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# Flow survival, maritime restoration, and commercial substitution: an empirical assessment of resilience in LNG supply-chain continuity during the 2026 Strait of Hormuz disruption

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Sustainable energy supply chains depend on the assumption that resilience and sustainability move together. The 2026 Strait of Hormuz disruption tests that assumption directly. For Qatar, a single-route LNG exporter with no pipeline bypass, the disruption produced a severe physical and logistical shock alongside a measurable macroeconomic one: QatarEnergy's leadership estimated $20 billion in annual lost revenue (approximately 37% of expected government revenue), while Q1 2026 GDP contracted 7% year-on-year, driven by a 26% collapse in mining and quarrying. Existing quantitative treatments operate at the macroeconomic level, modeling cascading impacts on importing economies or generic blockade scenarios, but none empirically measures the exporting system's resilience using verified, disaggregated flow, shipping, and contract data, or links that performance to its socio-economic and environmental consequences. This study addresses that gap through a multi-level empirical case analysis of QatarEnergy's LNG export system (from 28 February 2026 through August 2026), distinguishing chokepoint-level operating conditions from a documented firm-level commercial response. Three resilience dimensions are operationalized as ex-post empirical proxies adapted from the absorptive-adaptive-restorative capacity framework: a flow-survival ratio (EIA tanker-tracking data), a maritime restoration proxy (daily vessel-transit observations), and a commercial substitution ratio (a buyer-level force-majeure and replacement sequence), reported primarily by volume and secondarily by cargo count. Results show LNG flow survival (approximately 8% of pre-war baseline) was substantially more severe than oil flow survival (approximately 23%), consistent with Qatar's structural absence of pipeline bypass capacity. Maritime activity remained a small fraction of pre-war levels throughout, while volume-based commercial substitution for a major European buyer rose from 46% to a plateau of roughly 53% of canceled gas-equivalent volume, materially below the 72% implied by a cargo-count ratio for the same case. These findings indicate that physical, logistical, and commercial-adaptive resilience are empirically distinct dimensions, measured at different levels, that should be reported separately; even partial commercial substitution may mask, rather than resolve, underlying physical vulnerability whose socio-economic and environmental consequences persist regardless of contractual continuity. The study contributes a replicable, source-audited empirical methodology linking

firm-level resilience performance to the sustainability outcomes of commodity-dependent supply chains under active disruption.

KEYWORDS

commodity markets, empirical resilience metrics, energy security, liquefied natural gas, Qatar, Strait of Hormuz, supply chain resilience, sustainability

# 1 Introduction

## 1.1 Disruption, resilience, and sustainable supply-chain continuity

Global supply chains have increasingly been forced to confront disruptions whose origin is geopolitical rather than epidemiological, financial, or purely logistical in nature. The COVID-19 pandemic established, for a broad research community, that resilience and sustainability are not competing objectives but frequently reinforcing ones: diversification, visibility, and workforce stability investments made on sustainability grounds often proved decisive for operational continuity during acute shocks (Negri et al., 2021; Ivanov, 2022; Ivanov and Dolgui, 2020). The 2026 Iran war, and the associated closure and subsequent contested reopening of the Strait of Hormuz, constitutes a disruption episode of comparable severity but distinct structural character: rather than a diffuse, globally distributed shock, it is concentrated on a single maritime chokepoint through which approximately one-fifth of the world's traded LNG and roughly a quarter of seaborne oil transited prior to the war. This concentration makes the episode an unusually clear empirical setting in which to examine how resilience and sustainable continuity interact when redundancy at the point of maximum vulnerability is structurally limited or, for some producers, entirely absent.

## 1.2 Energy chokepoints and the structural vulnerability of single-route LNG export

Qatar occupies a distinctive position within this episode. As the world's second-largest LNG exporter, supplying markets across Asia and Europe from its Ras Laffan and Mesaieed facilities, QatarEnergy has no pipeline alternative to the Strait of Hormuz for LNG shipment; unlike Saudi Arabia and the United Arab Emirates, which retain partial pipeline bypass capacity for crude oil, Qatar's entire LNG export volume depends on a single maritime corridor. Following the outbreak of hostilities on 28 February 2026, Iranian strikes on Ras Laffan and Mesaieed removed an estimated 17% of Qatar's LNG export capacity, a loss QatarEnergy's own leadership indicated could take up to 5 years to fully repair, while the intermittent closure, blockade, and contested reopening of the Strait itself constrained the shipment of whatever volumes remained producible. This combination of production-side and transit-side disruption, occurring simultaneously and over a sustained period, distinguishes the episode from shorter or more geographically distributed disruptions previously studied in the resilience literature and provides the empirical basis for the present analysis. Because environmental and logistical costs—additional freight distance, elevated insurance and fuel burden from rerouting, and the emissions profile of substitute sourcing—scale directly with the severity and duration of such disruptions, the episode is simultaneously a resilience problem and a sustainability problem, not two separate concerns to be addressed by two separate literatures.

## 1.3 The resilience-measurement gap in existing quantitative treatments

Two quantitative studies of this episode's supply-chain consequences have appeared to date, and both operate at the macroeconomic rather than the firm- or system-level. Mishra et al. (2026) develop a multi-regional input–output optimization model to estimate how a disruption in Qatar's gas sector propagates to importing economies, finding the largest aggregate impacts concentrated in India, China, and South Korea, and evaluating the extent to which trade reallocation and expanded production elsewhere can mitigate the resulting losses. An et al. (2026) develop a complementary dynamic input–output stress test of a generic Strait of Hormuz blockade scenario, tracing how an upstream energy-route cost shock propagates through global industrial sectors before being absorbed by final demand. Both studies are, in effect, applications of ripple-effect analysis (Ivanov et al., 2014) to this specific episode, tracing how a disruption originating in one node propagates through a network to affect others. Both are methodologically rigorous within their own frame, and both treat Qatar as the origin of a shock whose consequences are measured elsewhere—in importing countries, in downstream industrial sectors, in global final demand. Neither asks, nor is designed to answer, a distinct and prior question: how resilient was the exporting system itself, empirically, during the disruption it caused? A third, more conceptual treatment (Sarwar, 2026) proposes a decision-intelligence framework linking sustainability practices to resilience outcomes across commodity-dependent supply chains generally, including a discussion of Qatar's exposure, but the analysis is narrative and does not compute disaggregated, source-verified empirical indicators for any single case. The result is a gap between two literatures: macroeconomic propagation models that do not measure exporter-level resilience directly, and conceptual or narrative resilience frameworks that are not grounded in verified, disaggregated empirical observation of a specific, ongoing episode. The literature search underlying this positioning was conducted through Google Scholar, Web of Science, and Scopus using combinations of the terms "Strait of Hormuz", "Qatar LNG", "supply chain resilience", "energy chokepoint", "maritime disruption", and "resilience-sustainability nexus", restricted to items published between January 2020 and August 2026 and supplemented by a manual search of recent working papers and preprints given the recency of the episode; studies were included if they provided a quantitative or empirical treatment of the 2026 Strait of Hormuz disruption or a closely comparable single-chokepoint energy-export disruption. Two further recent studies document how the LNG shipping network itself responded to unrelated geopolitical disruptions—Suez Canal risk (Polemis and Bentsos, 2025) and two other geopolitical shocks (Liu et al., 2025)—tracing network-level rerouting and flow-reallocation patterns; neither constructs firm- or

exporter-level resilience indicators or addresses the 2026 Strait of Hormuz episode specifically, leaving the gap this study addresses intact.

### 1.4 Research objectives and contributions

This study addresses that gap by developing and applying an empirical, ex-post resilience-measurement approach to QatarEnergy's LNG export system during the period from the war's outbreak through the most recently available verified data. The study makes three contributions. First, it operationalizes the absorptive-adaptive-restorative resilience framework of Hosseini et al. (2019)—previously applied by the author within an ex-ante stochastic network-design context—into three empirically observable, ex-post indicators suited to the analysis of a single realized disruption episode: a flow-survival ratio, a maritime restoration proxy, and a commercial substitution ratio, each computed from an independently sourced and verified dataset rather than a unified internal model. Second, it applies these indicators to QatarEnergy specifically, providing an exporter-focused empirical assessment that, among studies identified by the author as of the analysis date, complements rather than duplicates the existing importer-side and generic-scenario macroeconomic literature. Third, it demonstrates empirically that physical flow survival, observable maritime activity, and commercial-adaptive capacity are distinct dimensions that can diverge substantially from one another within a single disruption episode—a finding with direct implications for how resilience and sustainability should be jointly assessed, since strong performance on one dimension, such as commercial substitution, does not imply strong performance on another, such as physical throughput, and the two carry different environmental and logistical footprints. The remainder of the paper proceeds as follows. Section 2 situates the study within the theoretical literature on supply-chain resilience and its integration with sustainability. Section 3 details the data sources, verification procedure, and the formal definition of each empirical indicator, including the sensitivity analyses used to represent genuine disagreement across independent data sources. Section 4 reports results. Section 5 discusses theoretical, managerial, and policy implications, with explicit attention to the sustainability dimension required by the scope of this Research Topic. Section 6 states limitations, and Section 7 concludes.

## 2 Theoretical background

### 2.1 Supply-chain resilience: from disturbance-absorption to viability

Supply-chain resilience has been defined, since its earliest formulations, as the capacity of a system to prepare for unexpected events, respond to disruptions, and recover from them while maintaining continuity of operations at an acceptable level (Christopher and Peck, 2004; Ponomarov and Holcomb, 2009). Two conceptual shifts within this literature are directly relevant to the present study. First, resilience has progressively been distinguished from mere robustness: a robust system resists disturbance by remaining largely unchanged, whereas a resilient system may be substantially perturbed but retains the capacity to adapt and recover (Pettit et al., 2013), consistent with the broader argument that firms should pursue strategies that perform well both under normal fluctuation and under major disruption rather than optimizing for either condition alone (Tang, 2006). This distinction matters for a single-chokepoint LNG exporter, where robustness in the sense of undisturbed throughput was never a realistic possibility once the transit route itself was contested; the relevant empirical question is not whether disturbance occurred, but how the system's different components—physical flow, observable logistics activity, and commercial contracting—responded once it did. Second, more recent work has reframed resilience within a broader viability perspective, in which supply chains are treated as complex adaptive systems whose survival depends on the joint, sometimes decoupled, performance of structural, operational, and relational subsystems under sustained rather than transient disruption (Ivanov and Dolgui, 2020; Ivanov, 2022). The 2026 Hormuz episode, unfolding over months rather than days, sits squarely within this sustained-disruption frame rather than the shorter-horizon disruptions on which much of the earlier resilience literature was built.

### 2.2 Absorptive, adaptive, and restorative capacity

A widely used operationalization decomposes supply-chain resilience into three constituent capacities (Hosseini et al., 2019), adapting the concept of absorptive capacity originally developed in the organizational-learning literature (Cohen and Levinthal, 1990) to the supply-chain disruption context. Absorptive capacity refers to a system's ability to withstand a disruption's initial impact without requiring active intervention, typically through pre-positioned buffers, redundancy, or structural diversification. Adaptive capacity refers to a system's ability to reconfigure its operations during a disruption, through recourse actions such as rerouting, substitution, or reallocation, so as to limit the disruption's consequences. Restorative capacity refers to a system's ability to return to, or toward, its pre-disruption performance level once conditions permit. This tripartite decomposition has been applied primarily within ex-ante contexts, in which candidate network designs or sourcing strategies are evaluated and compared before a disruption occurs, using decision and recourse variables internal to a stochastic optimization or simulation model. The present study departs from that convention: the object of analysis is a single, already-realized disruption episode affecting one firm's actual operations, not a set of candidate designs to be ranked. Section 3 sets out explicitly how each construct is re-operationalized as an ex-post, independently verifiable empirical indicator suited to this different analytical setting, rather than assumed to transfer unchanged. Recent chokepoint-focused work has also begun formalizing disruption-risk evaluation and re-routing decision-making at maritime chokepoints generally (Wen et al., 2026), reinforcing the present study's premise that chokepoint concentration is a distinct structural vulnerability meriting dedicated empirical treatment.

### 2.3 The resilience–sustainability nexus

A separate but converging literature has argued that resilience and sustainability, often treated as competing managerial objectives subject to trade-off, are frequently complementary rather than opposed (Fiksel, 2003; Negri et al., 2021). Sustainability-motivated investments—supplier diversification undertaken to reduce environmental footprint, traceability systems adopted for regulatory compliance, workforce and community investment made on social-responsibility grounds—have been shown to generate resilience benefits as a

byproduct, because they create option value, redundancy, and information visibility that prove valuable precisely when disruption occurs, even though this was not their original purpose (Sheffi and Rice, 2005; Negri et al., 2021). The converse relationship, less thoroughly examined in the empirical literature, is equally important for the present case: how a firm responds to a disruption also carries sustainability consequences that persist beyond the disruption itself. Commercial substitution—rerouting cargoes, securing alternative supply, reallocating volumes across a global portfolio—restores contractual and revenue continuity, but it does so by lengthening transport distances, increasing fuel burn and emissions intensity, and redistributing environmental and logistical exposure across the network rather than eliminating it. A resilience assessment that reports only whether continuity was restored, without separately reporting how it was restored, risks treating commercial adaptation as costless when it is not. This is the conceptual basis for the present study's decision to report flow-survival, maritime-restoration, and commercial-substitution indicators separately rather than collapsing them into a single composite score: each dimension carries distinct sustainability implications, and aggregation would obscure precisely the trade-off this Research Topic is concerned with.

## 2.4 From theoretical constructs to observable indicators

Bridging Sections 2.2 and 2.3 requires an explicit mapping from the theoretical constructs of absorptive, adaptive, and restorative capacity to indicators that can be computed from independently verifiable, publicly available data for a single real-world case, rather than from internal model variables. Table 1 previews this mapping, which is developed formally in Section 3. Flow survival—the fraction of pre-disruption physical throughput that continued despite the shock—is conceptually closest to absorptive capacity, though it is more precisely described as an observed flow-performance outcome than a direct measurement of latent absorptive capacity, a distinction maintained explicitly throughout the empirical analysis. Maritime restoration—the recovery of observable shipping activity toward its pre-disruption level—is conceptually closest to restorative capacity. Commercial substitution—the extent to which canceled contractual volumes were replaced through alternative sourcing—is conceptually closest to adaptive capacity. This mapping is offered as an interpretive bridge rather than a claim of formal equivalence: each empirical indicator is defined independently in Section 3 according to what its underlying data source actually measures, and its relationship to the corresponding theoretical construct is stated as an interpretation, not asserted as a direct measurement.

# 3 Materials and methods

## 3.1 Case and disruption context

The empirical case is QatarEnergy's liquefied natural gas export system during the period from the outbreak of the 2026 Iran war on 28 February 2026 through the most recently available verified data as of the analysis date (late August 2026). Iranian strikes on the Ras Laffan and Mesaieed export facilities in March 2026 damaged an estimated 17% of Qatar's LNG export capacity, a figure stated by QatarEnergy's own leadership alongside an estimated repair horizon of up to 5 years. Independently of this production-side damage, the Strait of Hormuz—the sole maritime corridor available to Qatari LNG, which has no pipeline bypass—was subject to intermittent closure, a subsequent United States naval blockade beginning in April 2026, and a fragile, repeatedly contested reopening under an ongoing memorandum of understanding. QatarEnergy declared force majeure on LNG deliveries to multiple long-term buyers beginning in March 2026; this declaration has been extended repeatedly through the analysis period. A single-case design is adopted deliberately here, following established case-study methodology (Yin, 2018): the objective is an in-depth, empirically grounded account of a specific, theoretically significant instance of single-chokepoint exporter resilience, rather than statistical generalization across a sample of exporters, for which comparable public disclosure does not exist (see Figure 1).

TABLE 1 Mapping from theoretical resilience constructs (Hosseini et al., 2019) to this study's empirical proxies, units, analytical levels, and principal limitations.

| Theoretical construct (Hosseini et al., 2019) | Empirical proxy (this study) | What is actually measured (unit, analytical level) | Interpretation | Principal limitation |
|---|---|---|---|---|
| Absorptive capacity | Flow-survival ratio ($\varphi_{FS}$) | % of pre-disruption quarterly flow volume (chokepoint level, EIA) | Observed throughput outcome, not a direct measurement of absorptive capacity | Cannot separate production-side from transit-side causes of decline (Section 6) |
| Restorative capacity | Maritime restoration proxy ($\varphi_{RS,\,MAR,\,0}$) | % of pre-disruption daily vessel-transit count (chokepoint level, Kpler/Reuters) | Observed shipping-activity outcome, not a direct measurement of restorative capacity | Numerator/benchmark source comparability not independently verified; AIS undercounting; non-continuous daily series (Section 3.5) |
| Adaptive capacity | Commercial substitution ratio ($\varphi_{SUB,\,VOL}$ primary; $\varphi_{SUB,\,CARGO}$ secondary) | % of canceled gas-equivalent volume replaced, primary (firm/buyer level, Edison case); % of canceled cargoes replaced, secondary | Observed buyer-level commercial-adaptation outcome, not a direct measurement of adaptive capacity | Single-buyer case, not generalized to full portfolio; cargo-count version materially overstates volume replaced (Section 3.6) |

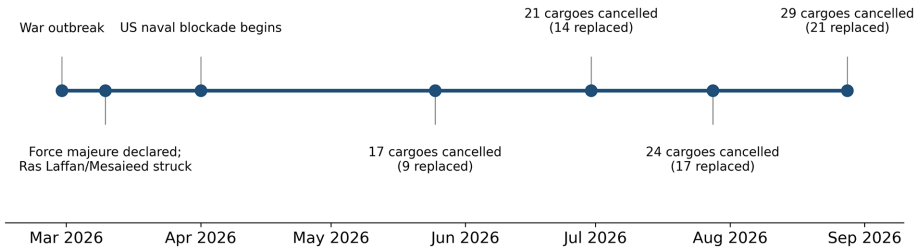


FIGURE 1
Timeline of the disruption episode and documented QatarEnergy-Edison force-majeure sequence.

## 3.2 Unit of analysis

This study's focal case is QatarEnergy and its LNG export network, but the three empirical indicators do not all measure that unit at the same level of resolution, and this distinction is maintained explicitly and consistently throughout this manuscript—in the Abstract, Methods, Results, Discussion, and Conclusion alike—rather than stated once in Methods and left for the reader to carry forward unassisted. Three analytical levels are distinguished. Chokepoint-level operating conditions describe the external environment through which all Hormuz traffic passed, regardless of exporter or flag; the flow-survival ratio (Section 3.4) and maritime restoration proxy (Section 3.5) are both constructed at this level, from EIA and Kpler/Reuters data that measure aggregate Strait of Hormuz activity, not QatarEnergy-specific production or shipment volume in isolation, because publicly available firm-level, real-time throughput data for QatarEnergy specifically do not exist. Commodity-level flow performance is a further distinction within the chokepoint-level data: flow survival is reported separately by commodity (oil versus LNG) precisely because the aggregate chokepoint conceals a divergence that matters for this study's argument. Firm- or buyer-level adaptation describes the commercial substitution indicator (Section 3.6), which is drawn from firm- and contract-level disclosure and directly measures a documented QatarEnergy buyer relationship rather than an aggregate environmental condition. The study is therefore best described as a multi-level case assessment: it documents the disrupted chokepoint- and commodity-level operating environment within which QatarEnergy's export system functioned, combined with a documented firm-level commercial response to that environment. Readers should interpret the physical and maritime indicators as characterizing the disrupted operating environment, and the commercial substitution indicator as characterizing a specific, firm-level response within it—not as three measurements of a single underlying resilience quantity. This distinction does not weaken the paper's central finding; if anything, it clarifies it: even the most severe environmental constraint (near-total LNG flow degradation at the chokepoint level) coexisted with a partial but non-trivial firm-level commercial adaptation, which is precisely the cross-level divergence the study documents.

## 3.3 Data sources and verification procedure

All data used in this study were independently verified by direct retrieval from a primary source or a specific, dated news article, rather than accepted from any single pre-compiled table. Three data sources are used. First, quarterly volumes of crude oil, condensate, petroleum products, and LNG transported through the Strait of Hormuz are drawn from the United States Energy Information Administration's Short-Term Energy Outlook, Global Energy Security Data, Table 4 (release of 12 August 2026), itself derived from Vortexa tanker-tracking analysis. These figures were retrieved directly from the EIA's own published table rather than a secondary compilation. EIA states explicitly that Hormuz-related figures for 2026 are being revised frequently, because AIS-based tracking became markedly less reliable after the end of February 2026; this limitation is treated as a stated data-quality constraint rather than resolved by extrapolation. Second, daily counts of commodity-vessel transits through the Strait of Hormuz are drawn from Kpler shiptracking data as reported contemporaneously by Reuters, retrieved article-by-article and cross-checked against the specific date and figure claimed. One vessel-count figure inherited from an earlier compilation (a claimed count for 20 August) was found on verification to be incorrect and was corrected; a second inherited Figure (26 August) could not be independently confirmed against any specific dated article and was excluded from the analysis entirely rather than retained on the basis of secondary compilation alone. Third, the sequence of QatarEnergy's force-majeure cargo cancelations and Edison S.p.A.'s (Italy) commercial replacement of those cargoes is drawn from Edison's own public disclosures as reported by Reuters and trade press (LNG Industry, gasworld, AGBI, GIIGNL, and others), forming a longitudinal series from March through August 2026. Full source attribution for every observation used in the calculations below is maintained in a source-audit log (Supplementary File 1), recording the originating organization, the specific article or statement, its publication date, and its verification status.

## 3.4 Flow-survival ratio

For each transported commodity $c$ (crude oil and condensate, petroleum products, and LNG) through the Strait of Hormuz, let $P_0c$ denote the pre-disruption quarterly baseline flow and $P_{\text{minpublished},c}$ denote the lowest quarterly flow published by EIA as of the analysis date. The flow-survival ratio is defined as:

$$\varphi_{\text{FS},c} = \frac{P_{\text{minpublished},c}}{P_0c}$$

The primary reference baseline is set at 4Q25 (October–December 2025), the last complete quarter preceding the outbreak of hostilities. As a robustness check, the analysis additionally computes each ratio using the 2025 quarterly mean as an alternative baseline. The indicator is bounded between 0 and 1, with lower values indicating more severe degradation of transported flow relative to baseline. Because EIA's

published series currently extends only through the second quarter of 2026, while independently verified vessel-transit data indicate continued severe disruption through August 2026, $P_{\text{minpublished},c}$ is explicitly interpreted as the lowest quarterly value published to date, not necessarily the physical trough of the complete disruption episode. No extrapolation is used to infer an unpublished third-quarter 2026 value; this limitation is stated directly rather than resolved analytically.

## 3.5 Maritime restoration proxy

Maritime restoration is assessed using observed daily commodity-vessel transits through the Strait of Hormuz. Because individual daily observations are highly volatile—ranging, within the verified dataset, from 0 to 10 vessels across adjacent days—the primary restoration measure uses a trailing five-day mean rather than single-day values, computed only when at least four valid daily observations are available within the five-day window; windows with fewer valid observations are reported as unavailable rather than computed from an incomplete average. Two complementary ratios are then defined. The principal measure, capturing restoration toward the pre-disruption state, divides this five-day mean by a pre-disruption benchmark, V0. Because independent maritime-information sources report materially different pre-disruption benchmarks—Lloyd's List/AFP reporting approximately 120 vessels per day, Reuters/Kpler repeatedly reporting a range of 130–140 per day, and the Joint Maritime Information Center, as reported by BBC Verify, reporting 138 per day—V0 is not treated as a single observed constant. The principal analysis adopts V0 = 135, the midpoint of the Reuters/Kpler range, explicitly as an analytical reference benchmark rather than a claimed point estimate, and reports sensitivity results using V0 = 120, 130, 138, and 140 as source-based scenarios rather than a statistical confidence interval. A secondary, complementary measure captures short-term recovery momentum by comparing the observed daily count to the contemporaneous 10-day moving average reported alongside it in the same source; this measure is explicitly labeled a momentum indicator rather than a restoration measure, since a moving average computed during an ongoing disruption is itself depressed relative to the pre-disruption state. Both measures are treated as proxies rather than direct measurements of physical resilience, since AIS-derived vessel counts may undercount actual movements and do not by themselves establish cargo volume, origin, or successful delivery. Two further caveats apply to this proxy and are stated here rather than left implicit. First, the underlying vessel-transit series is not a continuous daily record: it consists of selected, publicly reported daily observations on the specific dates for which a named outlet published a figure, not a complete day-by-day series, and restoration ratios reported in this study should be read as applying to those observed dates and the most recent available window, not as continuous coverage of the full episode. Second, the numerator and the V0 benchmark are not confirmed to describe identical vessel populations: the numerator is drawn from Kpler-reported commodity-vessel transits as relayed by Reuters, whereas the V0 benchmark is assembled from Lloyd's List/AFP, Reuters/Kpler, and Joint Maritime Information Center figures, which may apply different counting conventions, directions of movement, or vessel-class inclusion rules. This comparability could not be independently verified with the data available, and it is possible that part of the very low restoration ratio reported in Section 4.2 reflects a definitional mismatch between numerator and benchmark rather than disruption severity alone. The multi-scenario sensitivity analysis across V0 values addresses uncertainty in the benchmark's level but does not, by itself, resolve this potential source of definitional mismatch, which is why the maritime restoration proxy is treated throughout as a proxy rather than a validated measurement.

## 3.6 Commercial substitution ratio

Commercial adaptation is operationalized through a single documented buyer case: QatarEnergy's long-term LNG supply contract with Edison S.p.A. of Italy. Let Et denote the cumulative gas-equivalent volume, in billion cubic meters (bcm), of cargoes canceled or suspended under force majeure as reported by date t, and Ft the cumulative gas-equivalent volume, in bcm, of that canceled volume commercially replaced through alternative sourcing, drawn from multiple United States LNG sources, including the QatarEnergy-ExxonMobil Golden Pass facility (from which Italy began receiving cargoes in June 2026) alongside other US suppliers and spot-market purchases; the share attributable to Golden Pass specifically versus other US sources is not disaggregated in available disclosures and is not claimed here. The primary commercial substitution ratio is defined on a gas-equivalent volume basis, $\varphi_{\text{SUB, VOL}}$ (t) = Ft/Et, computed for the four observation dates at which both canceled and replaced volumes were disclosed. A secondary, cargo-count ratio, $\varphi_{\text{SUB, CARGO}}$ (t) = Rt/Ct, where Ct and Rt denote cumulative canceled and replaced cargo counts, is retained for comparability with cargo-level disclosures and as a robustness check, computed for all five observation dates including one (5 May) for which volume data were not disclosed. The two ratios are not interchangeable and are not expected to agree: cargo sizes in this sequence are not homogeneous (implied bcm per incremental replaced cargo ranges from approximately 0.10 to 0.18 across the observation window), so a cargo-count ratio can materially overstate the share of disrupted gas-equivalent volume actually replaced relative to a volume-based ratio computed from the same underlying disclosures. The volume-based ratio is therefore treated as the primary indicator, because it is denominated in the same physical units as the disrupted supply itself and is consequently more directly informative about the continuity of LNG supply than a count of contractually distinct shipments, consistent with this study's volume-based treatment of physical flow in Section 3.4; the cargo-count ratio is retained in full alongside it, rather than discarded, for transparency and comparability with the original submission. Both measures capture buyer-side commercial adaptation and are explicitly not interpreted as a measure of QatarEnergy's physical production restoration, which follows an independently reported, multi-year repair timeline for the damaged Ras Laffan and Mesaieed facilities. Because the analysis relies on a single buyer relationship, results are not generalized to QatarEnergy's full buyer portfolio, which includes long-term contracts with multiple Asian and European customers for which equivalent buyer-level disclosure was not identified during the verification process.

## 3.7 Sensitivity analysis

Three sensitivity checks are embedded directly in the calculation architecture rather than reported as a separate *post hoc* exercise. First, the flow-survival ratio is computed under both the 4Q25 baseline and the 2025 quarterly-mean baseline. Second, the maritime restoration ratio is computed under five source-based V0 scenarios (120, 130, 135, 138, 140), explicitly representing genuine disagreement across

independent maritime-information sources rather than a single assumed value. Third, the minimum-valid-observations rule (at least 4 of 5 days within a restoration window) is applied uniformly, so that no restoration ratio is computed from an incomplete or artificially smoothed window; one recent vessel-count observation that could not be independently verified during the source-audit process was excluded from the calculation entirely under this rule rather than imputed or estimated.

## 3.8 Non-aggregation strategy

The three primary indicators—flow survival, maritime restoration, and commercial substitution—are reported separately throughout this study and are not combined into a single composite resilience score. This decision follows directly from the theoretical argument developed in Section 2.3 and rests on four distinct, independently sufficient grounds. First, construct non-equivalence: the three indicators measure conceptually distinct phenomena—physical throughput, observable shipping activity, and buyer-side commercial adaptation—that are proxies for absorptive, restorative, and adaptive capacity, respectively, (Section 2.4), not interchangeable measurements of one underlying quantity. Second, analytical-level non-equivalence: as stated in Section 3.2, the physical and maritime indicators are constructed at the chokepoint level while the commercial substitution indicator is constructed at the firm/buyer level, so a weighted sum would combine quantities describing different units of analysis. Third, unit non-equivalence: the indicators are expressed as ratios of different physical quantities—throughput volume, vessel counts, and gas-equivalent contract volume—normalized against different and independently uncertain baselines (Sections 3.4–3.6), so their numerical magnitudes are not measured on a common scale and a difference of, say, ten percentage points does not mean the same thing across indicators. Fourth, and most directly relevant to this Research Topic's scope, sustainability non-equivalence: the three dimensions carry different environmental and logistical implications (Section 5.2), so an aggregate score would average away precisely the cross-dimensional divergence this study is designed to surface, concealing rather than revealing the trade-off between contractual continuity and physical or environmental cost that motivates the paper's central argument. Because all four grounds hold independently, no single weighting scheme could resolve them; aggregation would therefore require assumptions about commensurability across constructs, levels, units, and sustainability implications that are not established by, and are not recoverable from, the present empirical design. In place of aggregation, Section 4.4 reports the three indicators side by side in a dashboard format (Table 2, Figure 2) that preserves each indicator's own unit, analytical level, and observation window rather than collapsing them into one number.

# 4 Results

## 4.1 Physical flow survival

Under the primary baseline (4Q25), oil flow survival through the Strait of Hormuz reached $\varphi_{FS}$ = 22.7% at its lowest published quarterly value (2Q26: 4.9 mb/d against a 4Q25 baseline of 21.6 mb/d), essentially unchanged under the 2025 quarterly-mean sensitivity baseline (23.1%). LNG flow survival was substantially more severe: $\varphi_{FS}$ = 7.6% under the primary baseline (2Q26: 0.8 Bcf/d against a 4Q25 baseline of 10.5 Bcf/d), again essentially unchanged under the sensitivity baseline (7.3%). The near-identical results across both baseline choices indicate that this finding is not an artifact of baseline selection. The roughly three-fold divergence between oil and LNG flow survival is consistent with the structural asymmetry described in Section 1.2: Saudi Arabia and the United Arab Emirates retain partial pipeline bypass capacity for crude oil that does not require Hormuz transit, whereas Qatar's LNG exports have no such alternative and are entirely dependent on the contested strait. As stated in Section 3.4, these figures should be read as the lowest quarterly flow published by EIA as of the analysis date, not necessarily as the physical trough of the complete disruption episode, given that daily vessel-transit data (Section 4.2) indicate continued severe disruption through August 2026, after the close of EIA's published quarterly series.

## 4.2 Maritime restoration

The trailing five-day mean of verified daily vessel transits for the most recent available window (23, 24, 25, and 27 August 2026; 26 August excluded per the minimum-valid-observations rule, see Section 3.7) was 6.0 vessels per day. Against the five source-based V0 scenarios, this yields a pre-disruption restoration ratio ranging from

TABLE 2 Summary of empirical resilience indicators at most recent verified observation.

| Indicator | Dimension | Most recent value | Observation date | Interpretation |
|---|---|---|---|---|
| $\varphi_{FS}$ (oil) | Physical flow | 22.7% | 2Q26 (vs. 4Q25 baseline) | Severe but partial degradation |
| $\varphi_{FS}$ (LNG) | Physical flow | 7.6% | 2Q26 (vs. 4Q25 baseline) | Near-total degradation |
| $\varphi_{RS,\,MAR,\,0}$ | Maritime activity | 4.4% (4.3–5.0% across V0 scenarios) | 5-day mean, 23–27 Aug 2026 | Minimal recovery toward pre-war levels |
| $\varphi_{SUB,\,VOL}$ | Commercial adaptation | 52.6% | 28 Aug 2026 (Edison case; volume basis, primary) | Partial single-buyer substitution by disrupted gas-equivalent volume |
| $\varphi_{SUB,\,CARGO}$ | Commercial adaptation | 72.4% | 28 Aug 2026 (Edison case; cargo-count basis, secondary) | Substantial single-buyer substitution by cargo count (robustness check; overstates volume replaced, Section 3.6) |

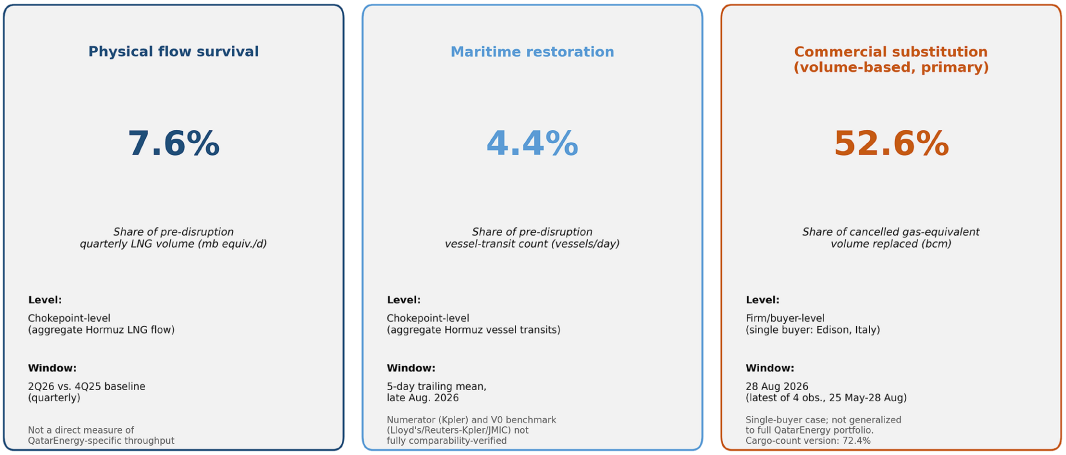


FIGURE 2
Cross-dimensional resilience dashboard, reporting each indicator's value alongside its unit, analytical level, and observation window; bar-length or panel-to-panel value comparisons are not measurements on a common resilience scale (Section 3.8).

4.3% (V0 = 140) to 5.0% (V0 = 120), with the primary benchmark (V0 = 135) giving $\varphi_{RS,\,MAR,\,0} \approx 4.4\%$. Unlike the flow-survival results, where baseline choice made little difference, the restoration ratio is not highly sensitive to which V0 scenario is selected either—all five scenarios cluster within a narrow 4.3–5.0% band—indicating that the substantive conclusion (maritime activity remained a small fraction of its pre-disruption level through late August 2026) is robust to the underlying source disagreement over the exact pre-war baseline. The complementary recovery-momentum ratio, which compares each day's observed transits to its contemporaneous 10-day moving average, was considerably more volatile across the observation window: 54.5% (11 August), 66.7% (12 August), 14.3% (24 August), 33.3% (25 August), and 66.7% (27 August). This volatility is expected given the ratio's construction—a 10-day average computed during an ongoing, unevenly disrupted period is itself unstable—and reinforces the methodological decision (Section 3.5) to treat this measure as a short-term momentum diagnostic rather than as the principal restoration indicator.

## 4.3 Commercial substitution

The primary, volume-based commercial substitution ratio for the QatarEnergy-Edison case rose from 45.5% (25 May: 1.0 of 2.2 bcm canceled gas-equivalent volume replaced) to 48.1% (30 June: 1.3/2.7 bcm) to 53.3% (28 July: 1.6/3.0 bcm), before easing slightly to 52.6% (28 August: 2.0/3.8 bcm). Unlike the cargo-count series reported below, the volume-based series shows no late-August acceleration toward full replacement; it rises through July and then plateaus at roughly half of disrupted gas-equivalent volume. For comparison, and as a robustness check, the secondary cargo-count ratio followed a non-monotonic trajectory across five verified observation dates: 66.7% (5 May: 8 of 12 cargoes), falling to 52.9% (25 May: 9 of 17), before recovering to 66.7% (30 June: 14 of 21), 70.8% (28 July: 17 of 24), and 72.4% (28 August: 21 of 29). The two series diverge materially at every date for which both are available, and most starkly at the most recent observation (52.6% volume-based vs. 72.4% cargo-count on 28 August), a divergence attributable to the non-homogeneous size of replacement cargoes in this sequence (Section 3.6): a larger share of disrupted cargoes was matched with a replacement cargo of some size than the share of disrupted gas-equivalent volume that was actually replaced. This pattern is itself an empirical finding distinct from either endpoint value alone: a resilience assessment based only on the cargo-count ratio would overstate the extent of physical-volume replacement achieved by late August 2026 (see Figure 3).

## 4.4 Cross-dimensional comparison

Table 2 summarizes the three primary indicators at their most recent verified observation. The comparison illustrates the central empirical finding of this study: the three dimensions of resilience examined here are not merely quantitatively different but move in substantively different ranges, at different analytical levels, and in different units, precisely the reasons non-aggregation was adopted as a methodological principle in Section 3.8. Physical LNG flow survival (7.6%) and maritime restoration (4.4%) both indicate severe, largely unrecovered disruption at the chokepoint level as of the analysis date, while the primary, volume-based commercial substitution ratio (52.6%) indicates partial, though substantial, buyer-side adaptive success at the firm level for the one buyer relationship examined; a secondary, cargo-count version of the same indicator (72.4%) indicates a materially larger apparent adaptation and is reported alongside it as a robustness check (Section 3.6). Reporting only the cargo-count substitution figure would suggest a supply chain that has substantially adapted to disruption on a physical-volume basis; reporting only the physical flow-survival figures would suggest a supply chain still in acute crisis with no commercial response at all. Neither reading alone is accurate: chokepoint-level physical flow remains severely degraded while firm-level commercial adaptation, measured correctly on a volume basis, has achieved roughly half of disrupted gas-equivalent supply, which is precisely the divergence, at the precise magnitude the primary indicator supports, that justifies reporting these indicators separately rather than as a single composite score.

## 4.5 Sensitivity analysis

Sensitivity checks embedded in the calculation architecture (Section 3.7) do not alter the substantive pattern reported above.

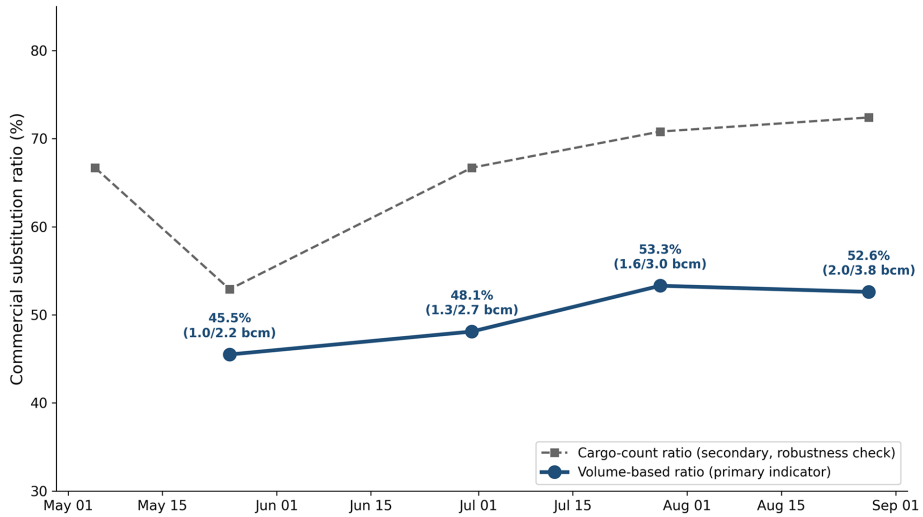


FIGURE 3
QatarEnergy-Edison commercial substitution ratio over time: the primary, volume-based ratio (gas-equivalent bcm replaced/canceled) versus the secondary, cargo-count ratio (cargoes replaced/canceled); the two diverge materially, most sharply at the most recent observation (52.6% vs. 72.4%, 28 August 2026).

Flow-survival results are essentially unchanged across the 4Q25 versus 2025-mean baseline choice (oil: 22.7% vs. 23.1%; LNG: 7.6% vs. 7.3%). Maritime restoration results cluster within a 4.3–5.0% band across all five V0 source scenarios, despite those scenarios spanning a 120–140 vessels/day range reflecting genuine disagreement among Lloyd's List, Reuters/Kpler, and the Joint Maritime Information Center (subject to the numerator-benchmark comparability caveat stated in Section 3.5). The commercial substitution indicator is the one primary indicator for which the choice of measurement basis materially changes the reported magnitude: the volume-based ratio (52.6%, primary) and the cargo-count ratio (72.4%, secondary) diverge by nearly twenty percentage points at the same observation date, for reasons explained in Section 3.6. An equal-weight composite across the three primary indicators was evaluated during the analysis and is not reported here: because the underlying indicators are not measured on a common scale (Section 3.8), such a composite would not carry a defensible substantive interpretation, and its omission is a deliberate methodological choice rather than an oversight.

# 5 Discussion

## 5.1 Theoretical implications

The results reported in Section 4 extend the absorptive-adaptive-restorative capacity framework (Hosseini et al., 2019) beyond its typical ex-ante, design-comparison application in a way that has a substantive, not merely methodological, implication. Within a single realized disruption episode, the three empirical proxies for these constructs—flow survival, maritime restoration, and commercial substitution—did not move together. Near-total physical degradation at the chokepoint level (7.6% LNG flow survival) coexisted with partial but substantial firm-level commercial-adaptive performance (52.6% volume-based substitution, or 72.4% on a cargo-count basis) for at least one major buyer relationship. Within the viability perspective advanced by Ivanov and Dolgui (2020) and Ivanov (2022), this decoupling is consistent with the argument that structural, operational, and relational subsystems of a supply chain can respond to sustained disruption at markedly different rates, through markedly different mechanisms, and at markedly different analytical levels; the present study provides direct empirical evidence of that decoupling for a single, well-documented case, rather than treating it as a theoretical possibility. This suggests a refinement to how resilience is theorized in future work: rather than asking whether a system "is" or "is not" resilient, it may be more productive to ask which of several distinguishable resilience dimensions, measured at which analytical level and in which unit, a given disruption response strategy addresses, and which it does not—since, as this case shows, meaningful adaptation on the most commercially visible and firm-specific dimension (contract continuity) can coexist with severe unresolved degradation on the physical, chokepoint-level dimension that ultimately underlies it, and the magnitude of that adaptation itself depends materially on which unit is used to measure it.

## 5.2 Sustainable supply-chain implications

The sustainability implications of this decoupling are direct rather than incidental, though they remain interpretive rather than directly measured in this study, and are stated as such. Edison's commercial substitution strategy, which achieved a 52.6% gas-equivalent-volume replacement ratio (72.4% on a cargo-count basis) by late August 2026, was accomplished substantially through LNG sourced from United States Gulf Coast facilities, including but not limited to Golden Pass (Section 3.6), delivered to an Italian Adriatic terminal. This substitution shifts sourcing to a different ocean basin entirely, with a distinct vessel-fleet and routing profile (trans-Atlantic rather than Suez-transit) than the displaced Qatar route; a precise voyage-distance, fuel-use, or emissions-intensity comparison between the two routings was not undertaken in this study and would require dedicated routing and emissions data beyond the scope of the present analysis. Accordingly, statements about the environmental burden of substitution are framed here as a plausible sustainability implication requiring further empirical

verification, not as a demonstrated environmental outcome: substitution plausibly relocates, rather than eliminates, the logistics and environmental footprint of supply, and a resilience assessment reporting only contract continuity would not capture this relocation, but the present study does not quantify its magnitude. The substitution ratio reported in Section 4.3, in other words, measures commercial and contractual continuity; it does not measure, and should not be read as implying, environmental or logistical equivalence to the disrupted route it replaces. This is the mechanism anticipated theoretically in Section 2.3: successful short-term adaptation can preserve supply continuity while plausibly redistributing, rather than eliminating, the environmental and logistical burden of the underlying disruption. For a Research Topic concerned with designing resilient and sustainable supply chains jointly, this case illustrates concretely why the two objectives cannot be assessed through a single continuity metric—a supply chain can score well on resilience, narrowly defined as continuity of delivery, while its sustainability profile plausibly deteriorates as a consequence of how that continuity was achieved, a hypothesis this study raises on qualitative grounds rather than confirms quantitatively. Future empirical work extending this study should quantify this trade-off directly, for example by estimating the emissions differential between the disrupted and substitute routing, which the present study's data sources do not support with sufficient precision to report as a verified figure.

Beyond the routing and emissions channel discussed above, the disruption's sustainability implications extend into the socio-economic domain, and the scale of that effect is documented independently of this study's own indicators. QatarEnergy's own leadership estimated the disruption's annual cost to the firm at approximately $20 billion in lost revenue—equivalent to roughly 37% of Qatar's total expected government revenue for 2026—with damaged production capacity requiring an estimated 3–5 years to repair (CNBC, 2026). Qatar's National Planning Council reported that first-quarter 2026 GDP contracted 7% year-on-year, driven by a 26% collapse in the mining and quarrying sector that encompasses hydrocarbon production, even as the non-hydrocarbon economy continued to grow (AGBI, 2026). LNG export volumes for the same quarter fell approximately 33% year-on-year, a decline consistent in direction and rough magnitude with this study's own flow-survival findings (Section 4.1), though measured through a different data source and time window. These figures situate the physical and commercial indicators developed in this study within a broader socio-economic context: they are consistent with, and plausibly associated with, a national fiscal and macroeconomic effect that a purely operational or logistical resilience framework would not capture, though this study's design does not permit a formal causal decomposition of the GDP and fiscal figures cited here, which are drawn from national accounts rather than computed from this study's own data. This is the socio-economic complement to the environmental redistribution argument developed above: sustainable supply-chain design in commodity-exporting economies plausibly needs to account not only for physical and commercial continuity, but for the fiscal and developmental exposure that a single-chokepoint dependency creates at the national level.

## 5.3 Managerial implications

For QatarEnergy and comparable single-chokepoint exporters, three managerial implications follow from the disaggregated results. First, the substantial divergence between physical flow survival and commercial substitution success indicates that portfolio-level equity positions in geographically diversified production—QatarEnergy's own joint-venture stake in the US Golden Pass facility being the salient example here—can function as a partial hedge against chokepoint risk to the firm's own long-term contractual obligations, independent of, and substantially faster to deploy than, physical repair or route diversification at the point of disruption itself. This is a structurally different resilience mechanism from the diversification pathways typically discussed in the pre-disruption sustainability-resilience literature (Section 2.3), since it operates through corporate ownership structure rather than through supply-chain configuration per se. Second, the primary, volume-based substitution trajectory documented in Section 4.3 rose from 45.5% to a plateau of roughly 53% over 3 months and did not approach full replacement of disrupted gas-equivalent volume within the observation window, while the secondary, cargo-count trajectory reached a materially higher 72.4% over the same period. This divergence itself carries a managerial implication distinct from either trajectory alone: firms and counterparties assessing adaptive capacity from cargo-level reporting alone risk overstating the physical-volume continuity actually achieved, because replacement cargoes in this sequence were not uniformly sized; portfolio and contract design should account explicitly both for the lag in establishing alternative sourcing and for the unit in which adaptive capacity is measured. Third, the minimal maritime restoration observed through the analysis window (Section 4.2), despite meaningful commercial substitution progress on either measurement basis, indicates that buyer-side adaptation should not be read by exporters or investors as evidence that transit-route risk itself has diminished; the two are empirically distinct signals, measured at different analytical levels, and conflating them risks premature reallocation of risk-management attention away from the underlying chokepoint exposure that remains largely unresolved.

## 5.4 Policy implications

Two policy implications follow directly from the empirical process of this study rather than from its substantive findings alone. First, the source-audit process documented in Section 3.3 and Supplementary File 1 encountered materially different pre-disruption vessel-transit baselines reported by independent, credible maritime-information organizations (Lloyd's List, Kpler/Reuters, and the Joint Maritime Information Center), a discrepancy large enough to require explicit sensitivity treatment (Section 3.5) rather than resolution to a single figure. This is itself a policy-relevant finding: the absence of a standardized, publicly reconciled measure of chokepoint vessel traffic constitutes a data-quality gap that complicates independent verification of disruption severity during an active crisis, for researchers, insurers, and policymakers alike. A standardized public reporting mechanism for critical maritime chokepoints, potentially coordinated through an international maritime body, would directly address this gap. Second, the structural asymmetry documented in Section 4.1—Qatar's complete absence of pipeline bypass capacity for LNG, versus partial bypass capacity available to Saudi Arabia and the UAE for crude oil—suggests that infrastructure-investment incentives aimed at physical route diversification (rather than, or in addition to, commercial-contractual diversification) may be warranted specifically for single-route LNG exporters, a category for which this study's findings

indicate substantially higher physical vulnerability than for diversified oil exporters facing the same chokepoint disruption.

## 6 Limitations

Several limitations should be stated explicitly. First, and most importantly, the disruption episode analyzed here was still ongoing at the time of writing (late August 2026). EIA's published quarterly flow series extends only through 2Q26, while verified daily vessel-transit data indicate continued severe disruption through August; the flow-survival ratios reported in Section 4.1 therefore represent the lowest published performance to date, not a confirmed episode trough, and should be revised if and when third-quarter 2026 EIA data become available. All results in this study should be read as a snapshot of a still-unfolding episode rather than a final post-mortem assessment.

Second, the commercial substitution ratio (Section 4.3) is derived from a single buyer relationship—QatarEnergy's long-term contract with Edison S.p.A. of Italy—for which unusually detailed public disclosure happened to be available. Equivalent buyer-level disclosure was not identified for QatarEnergy's larger-volume Asian long-term contracts (Japan, South Korea, China, India), which collectively account for a substantially greater share of Qatari LNG exports than European buyers. The reported substitution ratio—whether the primary, volume-based Figure (52.6%) or the secondary, cargo-count Figure (72.4%)—should therefore not be generalized to QatarEnergy's buyer portfolio as a whole; it demonstrates that partial-to-substantial single-buyer commercial adaptation was achievable in at least one documented case, not that comparable adaptation occurred, or was even attempted, across all buyer relationships. The material gap between the two measurement bases for this single case (Section 3.6) further cautions against treating either figure as a precise estimate of the buyer's true replacement rate, let alone the portfolio-wide rate.

Third, the maritime restoration proxy (Section 4.2) relies on AIS-derived vessel-transit counts, which are subject to known limitations during active conflict: vessels may operate with transponders deliberately disabled for security reasons, producing systematic undercounts of actual maritime activity whose magnitude cannot be estimated from the data used here. The measure also does not distinguish vessel transits by cargo type, size, or destination, meaning a given day's vessel count is not directly convertible into a corresponding volume of trade. This is precisely why the measure is labeled a proxy throughout this study rather than a direct measurement, and why it is reported alongside, rather than as a substitute for, the volume-based flow-survival ratio.

Fourth, the pre-disruption vessel-flow benchmark (V0) used in the maritime restoration calculation is not a single, universally agreed figure; independent maritime-information organizations report values ranging from approximately 120 to 140 vessels per day. This study addresses the disagreement through explicit multi-scenario sensitivity analysis (Section 3.5) rather than by selecting a single value and treating it as established fact, but the underlying source disagreement itself could not be resolved with the data available. A related and distinct limitation, not resolved by the sensitivity analysis, is that the numerator (Kpler-reported commodity-vessel transits) and the V0 benchmark sources (Lloyd's List/AFP, Reuters/Kpler, and the Joint Maritime Information Center) were not confirmed to apply identical counting conventions or vessel-population definitions (Section 3.5); part of the very low restoration ratio reported in Section 4.2 may therefore reflect definitional mismatch rather than disruption severity alone.

Fifth, this study reports empirical ratios and their sensitivity to alternative baselines and benchmarks; it does not conduct formal statistical inference. The sensitivity ranges reported throughout Section 4 reflect genuine disagreement across independent data sources and alternative reasonable analytical choices, not sampling variability in the traditional statistical sense, and should not be interpreted as confidence intervals. This is a deliberate design choice appropriate to a single-case, ex-post empirical study, but it limits the extent to which the precision of any reported figure can be formally quantified.

Sixth, the flow-survival ratio (Section 4.1) measures volume transported through the Strait of Hormuz; it does not, and cannot, cleanly separate two distinct underlying causes of that volume's decline—reduced production at Ras Laffan and Mesaieed due to physical infrastructure damage, and reduced ability to ship already-produced volumes due to transit-route disruption. Both mechanisms were operating simultaneously during the analysis period, and the data sources used in this study do not permit their independent attribution. This limits the extent to which the flow-survival ratio alone can distinguish absorptive failure at the production stage from absorptive failure at the transit stage.

Finally, a factual disclosure: the author is affiliated with a university based in Qatar. All data used in this study are drawn exclusively from publicly available sources—United States government statistics, independently reported shipping data, and public corporate disclosures—and no privileged or non-public QatarEnergy information was used at any stage of data collection or analysis.

## 7 Conclusion

This study set out to address a gap between two existing quantitative literatures on the 2026 Strait of Hormuz disruption: macroeconomic models that trace the episode's consequences for importing economies and global industrial sectors, and conceptual frameworks that discuss resilience-sustainability complementarity without computing verified, disaggregated indicators for a specific case. Using an empirical, ex-post adaptation of the absorptive-adaptive-restorative resilience framework, this study measured three distinct, multi-level empirical proxies associated with QatarEnergy's LNG export system during the disruption—chokepoint-level physical flow survival, chokepoint-level maritime restoration, and firm-level commercial substitution—from independently verified EIA, Kpler/Reuters, and Edison/QatarEnergy data. The central finding is that these three dimensions diverged substantially: LNG flow survival remained severely degraded (7.6% of pre-war baseline) and maritime activity showed minimal recovery (4.4% of pre-war levels) at the chokepoint level through the end of the observation window, while commercial substitution for a documented buyer relationship reached 52.6% of canceled gas-equivalent volume on a primary, volume-based measure (72.4% on a secondary, cargo-count basis) following a gradual, partial adaptation trajectory. No single composite score could represent this pattern without concealing it, and even the choice between two reasonable ways of measuring the same commercial-substitution construct materially changes its reported magnitude; the decision to report the three

indicators separately, each in its own unit and at its own analytical level, justified theoretically in Section 2.3 and Section 3.8 and demonstrated empirically in Section 4.4, is accordingly this study's central methodological argument as well as its central empirical finding.

For the Research Topic this study addresses, the practical implication is direct: resilience and sustainability cannot be jointly assessed through supply continuity alone, because continuity can be restored through commercial adaptation whose environmental and logistical costs are not reflected in a contract-fulfillment metric. A supply chain that appears resilient by one measure may simultaneously be redistributing, rather than resolving, the burden of the disruption that produced it. Future research should extend this disaggregated approach to additional single-chokepoint exporters and additional buyer relationships as further disclosure becomes available, and should, where routing and emissions data permit, quantify directly the environmental cost differential between disrupted and substitute supply routes that the present study was only able to identify qualitatively. As the underlying disruption episode remains active at the time of writing, the empirical indicators reported here represent a documented snapshot rather than a final assessment, and the source-audited dataset and workbook underlying this study (Supplementary material) are structured for straightforward extension as further data become available.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

KM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

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## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2026.1993267/full#supplementary-material

SUPPLEMENTARY FILE 1
Source-audit log recording the originating organization, specific article or statement, publication date, and verification status for every observation used in the calculations.

SUPPLEMENTARY FILE 2
Calculation workbook for the flow-survival, maritime restoration, and commercial substitution indicators.

## References

AGBI (2026) Qatar's economy shrinks in first quarter after LNG disruption. Available online at: https://www.agbi.com/economy/2026/08/qatar-economy-shrinks-after-disruption-to-lng-exports/ (Accessed 28 September 2026).

An, F., Ren, S., Liu, X., and Cui, J. (2026). Energy supply resilience and industrial continuity under a strait of Hormuz blockade. *Energies* 19:2719. doi: 10.3390/en19112719

Christopher, M., and Peck, H. (2004). Building the resilient supply chain. *Int. J. Logist. Manag.* 15, 1–14. doi: 10.1108/09574090410700275

CNBC (2026) Iran attack wipes out 17% of Qatar's LNG capacity for up to five years, QatarEnergy CEO says. Available online at: https://www.cnbc.com/2026/03/19/iran-attack-qatar-lng-capacity.html (Accessed 28 September 2026).

Cohen, W. M., and Levinthal, D. A. (1990). Absorptive capacity: a new perspective on learning and innovation. *Adm. Sci. Q.* 35, 128–152. doi: 10.2307/2393553

Fiksel, J. (2003). Designing resilient, sustainable systems. *Environ. Sci. Technol.* 37, 5330–5339. doi: 10.1021/es0344819

Hosseini, S., Ivanov, D., and Dolgui, A. (2019). Review of quantitative methods for supply chain resilience analysis. *Transp. Res. Part E, Logist. Transp. Rev.* 125, 285–307. doi: 10.1016/j.tre.2019.03.001

Ivanov, D. (2022). Viable supply chain model: integrating agility, resilience and sustainability perspectives: lessons from and thinking beyond the COVID-19 pandemic. *Ann. Oper. Res.* 319, 1411–1431. doi: 10.1007/s10479-020-03640-6

Ivanov, D., and Dolgui, A. (2020). Viability of intertwined supply networks: extending the supply chain resilience angles towards survivability. *Int. J. Prod. Res.* 58, 2904–2915. doi: 10.1080/00207543.2020.1750727

Ivanov, D., Sokolov, B., and Dolgui, A. (2014). The ripple effect in supply chains: trade-off "efficiency-flexibility-resilience" in disruption management. *Int. J. Prod. Res.* 52, 2154–2172. doi: 10.1080/00207543.2013.858836

Liu, M., Liu, Y., Wong, C. W. Y., Lai, K.-h., and Tu, E. (2025). The impacts of geopolitics on global liquefied natural gas (LNG) shipping network: evidence from two geopolitical events. *Ocean Coast. Manag.* 267:107706. doi: 10.1016/j.ocecoaman.2025.107706

Mishra, R., Gupta, D., Marathe, A., Yu, K.D., Schroeder, A., Swarup, S., et al (2026). Estimating the cascading global impacts of gas disruptions in Qatar. Available online at: https://arxiv.org/abs/2604.24960 (Accessed 27 April 2026).

Negri, M., Cagno, E., Colicchia, C., and Sarkis, J. (2021). Integrating sustainability and resilience in the supply chain: a systematic literature review and a research agenda. *Bus. Strateg. Environ.* 30, 2858–2886. doi: 10.1002/bse.2776

Pettit, T. J., Croxton, K. L., and Fiksel, J. (2013). Ensuring supply chain resilience: development and implementation of an assessment tool. *J. Bus. Logist.* 34, 46–76. doi: 10.1111/jbl.12009

Polemis, D., and Bentsos, C. (2025). LNG vessels transits through Suez Canal under the changing geopolitical context. *J. Shipp. Trade* 10:17. doi: 10.1186/s41072-025-00205-3

Ponomarov, S. Y., and Holcomb, M. C. (2009). Understanding the concept of supply chain resilience. *Int. J. Logist. Manag.* 20, 124–143. doi: 10.1108/09574090910954873

Sarwar, D. (2026). Sustainable and resilient supply chains: a decision-intelligence framework for managing disruptions in the post-COVID era. *Commodities* 5:10. doi: 10.3390/commodities5020010

Sheffi, Y., and Rice, J. B. (2005). A supply chain view of the resilient enterprise. *MIT Sloan Manag. Rev.* 47, 41–48.

Tang, C. S. (2006). Robust strategies for mitigating supply chain disruptions. *Int J Log Res Appl* 9, 33–45. doi: 10.1080/13675560500405584

Wen, T., Chen, Y.-W., Ma, J., Syed, T. A., and De, A. (2026). Evaluating disruption risks at the chokepoints of the maritime transport network to support re-routing decision-making. *Eur. J. Oper. Res.* doi: 10.1016/j.ejor.2026.07.006

Yin, R. K. (2018). *Case Study Research and Applications: Design and Methods*. 6th Edn Thousand Oaks, CA: Sage Publications.