes within-region heterogeneity concrete and provides the country-level inputs for the typology summarized below. Importantly, readiness and barrier severity are distinct constructs; a country may exhibit relatively high perceived readiness for hydrogen deployment while still facing severe regulatory or institutional barriers, which is the pattern observed for Palestine. The original heatmap version of this cross-national comparison is provided as Supplementary Figure S1.

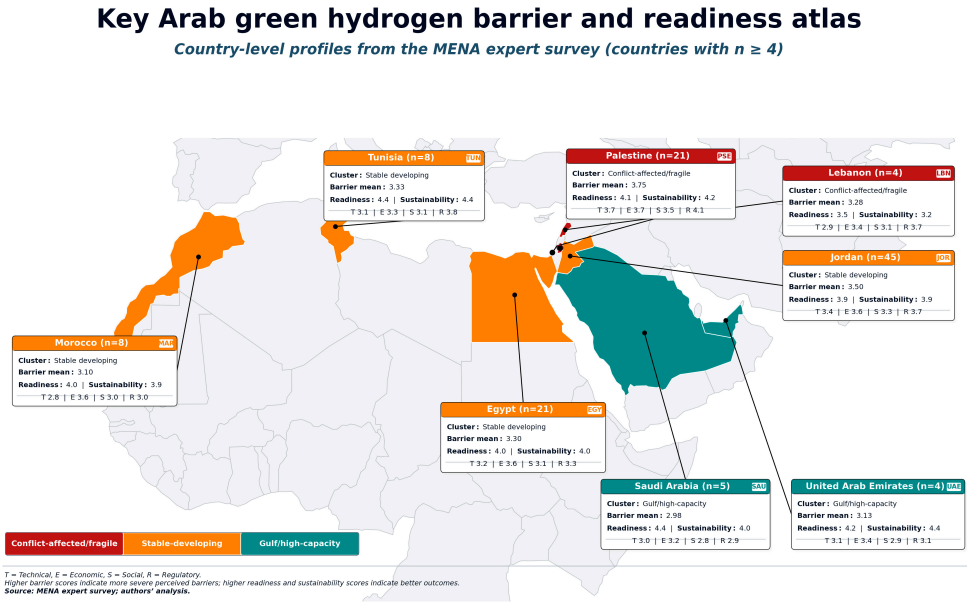


Figure 6. Key Arab green hydrogen barrier and readiness atlas (countries with $n \geq 4$). Country call-outs report cluster, barrier mean, readiness, sustainability, and the four barrier domains (T = technical, E = economic, S = social, R = regulatory); country colors denote institutional cluster; and the header tags show ISO country codes.

The same country evidence, read as a strategic map, sharpens the implication (Figure 7). Plotting each country ($n \geq 4$) by mean barrier load against readiness separates them along a diagonal: the Gulf states and Tunisia occupy the low-barrier, high-readiness quadrant, Palestine and Lebanon the high-barrier, low-readiness quadrant, and the stable developing states fall between. A single strategy template would drop these countries into very different starting positions, which is precisely why priorities must be re-weighted by context.

4.3. The Perceived–Predictive Divergence, Regionally

Within each cluster, the rank of barrier domains by direct severity rating diverges from their rank by association with the sustainability outcome (Figure 8; Table 7). The pattern is clearest in the stable cluster, where both correlation and regression place social barriers first among predictors even though they are rated least severe (social–sustainability r = 0.34, 95% CI [0.12, 0.52], n = 85; economic r = 0.26, [0.06, 0.45]). In the fragile cluster, social barriers correlate with sustainability at r = 0.41 ([0.10, 0.71], n = 36) while economic barriers do not (r = −0.02). In the Gulf cluster, the same direction appears but n = 16 makes rank ordering unstable (social r = 0.29 with a wide interval [−0.31, 0.75]), so we treat it as suggestive only. Across clusters, social barriers remain among the two strongest outcome-associated domains by both methods, while economic barriers are rated most severe yet associate weakly. This is the same perceived–predictive divergence documented for a single case, here recurring across regional data. The practical implication mirrors the

single-case one: strategy built on unaided severity rankings would under-invest in the social and institutional factors most closely tied to outcomes. The recurrence is consistent with salience weighting in the behavioral decision literature: experts foreground visible, engineering-tractable factors such as technology and cost while under-weighting diffuse, structurally embedded factors such as social acceptance and institutional trust, whose effects materialize later in deployment. The divergence is not an artifact of less-experienced respondents; among experts with more than ten years' experience, the social–sustainability association is at least as strong (r = 0.42) as among less-senior experts (r = 0.28), while the economic association stays weak in both). One boundary is worth stating plainly: unlike the fragility gradient, the perceived–predictive divergence does not survive aggregation to eight country means (social–sustainability r close to 0), consistent with its being a respondent-level cognitive pattern—salience weighting in individual judgement—rather than a country-level structural one. We therefore treat it as an individual-level finding, and rely on the cluster-level profiles and the gradient's country-level robustness for the structural claims.

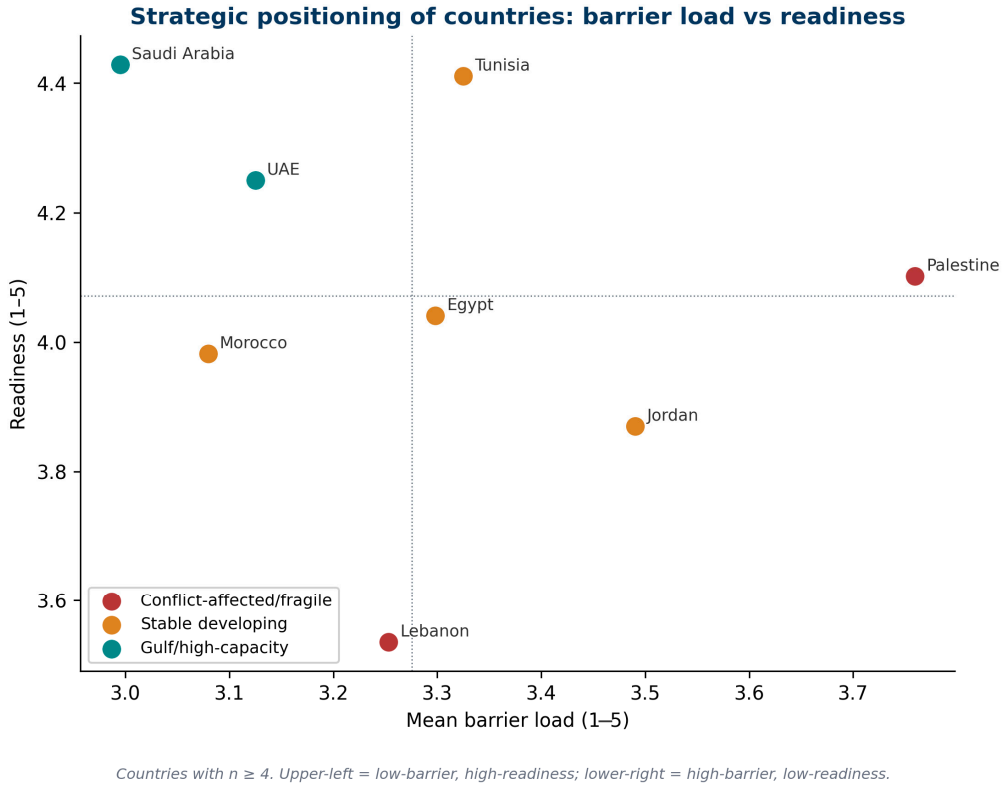


Figure 7. Strategic positioning of countries ($n \geq 4$): mean barrier load against readiness, colored by cluster. Upper left = low-barrier, high-readiness; lower right = high-barrier, low-readiness.

Table 7. Perceived-versus-predictive barrier ranks by cluster (social and economic domains).

Cluster	Domain	Perceived	Predictive (Corr)	Predictive (β)	Gap
Stable developing	Social	4	1	1	+3
Stable developing	Economic	1	3	3	−2
Gulf/high-capacity	Social	4	1	2	+3
Gulf/high-capacity	Economic	1	4	4	−3
Conflict-affected/fragile	Social	3	2	1	+1
Conflict-affected/fragile	Economic	2	4	3	−2

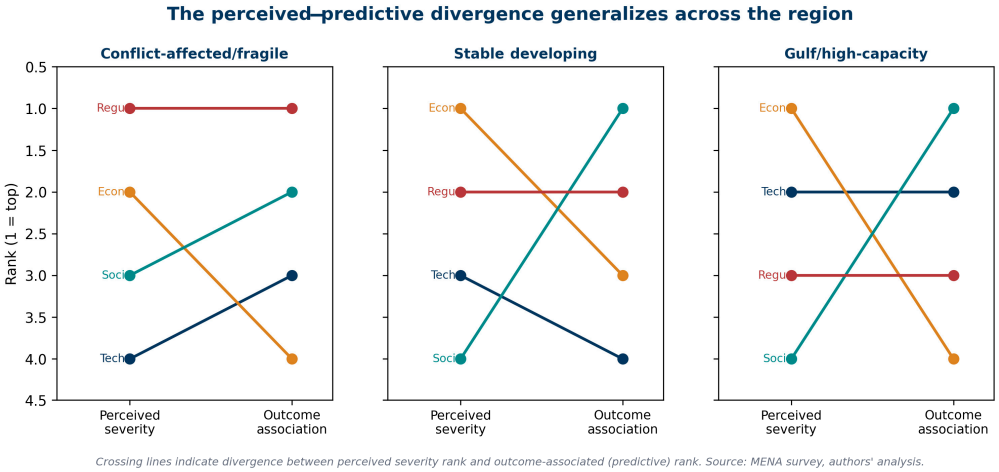


Figure 8. The perceived–predictive divergence across clusters. Crossing lines indicate divergence between direct severity rating and association with the sustainability outcome.

The same divergence can be read as a decision tool. An importance–performance map plots each barrier domain by its outcome-associated importance (correlation with sustainability) against its perceived severity (Figure 9). Social barriers fall in the high-importance, low-perceived-severity quadrant—the under-resourced priority zone—while economic barriers occupy the opposite, over-attended quadrant, and regulatory barriers are both important and recognized. The map operationalizes the finding: it is the lower-right domains that warrant a reallocation of attention and resources.

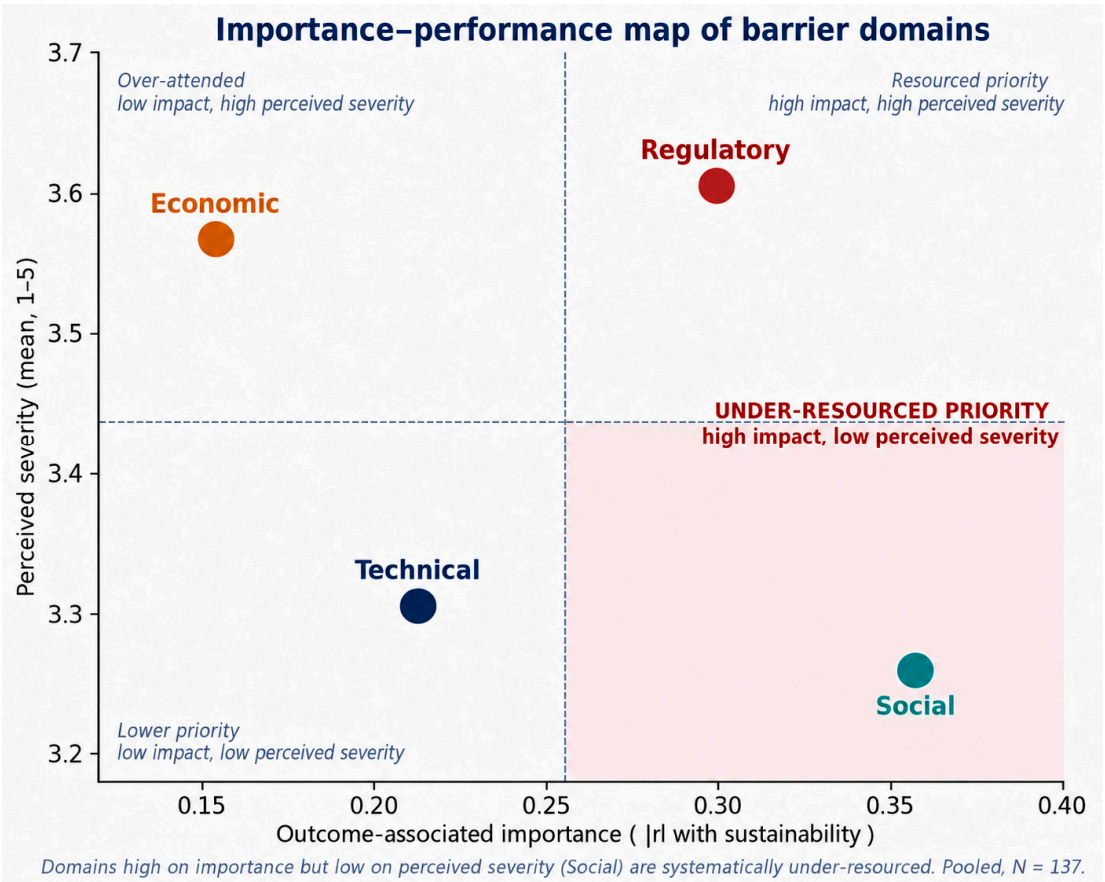


Figure 9. Importance–performance map of barrier domains (pooled, N = 137). Horizontal axis: outcome-associated importance (|r| with sustainability); vertical axis: perceived severity. Social barriers fall in the under-resourced priority quadrant.

4.4. Conditional Transferability: Measurement Comparability and the Shared Mechanism

Before testing whether the mechanism differs across clusters, the pooled construct correlations show the relationships the structural model formalizes (Figure 10). Adoption, governance, and sustainability are positively and strongly intercorrelated, whereas the barrier domains correlate only weakly with sustainability—an early indication that it is governance and adoption, rather than barrier severity itself, that carry the association with outcomes.

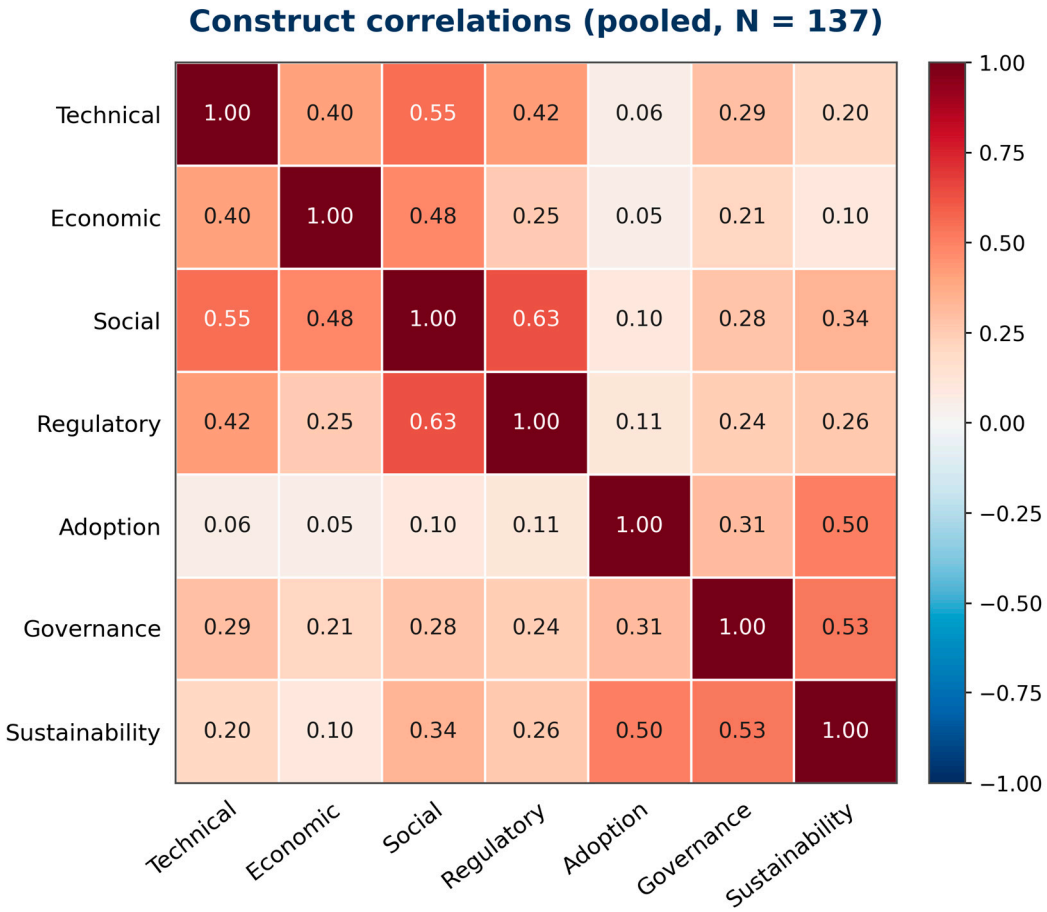


Figure 10. Construct correlation matrix (pooled, N = 137). Warmer cells denote stronger positive correlations.

Do these heterogeneous burdens imply a different mechanism in each context? The evidence indicates not (Figure 11; Tables 8 and 9). Measurement comparability is established first: MICOM confirms full compositional invariance for every construct ($c \geq 0.999$), and composite means and variances are equal across the fragile and stable clusters for all constructs except the regulatory one, whose mean and variance differ ($p = 0.001$ and $p = 0.012$). Because the clusters are defined partly by institutional fragility, this regulatory difference is expected rather than surprising; it is consistent with the grouping—regulatory burden tracks the external fragility classification—and, importantly, the difference is in the construct's level, not in how it is measured, so partial measurement invariance still holds and the path comparison remains valid. With comparability established, the dominant relationships recur across clusters: adoption is associated with sustainability in both fragile ($\beta = 0.35$) and stable ($\beta = 0.51$) states and governance with sustainability in both ($\beta = 0.41$ and 0.33), with the sustainability sub-model explaining 43% and 51% of variance, respectively. A permutation-based multi-group analysis (2000 permutations) finds no statistically detectable fragile–stable difference in any structural path (all $p > 0.05$); every

observed path difference falls well within its permutation null distribution (Figure 12), and the closest is the governance-by-adoption interaction ($p = 0.08$), discussed in Section 5.1. Given the limited power to detect modest differences (Section 3.5), we adopt a consistent posture: the data are consistent with mechanism transferability but do not establish it. We find no evidence of structural differences while acknowledging that only large ones would be detectable, and treat the mechanism as provisionally comparable pending replication. The pattern is robust to influential cases: excluding the largest national sample (Jordan, $n = 45$), the regulatory gradient and the fragile–stable regulatory difference persist ($p < 0.001$), and no structural path becomes detectably different. Comparability is strongest for the sustainability sub-model. The barrier-to-adoption paths remain exploratory because of a ceiling effect in the adoption attitude construct, so we do not claim that the full barrier→adoption→sustainability chain is equally robust across clusters. The practical implication is therefore bounded: a framework validated in one fragile state can be transferred only through local calibration of barrier weights and light-touch structural revalidation. The evidence supports provisional comparability, not universal invariance—the precise sense in which the mechanism appears to travel while the priorities do not.

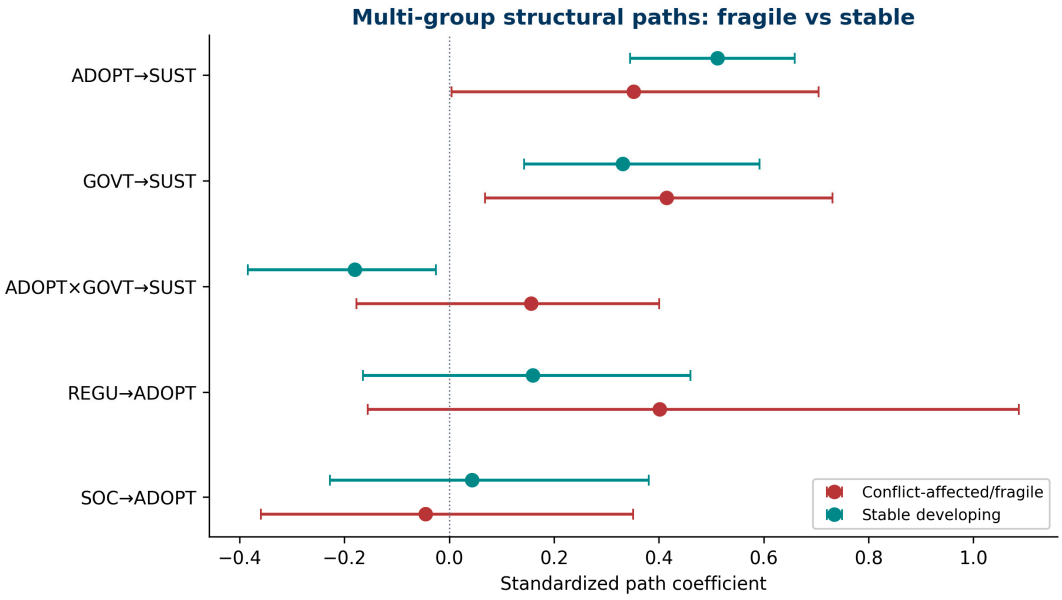


Figure 11. Multi-group path model across state types (standardized coefficients; 95% bootstrap CIs). No path differs detectably between fragile and stable clusters (permutation analysis, 2000 permutations; all $p > 0.05$).

Table 8. Selected structural paths by cluster and multi-group comparison (Fragile vs. Stable).

Path	β Fragile	β Stable	β GCC	Perm *p*	Verdict
ADOPT → SUST	0.35 *	0.51 ***	0.37	0.43	No detectable diff.
GOVT → SUST	0.41 *	0.33 **	0.63	0.70	No detectable diff.
ADOPT × GOVT → SUST	0.16	−0.18 *	0.14	0.08	Exploratory; no detectable difference
REGU → ADOPT	0.42	0.16	−0.58	0.39	No detectable diff.
SOC → ADOPT	−0.22	0.06	0.84	0.38	No detectable diff.

Note: Standardized Mode-A PLS coefficients; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (bootstrap). Perm p = permutation two-sided p (2000 permutations), fragile vs. stable. GCC ($n = 16$) reported descriptively. R2(SUST) = 0.43/0.51/0.65.

Table 9. Measurement invariance of composite models (MICOM), fragile vs. stable.

Construct	Compositional Invariance (c)	Equal Mean	Equal Variance
Technical	1.000	Yes	Yes
Economic	1.000	Yes	Yes
Social	0.999	Yes	Yes
Regulatory	0.999	No (p = 0.001)	No (p = 0.012)
Adoption	1.000	Yes	Yes
Governance	1.000	Yes	Yes
Sustainability	1.000	Yes	Yes

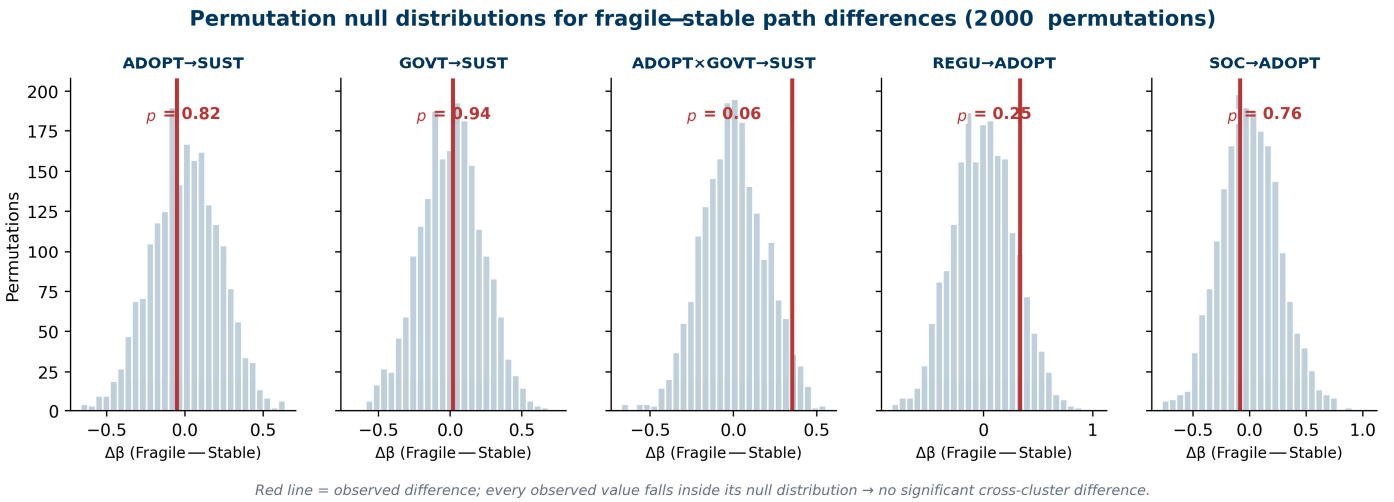


Figure 12. Permutation null distributions for fragile–stable path differences (2000 permutations). Red line = observed difference; all observed values fall within the null.

The permutation test behind this result can be read directly (Figure 12). For each of the five structural paths, the observed fragile–stable difference (red line) falls within the distribution of differences produced by randomly relabeling clusters, and none crosses the pre-specified two-sided significance threshold. The governance-by-adoption interaction lies closest to a tail (p = 0.08) and is therefore treated only as an exploratory, hypothesis-generating pattern.

4.5. An Empirical Typology of Green Hydrogen Readiness Profiles

Ward hierarchical clustering of countries on their standardized barrier and readiness profiles yields three coherent types (Figure 13): a constrained, high-barrier type groups Palestine, Iraq, and Syria (with Kuwait being an artifact of the small sample); a high-readiness type groups the UAE, Saudi Arabia, and Tunisia; and a stable developing core groups Jordan, Egypt, Morocco, Algeria, and Lebanon. The typology is exploratory given the modest per-country samples, but it maps closely onto the institutional clusters and provides an empirical, rather than assumed, basis for differentiated strategy. Internal validation supports reporting three types: silhouette scores are highest for a two-type split (0.31) and nearly as high for three (0.29), and we adopt the three-type solution because it aligns with the externally defined institutional clusters and is more informative for differentiated strategy. A principal component projection of the same country profiles corroborates the structure, with the first two components capturing 86% of the variance (58% and 28%) and separating the constrained, high-readiness, and stable core groups

along interpretable barrier and readiness axes (Figure 14). Table 10 relates this data-driven typology to descriptive strategy classifications used in the MENA policy literature.

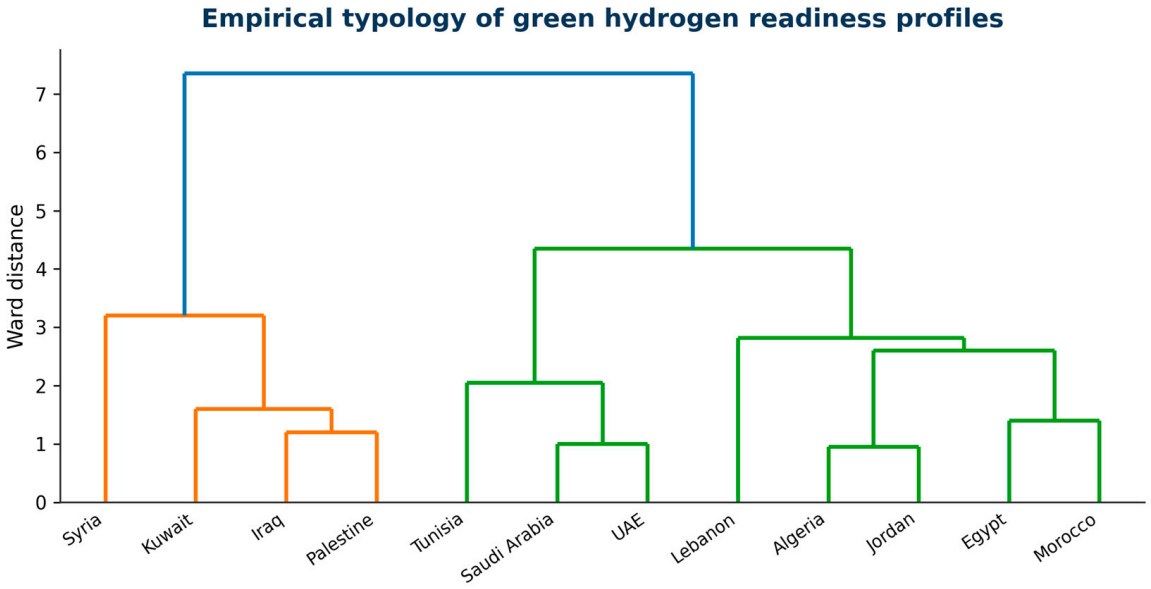


Figure 13. Empirical typology of green hydrogen readiness profiles. Ward hierarchical clustering of countries on standardized barrier and readiness profiles.

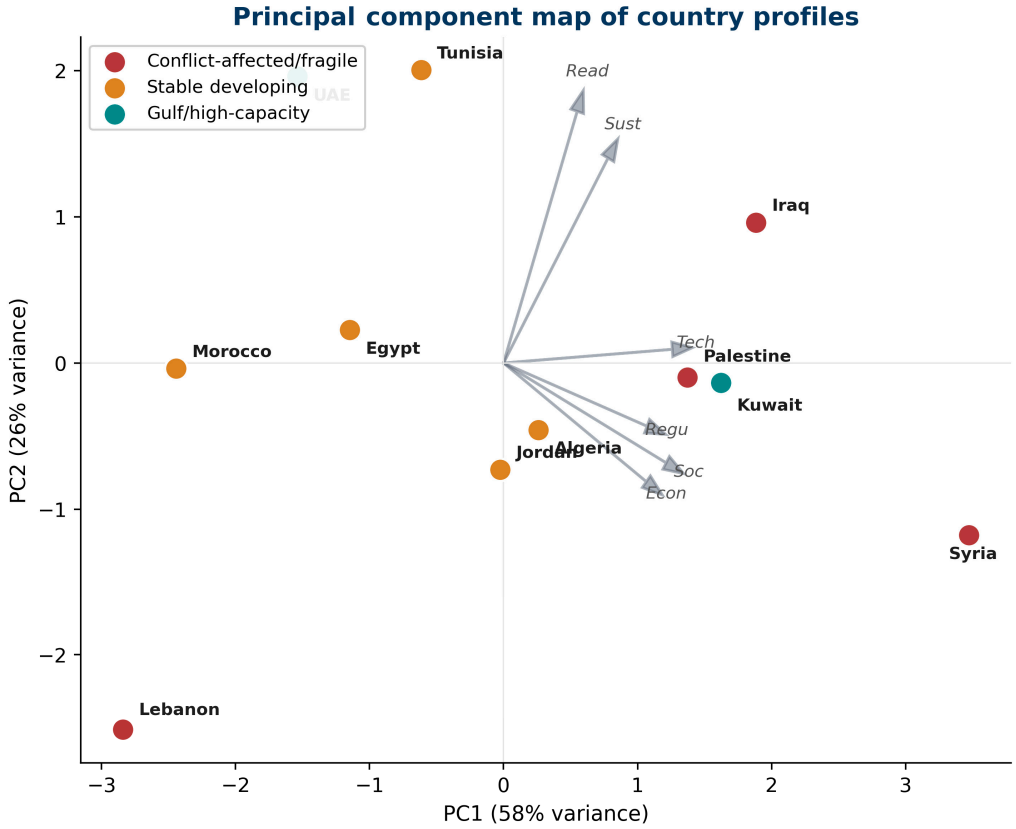


Figure 14. Principal component map of country profiles. PC1 (58%) and PC2 (28%) capture 86% of variance and reproduce the three groups; arrows are domain loadings.

Table 10. Correspondence between the data-driven typology and descriptive MENA strategy classifications.

Empirical Type (This Study)	Illustrative Members	Related Dimension in MENA Reviews	Refinement Our Data Add
Constrained/high-barrier	Palestine, Iraq, Syria	Policy and institutional capacity	Quantifies institutional/regulatory barriers as the binding constraint
High-readiness	UAE, Saudi Arabia, Tunisia	Project and value chain scalability	Groups by perceived readiness, placing Tunisia with Gulf states despite lower deployment
Stable core	Jordan, Egypt, Morocco, Algeria, Lebanon	Financing and market development	Identifies economic and finance barriers as the lead constraint

4.6. Priority Sectors by State Type

Finally, the priority application for hydrogen differs by state type (Figure 15). Power generation, industry, and energy storage dominate across clusters, but heavy and light transport feature more prominently in the stable and fragile groups, while the high-capacity group leans further toward industry and storage—consistent with the export- and industry-scale ambition of the Gulf and the community- and resilience-scale logic appropriate to fragile states.

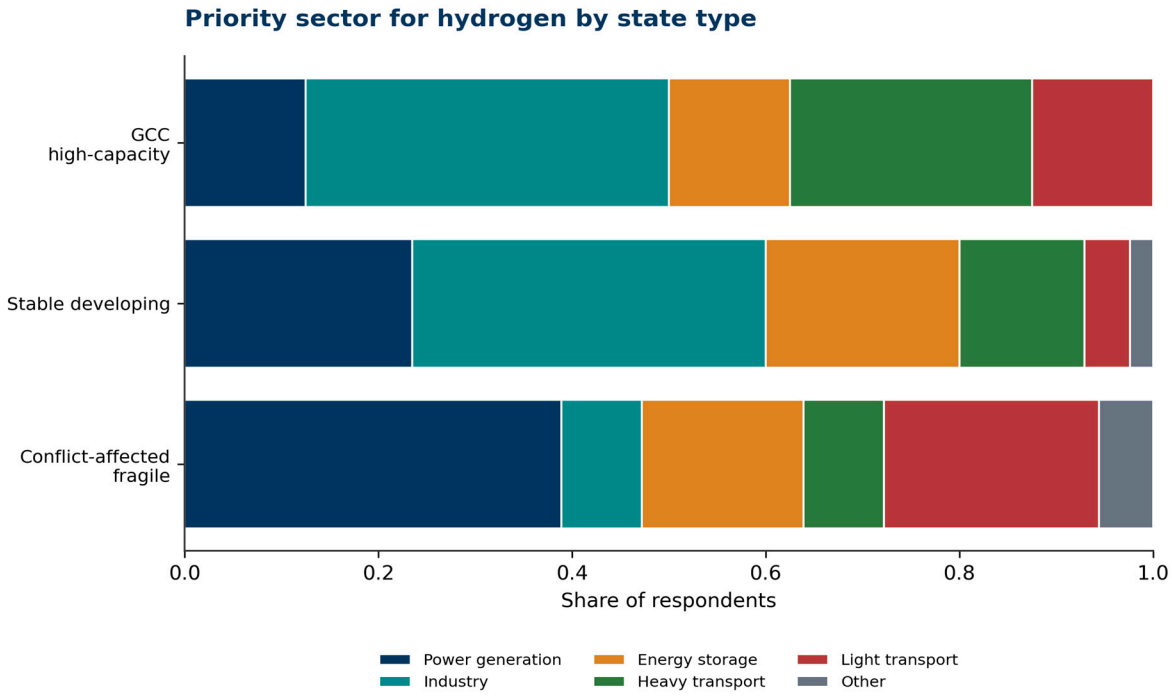


Figure 15. Priority sector for hydrogen by state type (share of respondents).

5. Discussion

5.1. Heterogeneous Burdens, Shared Mechanism: Conditional Transferability

The central result is a pairing that single-case research cannot produce. Barrier burdens are heterogeneous and follow an institutional fragility gradient, yet the mechanism linking adoption and governance to sustainability is measurement-comparable and shows no detectable cross-cluster difference. This pattern supports the conditional transferability proposition under the present sample and power constraints: what appears to transfer is the pattern that adoption and governance are positively associated with sustainability, while the priorities the mechanism implies must be re-weighted by context, because the binding barrier in a fragile state (institutional) is not the binding barrier in a Gulf state (economic).

The three findings carry different evidential weight, and we flag this explicitly: the fragility gradient in regulatory barriers is strongly supported (significant trend, medium-to-large effects, robust to weighting and case removal); the perceived–predictive divergence is moderately supported (consistent in direction across clusters but imprecise in the small Gulf sample); and the absence of cross-cluster path differences is provisional (no detectable difference at limited power, not demonstrated equality). Transferability is therefore conditional, not blanket. We stop short of claiming invariance; the multi-group test establishes no detectable difference at the present sample size, which is weaker than proven equality and should be revisited with larger national samples. The governance-by-adoption coefficients differ in sign across the fragile (+0.16) and stable (−0.18) estimates, but the between-group permutation test is non-significant ($p = 0.08$). Accordingly, this is not evidence of a sign reversal, governance amplification, or substitution. Figure 16 is retained only as an exploratory visualization of the observed coefficients and as a hypothesis-generating prompt for a higher-powered confirmatory study. Phrased precisely, we cannot reject the hypothesis of no difference at current power, which is weaker than having demonstrated equality.

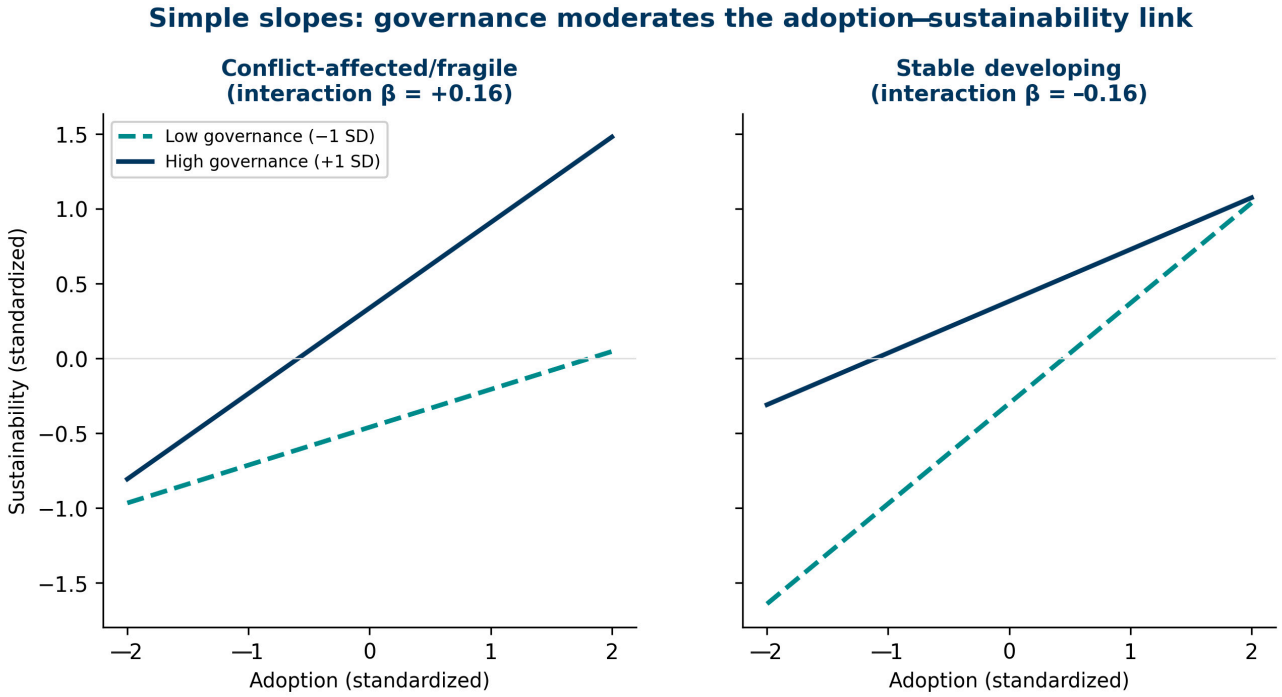


Figure 16. Exploratory simple slopes for the governance × adoption interaction on sustainability, by cluster. The plotted fragile and stable patterns visualize the observed coefficients but do not establish amplification, substitution, or a sign reversal. The between-group interaction difference is non-significant (permutation $p = 0.08$).

The dissociation at the heart of CAET can be stated as a single contrast. Barrier priorities re-order sharply across clusters: regulatory barriers move from the third-ranked constraint in the Gulf to the second in stable states to the first in fragile states (rank 3 to 2 to 1), and the fragile and Gulf clusters share essentially no common priority ordering (Spearman rho = 0.00 across the four barrier domains). The core mechanism does not re-order: the adoption- and governance-to-sustainability coefficients are near-identical across the fragile and stable clusters (within 0.06 of one another; permutation MGA $p > 0.05$). The combination of re-ordered priorities and a provisionally comparable core mechanism is precisely the CAET framework's falsifiable signature, and it is what separates the framework from the trivial claim that fragile states simply face more of everything. A finding

of re-ordered priorities together with re-ordered paths would refute it, whereas the data show the former without the latter. Table 11 summarizes the hypotheses, their supporting evidence, and the resulting verdicts.

Table 11. Hypotheses, evidence, and verdicts.

Hypothesis	Evidence	Verdict	Strength
H1: regulatory severity rises with fragility	Monotonic means; Jonckheere–Terpstra ($z = 3.87$); Spearman; effect sizes; leave-one-out; country-level	Supported	Strong
H2: perceived–predictive divergence recurs	Social under-rated yet outcome-associated by both methods (respondent-level)	Mostly supported	Moderate (Gulf n small)
H3a: measurement comparability	MICOM compositional invariance ($c \geq 0.999$)	Supported	Strong (fragile–stable)
H3b: no structural path differs	Permutation MGA, all $p > 0.05$	No detectable difference	Provisional (limited power)

5.2. Institutional Fragility as the Binding Regional Constraint

That regulatory/institutional barriers are most severe precisely where sovereignty is most constrained gives the gradient an analytical, not merely descriptive, meaning. In fragile and occupied economies, the institutional barrier can reflect contested authority to govern a transition. The present study interprets the gradient partly as a distribution of that governing capacity rather than measuring contested authority directly. This reframes institutional reform from a technical checklist into the central strategic question for hydrogen in fragile states, and it explains why a roadmap transplanted from a high-capacity exporter would misfire: it would optimize for constraints these states do not primarily face while neglecting the one they do. External risk-oriented analysis provides corroborating context: a country-risk assessment of green hydrogen development across the MENA identifies internal and external conflict and unpredictable government intervention among the prominent risks affecting project timelines, financing, and costs, with greater exposure in more fragile settings [38]. This evidence is consistent with, but does not independently prove, the interpretation that institutional barriers affect project viability rather than merely adding administrative friction.

Two counter-arguments deserve acknowledgement: one holds that institutional fragility is a transient condition that deployment itself will resolve, so strategy need not treat it as a design parameter; the other holds that top-down, export-oriented models are precisely what build institutional capacity, by attracting the investment and external discipline that reform requires. We do not dismiss these; however, the gradient's persistence across independent country-risk evidence [38], and the experience of export-first projects that have reproduced extractive dynamics in constrained-sovereignty settings, suggest that, in the most fragile contexts, capacity building must precede rather than follow scale. The CAET prescription is conditional on fragility, not a claim that institutions-first is universally optimal.

5.3. Energy Justice and the Green Colonialism Risk

The fragility gradient also has a justice dimension that bears on pathway choice. Read through the six dimensions of hydrogen justice [24], the cluster results imply different exposures: fragile states face procedural and recognitional deficits as weak institutions limit participation and relational risks as scarce water is drawn toward electrolysis; and export-oriented strategies in higher-capacity states raise distributive questions about where

value accrues. The green colonialism critique sharpens the point: externally financed, export-led mega-projects can reproduce extractive patterns unless local ownership and benefit sharing are designed from the start [26]. For fragile states, this aligns justice with resilience—community-scale, locally governed deployment is both fairer and more robust to political disruption—whereas, for high-capacity exporters, the justice task is to ensure domestic value retention alongside export ambition. Because the survey contains no justice items, these readings are interpretive applications of the framework rather than empirical findings; they should not be read as measured effects of justice—a distinction maintained here and in the policy discussion.

5.4. Theoretical and Methodological Contribution

Two contributions generalize beyond the present case: Theoretically, the Conflict-Affected Energy Transitions framework and the conditional transferability proposition reposition institutional fragility from an exogenous risk to a constitutive design variable, and separate the portable mechanism from the context-specific priority ranking—a distinction that lets strategy be transferred without being copied. Methodologically, the paper shows how a perceived-versus-predictive comparison can reveal the systematic mis-ranking of barriers that expert-led planning is prone to, and how MICOM combined with permutation-based multi-group analysis offers a disciplined test of whether a strategy mechanism is comparable across institutional contexts rather than assumed to be so. Both are applicable to other settings and technologies where strategy is built on expert judgement under heterogeneous institutions.

Operationally, conditional transferability is a three-step test rather than a slogan: a candidate strategy framework may be transferred only after (i) measurement comparability is established across source and target contexts, (ii) local barrier weights are re-elicited and re-ranked, and (iii) a minimal structural revalidation confirms the mechanism holds. This turns the concept from a conclusion into a usable procedure for analysts and lenders.

5.5. Differentiation from Prior Single-Case Work

These contributions are distinct from, and complementary to, the authors' single-case framework [13]. That paper established a barrier–adoption–sustainability framework for one country and used this survey only to confirm its propositions in binary form. The present paper analyzes the same survey as primary cross-national data to characterize heterogeneity, test the recurrence of the perceived–predictive divergence, and assess mechanism comparability—analyses absent from the prior work and not reducible to it. The single-case findings are the baseline; the comparative diagnosis, the CAET framework, and the conditional transferability proposition are new here.

5.6. Limitations

Five limitations bound the claims: First, the structural results use a Mode-A partial-least-squares weighting with MICOM and permutation analysis. While this establishes measurement comparability and tests path differences directly, replication with alternative estimators such as consistent PLS (PLSc) or ADANCO is a useful next step. Second, the adoption attitude measure shows a ceiling effect—its composite mean is 4.0 on a five-point scale, with about a fifth of respondents at or near the maximum—which weakens the barrier-to-adoption paths. The model is therefore best read as two tiers, a robust governance/adoption-to-sustainability sub-model and a more exploratory barrier-to-adoption sub-model, and the core claim does not depend on the weaker tier. Third, the Gulf cluster (n = 16) and several single-country samples are small, so cluster-level inferences are robust while single-country estimates are indicative. The Gulf cluster is reported descriptively only and is excluded from the formal multi-group comparison, and

no detectable difference denotes limited power rather than proven equality. Fourth, because respondents are nested within countries with unequal samples, individual-level standard errors may understate dependence; we therefore treat individual-level tests as indicative and rely on cluster-level profiles, country equal weighting, leave-one-country-out checks, and the country-level gradient for robustness, with multi-level modeling on larger national samples being a clear next step. Fifth, common-method bias cannot be excluded for a single-survey design. The full collinearity and Harman diagnostics found no strong indication of severe bias but cannot rule it out, and the justice interpretation is theory-guided rather than survey-measured, since the instrument contains no justice items. The data are cross-sectional self-reports from a purposive regional panel sharing an instrument with the authors' prior validation. We confine claims to the country-level, comparative analyses that prior work did not perform, and flag longitudinal tracking, independent application, triangulation with non-expert stakeholders, and extension to other fragile regions (the Sahel, the Horn of Africa, Central Asia) as priorities. Two further avenues follow directly from these limitations: formal equivalence testing—for example, the two one-sided tests procedure with pre-specified equivalence bounds—in larger national samples is the designated confirmatory next step for the invariance question, and treating institutional fragility as a continuous, index-based moderator rather than a trichotomy is a natural extension of the cluster design.

6. Policy Implications: Cluster-Specific Pathways

The findings translate into differentiated rather than uniform strategy, and the external record supports each emphasis. For fragile states, where institutional barriers bind hardest and sovereignty is constrained, the priority is an institutions-first, community-scale pathway: enabling regulation and governance capacity before scale, with modular, off-grid deployment for resilience and mandated local ownership to pre-empt extractive dynamics. This recommendation must reckon with a paradox the data expose—the regulatory capacity it calls for is precisely what is most contested in fragile states—so the realistic sequence begins with executive instruments and simplified permitting pilot zones, supported by international technical assistance, before primary legislation and scale. Lebanon, the region's clearest low-readiness, high-stress case (Figure 6), illustrates the cost of skipping this. For stable developing states, where economic barriers lead, the priority is finance and market formation—blended finance to lower the cost of capital, offtake certainty, and certification readiness—consistent with international assessments that identify high capital costs and unclear regulation as the principal brakes on hydrogen in emerging and developing economies, and that note the risk of over-reliance on export markets [2,39]. Jordan, whose national green hydrogen strategy already frames this finance and market formation challenge, exemplifies it, and European offtakers' own due diligence—screening partner countries by fragility, corruption, and water stress indicators—shows why certification readiness and bankability are the levers that attract foreign capital [40]. For Gulf/high-capacity states, where barriers are lowest and readiness highest, the priority is export- and industry-scale deployment and regional infrastructure, for which the region's solar and wind endowment offers a favorable techno-economic basis [41], coupled with domestic value retention. The UAE's export build-out, anchored by Masdar and national hydrogen roadmaps, exemplifies the pathway. Across all three, the regional divergence between perceived and predictive importance cautions against allocating effort in proportion to perceived severity; the social and institutional factors most closely tied to outcomes are systematically under-weighted by expert intuition and should be resourced accordingly. Table 12 sets out the operationalized policy pathway for each cluster, and Table 13 sequences its implementation.

Table 12. Operationalized policy pathways by cluster.

Cluster	Binding Barrier	Strategic Priority	Key Instruments	Justice Dimension	Key Metric
Conflict-affected/fragile	Regulatory/institutional	Institutions-first, community-scale	Framework law; single-window permitting; local co-ownership mandate	Procedural, recognitional	Readiness score; local ownership %
Stable developing	Economic (cost of capital)	Finance and market formation	Blended finance; offtake contracts (CCfDs); certification readiness	Distributive	LCOH; WACC reduction
Gulf/high-capacity	Readiness/scale	Export and industry-scale deployment	Regional corridors; sovereign fund participation; port readiness	Distributive (value retention)	Export volume; jobs created

Table 13. Implementation sequencing by cluster.

Phase	Conflict-Affected/Fragile	Stable Developing	Gulf/High-Capacity
First 12 months	Executive hydrogen framework; pilot zone permitting; donor coordination; water safeguards	Blended finance facility; offtake scoping; certification roadmap	Corridor agreements; port readiness; value retention targets
2–5 years	Modular pilots; local ownership; capacity building; technical standards	WACC reduction instruments; industrial demand anchors; standards	Industrial-scale electrolysis; export build-out; local manufacturing
Scale-up gate	Single-window permitting; verified water-energy safeguards; benefit sharing	Signed offtake; certification in place; bankable WACC	Domestic value retention met; desalination coupling secured

Across all three clusters, the perceived–predictive divergence carries a cross-cutting caution: effort should not be allocated in proportion to perceived severity. The social and institutional factors most closely tied to sustainability outcomes are systematically under-weighted by expert intuition, and should be resourced accordingly, regardless of cluster—through the participatory siting, social acceptance measures, and institutional trust building that conventional, technology-led strategy tends to defer. Each pathway is also gated; fragile states should not scale past pilots until a hydrogen framework is drafted, single-window permitting operates, and water source and local ownership safeguards are in place; stable developing states until offtake and certification establish bankability; and Gulf states until domestic value retention and water desalination coupling are secured. A final caution tempers all three: hydrogen should be deployed where it is the efficient option, not by default—direct electrification and batteries are preferable for many end-uses—so these gates should screen out applications better served by those alternatives, lest the critique of techno-economic determinism give way to hydrogen hype. The institutions-first prescription also has a political economy: regulatory reform redistributes authority, so its winners (reform-minded ministries, new entrants, communities gaining procedural voice) and its losers (incumbents who benefit from discretionary permitting) shape what is feasible, and sequencing should anticipate that resistance. The sector priorities in Figure 15 map onto these pathways: fragile states should lead with power generation and local resilience applications, stable developing states with industry, storage, and transport where finance and offtake can be secured, and Gulf states with industrial feedstock, export corridors, and port-linked infrastructure.

7. Conclusions

Analyzing a regional survey at the country level—data previously used only for binary validation—this study shows that green hydrogen barrier burdens across the MENA are heterogeneous and follow a clear institutional fragility gradient, that the divergence between perceived and predictive barrier importance recurs across the region, and that, despite these differences in burden, the mechanism linking adoption and governance to sustainability is measurement-comparable and shows no statistically detectable cross-cluster difference. Because the design affords 80% power only for large between-cluster path differences, we do not accept the null hypothesis of equality; absence of evidence under limited power is not evidence of absence. We therefore frame the mechanism as provisionally comparable—a proposition supported, not proven—pending larger national samples and formal equivalence testing. Framed through a Conflict-Affected Energy Transitions lens, these results yield a conditional transferability proposition: the mechanism appears to travel, while the priorities do not. The proposition reaches beyond the MENA. For any fragile or developing economy designing a hydrogen strategy, the sequence is what matters: diagnose institutional fragility, correct for expert perception bias, deploy at small scale through readiness gates, and only then consider scale-up. The alternative—copying the pathway of high-capacity exporters—misallocates scarce resources and risks reproducing the very dependencies that hydrogen is meant to reduce. Confirmatory multi-group modeling on larger national samples and longitudinal tracking as institutions reform are the natural next steps. In the global hydrogen transition, the hardest cases—conflict-affected and fragile economies—demand a strategy that treats constraint as a design parameter rather than an obstacle.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/hydrogen7030124/s1: Figure S1: Original heatmap version of the cross-national barrier and readiness atlas (countries with $n \geq 4$; Panel A, barrier severity; Panel B, readiness and sustainability); Table S1: Cluster-level construct profiles; Table S2: Measurement and reliability diagnostics; Table S3: Full structural path estimates with permutation-based multi-group comparison; Table S4: MICOM measurement invariance results; Table S5: Country-level summaries with the Fragile States Index 2024; Table S6: Justice interpretive mapping (operationalized policy pathways by cluster); Table S7: Robustness of the fragility gradient to sample composition and classification checks. The anonymized analytic dataset (n = 137) and all computation layers are available from the corresponding author on reasonable request (see Data Availability Statement).

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Abbreviations

CAET, Conflict-Affected Energy Transitions; GH_2, green hydrogen; MENA, Middle East and North Africa; AHP, analytic hierarchy process; PLS-SEM, partial least-squares structural equation modeling; MGA, multi-group analysis; MICOM, measurement invariance of composite models; GCC, Gulf Cooperation Council; TOE, technology–organization–environment; TIS, technological innovation systems; CI, confidence interval; FSI, Fragile States Index; PLSc, consistent partial least squares; VIF, variance inflation factor.

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