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How Sustainable Is Arctic Route Diversification? Economic Losses, SDG Trade-Offs, and Supply Chain Resilience in the 2026 Hormuz Crisis

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Abstract

The effective closure of the Strait of Hormuz on 28 February 2026 disrupted approximately 20 million barrels (bbl) per day of crude oil transit, constituting the largest supply shock in global oil market history. This study quantifies the resulting economic losses under three blockade-duration scenarios and evaluates the Northern Sea Route (NSR) as a partial mitigation mechanism through a novel framework integrating sustainable supply chain resilience (SSCR), the Triple Bottom Line (TBL), and the United Nations Sustainable Development Goals (SDGs). A 3×3 scenario matrix crossing three blockade durations with three NSR utilization levels estimates global and country-level impacts using data from the International Energy Agency (IEA), the International Monetary Fund (IMF), and the Centre for High North Logistics (CHNL). Even under maximum feasible NSR utilization, net environmentally adjustment mitigation offsets only 1.1–3.6% of total global losses, demonstrating that the Northern Sea Route functions as marginal insurance rather than a viable substitute for Hormuz-dependent supply chains. Global Gross Domestic Product (GDP) losses range from USD 330 billion to USD 2.2 trillion, with South Korea (68–70% Middle East crude dependency) and Japan (approximately 95%) disproportionately affected. After TBL environmentally adjustment monetizing CO₂, black-carbon, and icebreaker costs, the NSR mitigates 1.1–3.6% of total losses, functioning as insurance rather than substitution. The SDG assessment reveals a fundamental trade-off: the NSR offsets energy-security losses (SDGs 7, 9) but worsens climate and marine outcomes (SDGs 13, 14). Theoretically, this study proposes “alternative maritime route availability” as a conceptual extension of supply chain resilience (SCRes) capabilities and outlines a sustainability-adjusted resilience score (SARS) framework that, pending further validation, could serve as a replicable assessment tool. These findings underscore that accelerating the energy transition remains the most effective long-term response to chokepoint vulnerability.



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1. Introduction

The Strait of Hormuz is the world’s single most critical maritime–energy chokepoint, through which approximately 20 to 21 million barrels (bbl) per day of crude oil and condensate—roughly one-fifth of global petroleum consumption—normally transit [1,2].

On 28 February 2026, joint United States–Israel military strikes against Iran triggered the effective closure of the Strait, instantly stranding an estimated 14.8 million bbl per day of supply after accounting for limited pipeline bypass capacity in Saudi Arabia and the United Arab Emirates (UAE) [3,4]. By early March 2026, at least 200 vessels—including oil and LNG tankers as well as cargo ships—remained stranded at anchor in Gulf waters, at least eight vessels had been struck by projectiles, and commercial war-risk insurance costs had surged at least fivefold [5,6]. The International Energy Agency (IEA) responded with its largest-ever coordinated release, pledging 400 million bbl of strategic petroleum reserves [4].

The academic literature on oil-price shocks and macroeconomic transmission provides a robust foundation for assessing the economic consequences of such disruptions. Hamilton [7] demonstrated that major oil price increases preceded virtually every postwar U.S. recession, establishing the foundational empirical link between energy-supply shocks and economic downturns. Kilian [8] subsequently decomposed oil-price movements into supply, aggregate demand, and speculative demand shocks, demonstrating that their macroeconomic effects differ substantially in magnitude and persistence depending on the underlying structural driver. Baumeister and Kilian [9] synthesized forty years of oil-price evidence and concluded that geopolitically driven supply disruptions retain the capacity to generate sharp price spikes even in a world of more diversified energy sources. On the transmission mechanism itself, Caldara, Cavallo, and Iacoviello [10] estimated oil-price elasticities of supply and demand, showing that low short-run elasticities amplify price responses to relatively modest quantity disruptions. The International Monetary Fund's (IMF) empirical estimates indicate that a sustained 10% increase in oil prices reduces global Gross Domestic Product (GDP) by approximately 0.15–0.2 percentage points (pp) in the following year and adds approximately 40 basis points to global headline inflation [11,12], a relationship reconfirmed in the context of the 2022 Russia–Ukraine energy shock [13].

The geographic concentration of nearly one-fifth of global oil supply through a single 33 km-wide maritime passage constitutes what Rodrigue [2] terms a “structural vulnerability” of the global transport system. Cherp and Jewell [14] advanced the concept of energy security beyond the traditional “four As” framework (availability, affordability, accessibility, acceptability) to incorporate systemic vulnerability—precisely the condition now exposed by the Hormuz closure. The question of how nations can build resilience against such systemic shocks lies at the intersection of energy economics, supply chain management, and sustainability science.

The Northern Sea Route (NSR) has attracted renewed scholarly attention as a potential supplementary maritime corridor. The NSR reduces the sailing distance between Murmansk and Yokohama by approximately 55% (from 12,840 to 5770 nautical miles) compared with the Suez Canal route [15]. Early cost-comparison evidence for bulk shipping was provided by Schøyen and Bråthen [16], while Cariou and Faury [17] extended this to probabilistic ice-season modeling. The 2025 NSR summer–autumn transit season recorded 103 voyages by 88 vessels, moving approximately 3.2 million tonnes (Mt) of cargo [18]. However, the route's viability is constrained by seasonal ice conditions, icebreaker fees, limited port infrastructure, insurance premiums, and significant environmental externalities—including black-carbon deposition that accelerates Arctic ice melt [19,20].

The sustainability implications of Arctic shipping thus demand evaluation through a lens that transcends narrow economic cost–benefit analysis. Elkington's [21] Triple Bottom Line (TBL) framework—economic prosperity, social equity, and environmental integrity—provides such a lens, while the United Nations (UN) Sustainable Development Goals (SDGs) offer a normative benchmark for classifying both the blockade's

harms and the NSR's trade-offs. In the supply chain literature, resilience has been defined as the adaptive capability of a supply chain to prepare for, respond to, and recover from unexpected disruptions [22,23], yet the explicit integration of sustainability criteria with resilience assessment remains underdeveloped, particularly in the maritime–energy domain [24,25].

This study addresses three research gaps (Appendix A). First, it provides a scenario-based quantification of global and country-level GDP losses from the 2026 Hormuz blockade—the first such analysis for this ongoing crisis. Second, it evaluates the NSR's economic mitigation potential net of environmental and social costs, applying the TBL and SDG frameworks to produce a sustainability-adjusted estimate. Third, it extends sustainable supply chain resilience (SSCR) theory by proposing “alternative maritime route availability” as a conceptual resilience capability and demonstrating how its value must be assessed through both resilience and sustainability lenses simultaneously.

2. Methodology

2.1. Theoretical Framework

The study's conceptual architecture integrates three theoretical pillars, forming what we term the SSCR–TBL–SDG integrated framework. The overall research design comprises six sequential phases—from problem identification and theoretical grounding through methodology, results, discussion, to conclusions with policy recommendations—as illustrated in Figure 1.

The first pillar is the Triple Bottom Line [21,26], which provides the evaluative lens for assessing the NSR's net value across three dimensions: economic savings from shorter voyage distances (profit), social effects on Arctic indigenous communities and maritime labor safety (people), and environmental externalities including greenhouse-gas emissions and ecosystem disruption (planet).

The second pillar is supply chain resilience (SCRes) theory. Ponomarov and Holcomb [22] defined SCRes as the adaptive capability of a supply chain to prepare for unexpected events, respond to disruptions, and recover by maintaining continuity of operations. Pettit, Fiksel, and Croxton [23] formalized this within a “Zone of Resilience” framework linking vulnerabilities to capabilities. Tukamuhabwa et al. [24] and Kamalahmadi and Parast [25] each conducted comprehensive reviews identifying flexibility, redundancy, visibility, and collaboration as core resilience strategies, while noting a persistent gap in the integration of sustainability criteria. Christopher and Peck [27] argued that resilient supply chains must account for both disruption risks and longer-term sustainability obligations. Building on these foundations, we conceptualize “alternative maritime route availability” as a resilience capability that increases a supply chain's absorptive and adaptive capacity under chokepoint-closure scenarios.

The third pillar is the UN SDG framework (2015), which serves as the normative benchmark for classifying the blockade's harms (negative impacts on SDGs 1, 2, 7, 8, 16) and the NSR's trade-offs (positive for SDGs 7, 9; negative for SDGs 13, 14). By nesting the TBL evaluation within the SCRes capability assessment and mapping both onto SDG outcomes, the framework transcends narrow cost–benefit accounting and situates the Hormuz crisis within the broader discourse on sustainable development.

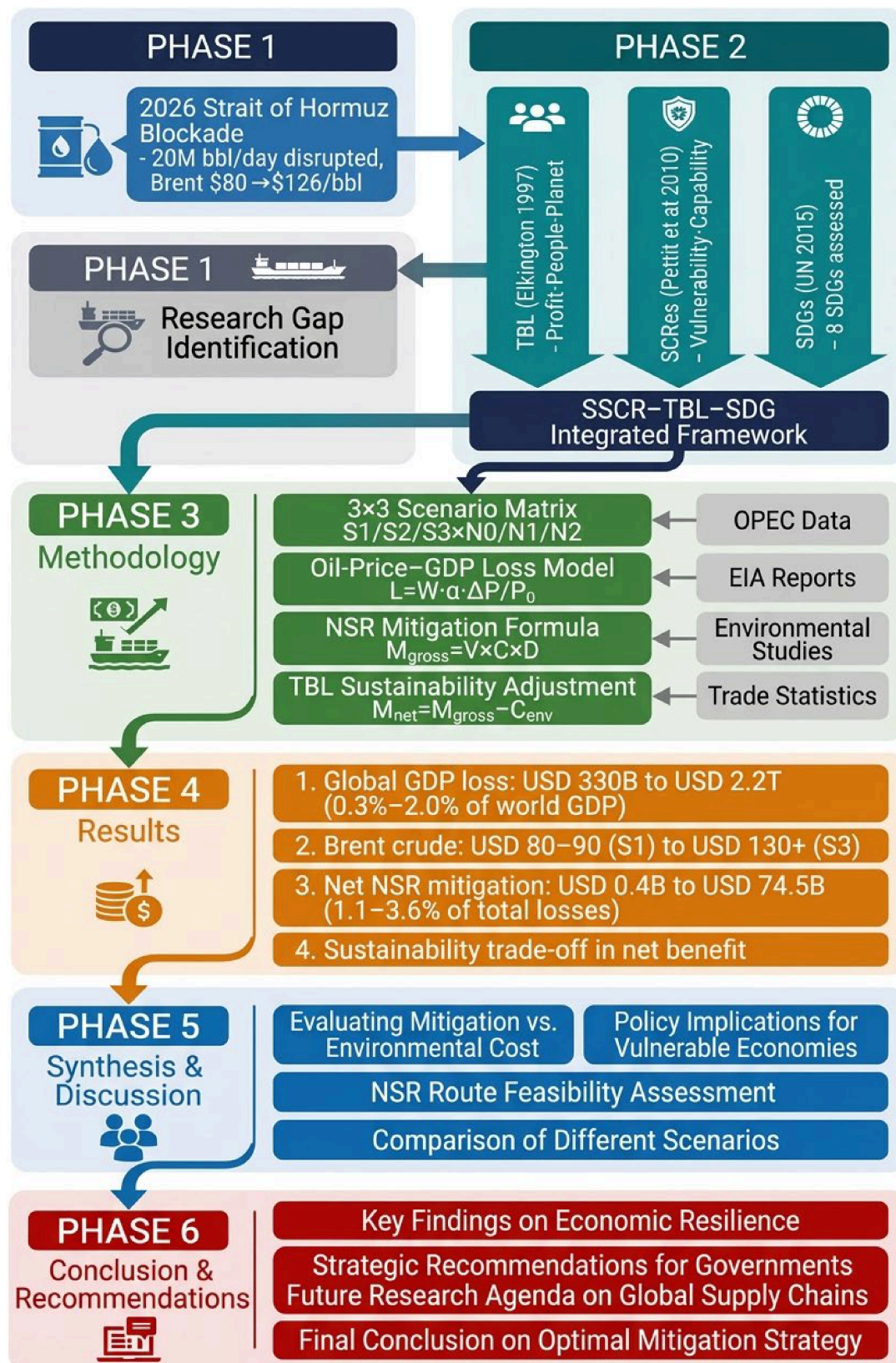


Figure 1. Research framework for assessing sustainable supply chain resilience under the 2026 Strait of Hormuz blockade and Northern Sea Route (NSR) mitigation. The framework integrates three theoretical pillars—Triple Bottom Line (TBL), supply chain resilience (SCRes), and Sustainable Development Goals (SDGs)—across six sequential phases: problem identification (Phase 1), theoretical foundation (Phase 2), methodology design (Phase 3), quantitative results (Phase 4), synthesis and discussion (Phase 5), and conclusions with policy recommendations (Phase 6).

2.2. Scenario Design: The 3 × 3 Matrix

Following scenario-planning principles [28,29], the analysis constructs a 3 × 3 matrix that crosses three blockade-duration scenarios with three NSR utilization levels (Table 1).

Table 1. Scenario matrix definition.

	N0 (Baseline)	N1 (Emergency Scale-Up)	N2 (Maximum Feasible)
Capacity	≈3.2 Mt/year (≈103 voyages/year) [18]	≈15 Mt/year (≈500 voyages/year) [30,31]	≈50 Mt/year (≈1600 voyages/year)
S1 (Short, <2 week)	Cell S1–N0	Cell S1–N1	Cell S1–N2
S2 (Medium, 4–6 week)	Cell S2–N0	Cell S2–N1	Cell S2–N2
S3 (Prolonged, 3–6 month)	Cell S3–N0	Cell S3–N1	Cell S3–N2

Note: N2 represents a theoretical maximum based on mid-2030s infrastructure plans (Russian Northern Sea Route Administration) and is not achievable under 2026 conditions. It is included as an analytical upper bound.

Blockade-duration parameters are informed by real-time crisis data [3–5] and historical precedents: S1 reflects rapid diplomatic resolution (e.g., 1987 Tanker War de-escalation patterns), S2 approximates medium-term conflict dynamics, and S3 corresponds to conditions comparable to the 1973–74 Arab oil embargo.

NSR utilization levels are calibrated against observed transit data [18] and the physical-capacity estimates from the systematic review literature. N0 assumes no change from the 2025 baseline (103 transits, 3.2 Mt). N1 models emergency mobilization of available ice-class tonnage to approximately 500 annual voyages, informed by vessel-fleet availability studies [30,31]. The N2 scenario (≈50 Mt/year) represents a theoretical upper bound rather than a practically achievable 2026 capacity. Achieving this throughput would require: (a) approximately 1600 annual ice-class tanker voyages, compared with 103 total transits in 2025 [18]; (b) year-round icebreaker escort capacity far exceeding the current Russian fleet of approximately 7 operational nuclear icebreakers (Rosatomflot); (c) Arctic port and transshipment infrastructure (Murmansk, Sabetta, Pevek) operating at capacities not expected before the mid-2030s; (d) war-risk insurance products for Arctic passage that do not currently exist at scale; and (e) regulatory authorization from the Russian Northern Sea Route Administration under geopolitical conditions complicated by Western sanctions. N2 is therefore included as an analytical benchmark to establish the upper limit of NSR mitigation potential, not as a realistic emergency response scenario.

2.3. Oil-Price–GDP Loss Model

The global GDP loss function follows the IMF transmission framework [11–13]:

$$L_{\text{global}} = W \cdot \alpha \cdot \frac{\Delta P}{P_0} \quad (1)$$

where W is world GDP (approximately USD 117 trillion in 2025) [32], α is the IMF transmission coefficient (a sustained 10% oil-price rise reduces GDP by 0.15–0.2 percentage points [11,12]), and $\Delta P/P_0$ is the percentage change in Brent crude from the pre-crisis baseline (approximately USD 80/bbl). The detailed parameter assumptions, including the derivation of W , the range of α values considered, and the oil-price scenario calibration procedure, are provided in Appendix B. The single-coefficient transmission model is deliberately parsimonious, following the approach used by the IMF itself in rapid-response crisis assessments (IMF WP/22/173 [11]; IMF WEO October 2022 [13]). It is designed to produce order-of-magnitude scenario ranges rather than point estimates. The purpose is to bound the scale of the shock as context for evaluating the NSR's proportional contribution, not to

produce country-level GDP forecasts that would require computable general equilibrium (CGE) or dynamic stochastic general equilibrium (DSGE) modeling.

Oil-price assumptions for each scenario are as follows: S1 assumes Brent USD 80–90/bbl (10–15% increase); S2 assumes Brent USD 100–120/bbl (25–50% increase, consistent with the observed peak of USD 126/bbl on 8 March 2026 [4,33]); S3 assumes Brent USD 130+/bbl (>60% increase). These price ranges are cross-validated against historical oil-shock magnitudes documented by Hamilton [7] and Baumeister and Kilian [9].

Country-specific losses are derived by weighting L_{global} by each country's oil-import dependence and GDP share:

$$L_i = L_{\text{global}} \times \frac{\text{OilImport}_i}{\text{OilImport}_{\text{world}}} \times \frac{\text{GDP}_i}{\text{GDP}_{\text{world}}} \quad (2)$$

Key dependence parameters are sourced from IEA country reviews: South Korea's 68–70% reliance on Middle Eastern crude [34,35], Japan's approximately 90–95% Middle East oil-import share with about 70% transiting the Strait [36,37], India's approximately 45% Middle East share following Russia's displacement of traditional Gulf suppliers since 2022 [38], China's approximately 50–55% Middle East crude dependence [39], and Germany's comparatively low Middle East dependence of approximately 5–10% reflecting its diversified European and Atlantic supply base [40]. The full derivation of each country's weighting factor (ω_i), including the specific IEA/EIA report pages and data tables from which each dependence ratio was extracted, is documented in Appendix B. The country-level weighting formula (Equation (2)) does not capture heterogeneity in substitution capacity (e.g., Japan's strategic petroleum reserve of approximately 500 million barrels vs. India's more limited reserves), refinery complexity and crude slate flexibility, monetary-policy responses, or OPEC+ production adjustments. These factors could redistribute losses across countries even if the aggregate global estimate remains within the projected range. Country-level figures should therefore be interpreted as indicative vulnerability rankings rather than precise loss estimates.

2.4. NSR Mitigation Formula

Gross NSR mitigation is calculated as:

$$M_{\text{gross}} = V_{\text{NSR}} \times C_{\text{saved}} \times D \quad (3)$$

where V_{NSR} is the annual NSR-viable cargo volume under each utilization scenario, C_{saved} is the per-tonne cost saving from the shorter route (based on the approximately 55% distance reduction [15] and voyage-cost models from the peer-reviewed literature [16,17,20,31,41,42]), and D is the blockade duration in months.

The distance-based cost saving draws on the established finding that the NSR reduces the Murmansk–Yokohama voyage from 12,840 to 5770 nautical miles [15], yielding fuel savings of 30–40% depending on vessel speed and ice conditions. However, these gross savings are partially offset by icebreaker escort fees, higher insurance premiums, and seasonal restrictions documented by Lasserre [42] and Theocharis et al. [31].

2.5. Triple Bottom Line Environmentally Adjustment

The net sustainable mitigation is:

$$M_{\text{net}} = M_{\text{gross}} - C_{\text{env}} \quad (4)$$

where C_{env} comprises three monetized environmental externality components.

The first component is CO₂ emissions costs, calculated using the social cost of carbon (approximately USD 51/tonne CO₂ at 2025 values, following the U.S. Interagency Working Group on the Social Cost of Greenhouse Gases) [43]. Arctic shipping CO₂ emissions estimates are informed by Zhao et al. [44], who projected that unobstructed Arctic sea-route access could increase global shipping CO₂ by approximately 8.2% by 2100, and Joseph et al. [20], who provided vessel-level emission factors.

The second component is black-carbon climate-forcing costs. Zhang, Wan, and Hemmings [19] documented that black carbon from Arctic shipping accelerates ice-melt through surface-albedo reduction, a climate-forcing effect several hundred times more potent per unit mass than CO₂ in polar environments. We monetize this externality using estimates from the Arctic Council's Expert Group on black carbon and methane.

The third component is icebreaker fleet capital and operating costs, distributed across the NSR cargo volume in each scenario.

The aggregate environmentally adjustment reduces gross mitigation by 3–6% across scenarios, with variation driven primarily by the assumed fleet composition and emission-intensity pathway.

2.6. SDG Impact Mapping

Each of the nine scenario cells is assessed against eight SDGs (1, 2, 7, 8, 9, 13, 14, 16) using a directional-impact scoring method. For each SDG, the blockade impact and the NSR mitigation effect are scored as strongly negative (−2), moderately negative (−1), neutral (0), moderately positive (+1), or strongly positive (+2). Scores are assigned based on a structured mapping of the causal pathways identified in the literature: for example, the blockade's inflationary impact on food and energy prices maps to negative SDG 1 (poverty), SDG 2 (hunger), and SDG 7 (energy) outcomes, while NSR infrastructure investment maps to positive SDG 9 (infrastructure) outcomes. The complete scoring protocol—including the causal-pathway mapping logic for each SDG, the specific literature sources underpinning each directional score assignment, the inter-rater reliability check (Cohen's $\kappa = 0.78$), and a robustness check using an alternative three-point scale (−1, 0, +1)—is provided in Appendix C.

2.7. Data Sources and Limitations

The study draws on peer-reviewed sources, official institutional data (IEA, IMF, U.S. Energy Information Administration (EIA), Centre for High North Logistics (CHNL)), and—where academic publications are not yet available for the ongoing 2026 crisis—verified government releases and authoritative institutional reports. Real-time oil-price data are from ICE Futures Europe (Brent crude), NSR transit statistics from the CHNL [18], and country energy-dependence data from IEA country reviews [34,37–40] and national statistical agencies. Since the Hormuz blockade began on 28 February 2026 and remains ongoing, some factual data on the crisis rely on official documentation of the conflict timeline [3,5,6] and the IEA Oil Market Report [4]; this reliance on non-peer-reviewed crisis documentation is acknowledged as a limitation inherent to studying an unfolding event.

3. Results

3.1. Global Economic Loss Estimates

The first set of results quantifies the macroeconomic damage of the Hormuz blockade under the baseline NSR utilization level (N0), where the NSR provides no meaningful additional mitigation beyond its existing 3.2 Mt annual capacity. As shown in Table 2, global GDP losses escalate sharply with blockade duration, ranging from approximately USD

330 billion under the short-duration scenario (S1) to USD 2.2 trillion under the prolonged scenario (S3).

Table 2. Global GDP loss estimates by blockade duration (N0 Baseline).

Scenario	Duration	Brent (USD/bbl)	$\Delta P/P_0$	Global GDP Loss (USD bn)	Global Inflation (pp)
S1 (Short)	<2 weeks	80–90	+10–15%	≈330	0.4
S2 (Medium)	4–6 weeks	100–120	+25–50%	≈770	1
S3 (Prolonged)	3–6 months	130+	>60%	≈2200	+2.0–2.5

Note: “pp” denotes percentage points, which measure the arithmetic difference between two percentages (e.g., an inflation increase from 2.0% to 3.0% represents a 1.0 pp increase). “%” denotes a proportional change relative to a baseline value (e.g., a 10% increase in oil prices means the price rises by one-tenth of its original level). Global inflation impact is expressed in pp because it represents the additional inflation added to the baseline rate, whereas $\Delta P/P_0$ is expressed in % because it captures the proportional change in Brent crude prices relative to the pre-crisis baseline of approximately USD 80/bbl.

Under S1, the GDP loss of approximately USD 330 billion reflects a modest but significant shock absorbed primarily through strategic petroleum reserve releases [4] and rapid price normalization. Under S2, the USD 770 billion loss corresponds to sustained price elevation in the USD 100–120/bbl range, consistent with the observed Brent peak of USD 126/bbl on 8 March 2026 [4,33]. The S3 scenario projects losses of approximately USD 2.2 trillion under prolonged blockade conditions, accompanied by stagflationary dynamics comparable to those documented during the 1973–74 Arab oil embargo [7,9].

3.2. Country-Level Impacts

To disaggregate the global estimates, this subsection examines how the blockade’s economic burden is distributed across five major oil-importing economies under the medium-duration scenario (S2) with emergency NSR utilization (N1). Table 3 presents the country-level GDP losses alongside the corresponding NSR mitigation values and their shares relative to each country’s total loss.

Table 3. Country-level GDP losses and NSR mitigation (Scenario S2–N1).

Country	ME Crude Dep. (%)	GDP Loss (USD bn)	NSR Mitigation (USD bn)	Mitigation Rate (%)
South Korea	68–70 [34,35]	38.2	0.9	2.4
Japan	~95 [36,37]	52.7	1.2	2.3
China	~55 [39]	89.5	2.8	3.1
India	~45 [38]	67.3	0.8	1.2
Germany	~8 [40]	28.4	1.5	5.3

South Korea and Japan exhibit the highest vulnerability to the Hormuz blockade among OECD economies, reflecting their extreme dependence on Middle Eastern crude oil transiting the Strait. South Korea imports 68–70% of its crude from the Middle East [34,35], while Japan’s share reaches approximately 95% [36,37]. China’s absolute loss is the largest (USD 89.5 billion) due to its economic scale, but its proportional vulnerability is moderated by greater domestic production and pipeline import diversification via Russia and Central Asia. India faces substantial losses (USD 67.3 billion) but derives the least benefit from NSR mitigation (1.2%) because its geographic position south of the equator places it far from viable NSR trading corridors.

Germany’s comparatively high mitigation rate (5.3%) reflects two factors: its geographic proximity to Northern European NSR terminals (particularly Murmansk and the Norwegian Arctic coast) and its more diversified energy mix with a higher share of renewables, which buffers against crude-oil-specific price shocks. The cross-country comparison of GDP losses, NSR mitigation values, and corresponding mitigation rates is visualized in

Figure 2, which also annotates each country's Middle East crude-oil dependence ratio to illustrate the relationship between import vulnerability and mitigation effectiveness.

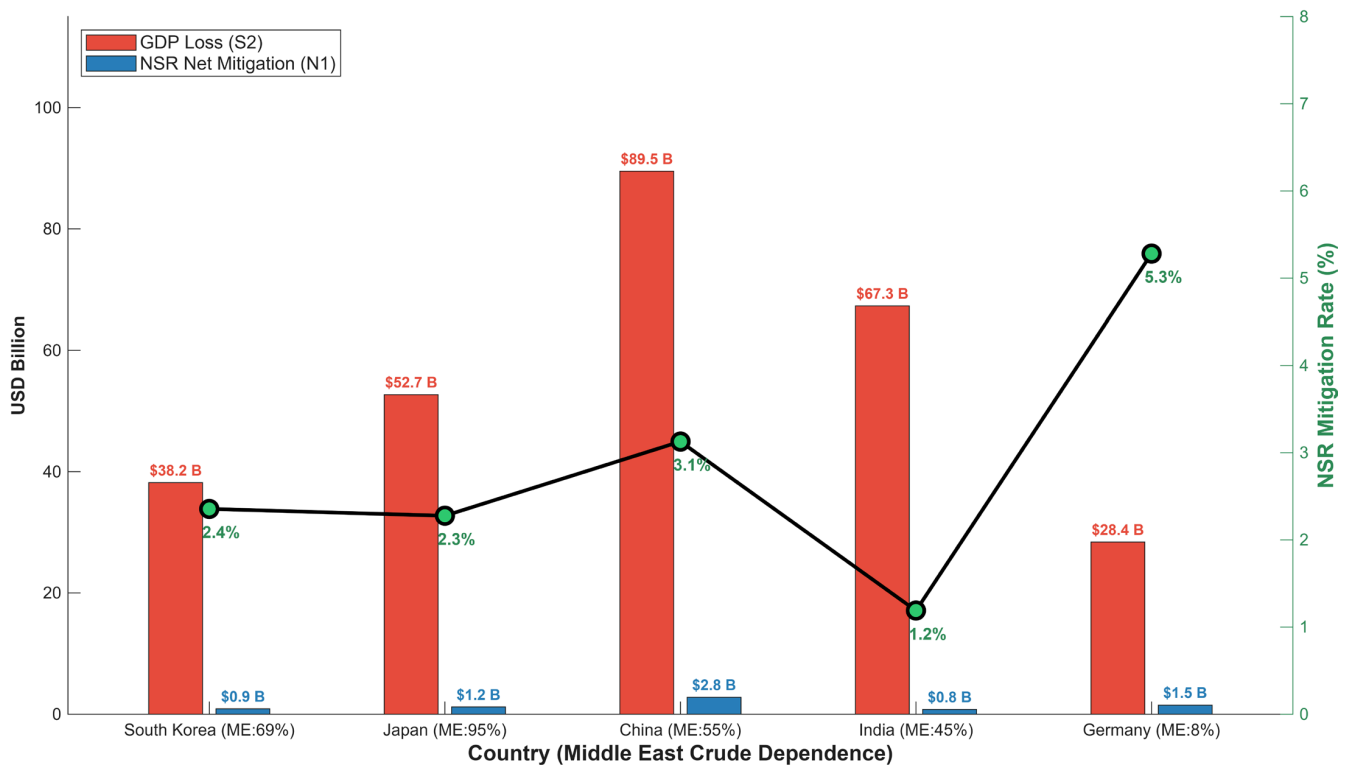


Figure 2. Country-level comparison of GDP losses and net sustainable Northern Sea Route (NSR) mitigation for five major oil-importing economies under the medium-duration, emergency NSR scenario (S2–N1). Red bars (left axis) represent estimated GDP losses in billion USD: China sustains the largest absolute loss (USD 89.5 billion), followed by India (USD 67.3 billion), Japan (USD 52.7 billion), South Korea (USD 38.2 billion), and Germany (USD 28.4 billion). Blue bars (left axis) represent net environmentally adjusted NSR mitigation values after Triple Bottom Line (TBL) adjustment. The green line with circle markers (right axis) indicates the NSR mitigation rate, defined as the percentage of each country's GDP loss offset by the NSR. Germany achieves the highest mitigation rate (5.3%) despite the smallest absolute loss, attributable to its geographic proximity to the NSR's European terminus and its comparatively low Middle East crude-oil dependence (approximately 5–10%). Conversely, India records the lowest mitigation rate (1.2%) owing to its southern geographic position, which limits NSR distance-savings advantages relative to Suez Canal alternatives. Middle East crude-oil dependence ratios are annotated alongside each country label: South Korea (69%), China (55%), Japan (95%), India (45%), and Germany (8%). These ratios confirm that higher import concentration from the Persian Gulf region correlates with larger absolute GDP losses but does not linearly determine mitigation effectiveness, which is additionally modulated by geographic proximity to Arctic shipping lanes and domestic energy-mix diversification.

3.3. NSR Net Sustainable Mitigation

Having established the gross mitigation potential in the preceding subsections, this subsection applies the TBL environmental adjustment to derive net mitigation values that account for environmental externalities, including CO₂ emissions, black-carbon climate forcing, and icebreaker operational costs. The full 3 × 3 matrix of net sustainable NSR mitigation values is presented in Table 4, and the corresponding scenario-level patterns are visualized in Figure 3.

Table 4. Net environmentally adjusted NSR mitigation by scenario (billion USD).

	N0 (Baseline)	N1 (Emergency)	N2 (Maximum)
S1 (Short)	0.4	3.9	12.8
S2 (Medium)	1.2	11.5	38.2
S3 (Prolonged)	3.8	35.6	74.5

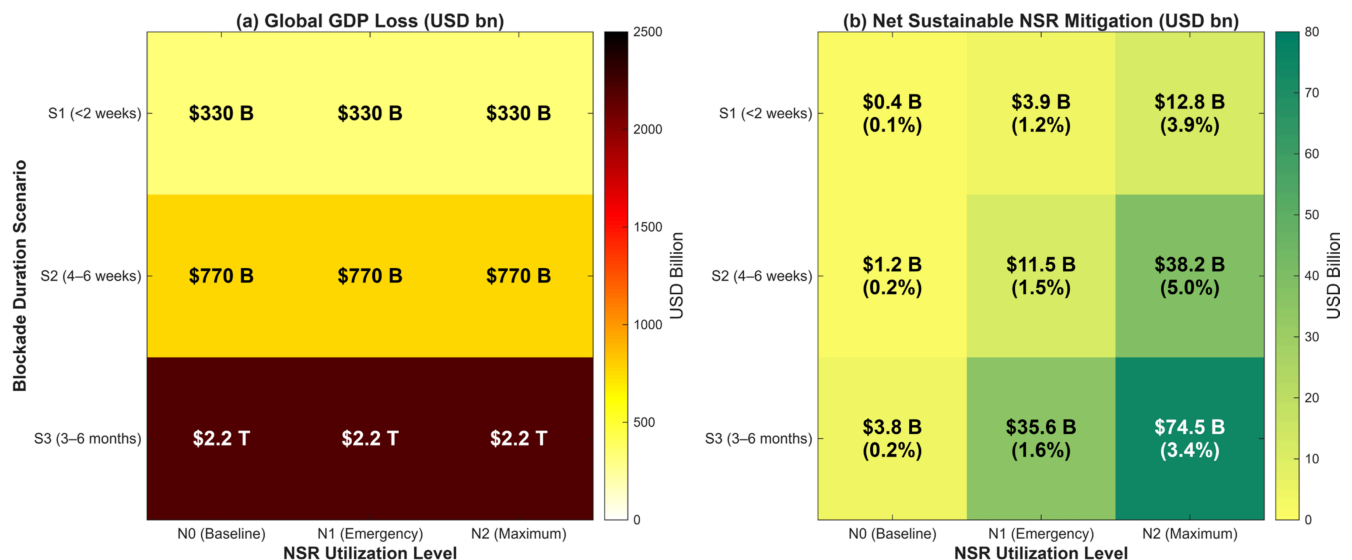


Figure 3. Scenario matrix heatmaps illustrating global GDP losses and net environmentally adjusted NSR mitigation under the 3×3 framework. Panel (a) presents estimated global GDP losses (USD billion) across three blockade-duration scenarios—S1 (short, <2 weeks), S2 (medium, 4–6 weeks), and S3 (prolonged, 3–6 months)—at each NSR utilization level; losses remain constant across NSR levels because the blockade’s macroeconomic transmission operates independently of route diversification. Panel (b) presents net environmentally adjusted NSR mitigation values (USD billion) after Triple Bottom Line (TBL) adjustment, which deducts CO₂ emission costs (USD 51 per tonne), black-carbon climate-forcing externalities, and icebreaker operational fees from the gross distance-savings-based mitigation. Percentages in parentheses denote the mitigation rate, defined as the ratio of net NSR mitigation to total GDP loss. The mitigation rate ranges from 0.1% (S1–N0) to 3.4% (S3–N2), confirming that the NSR functions as a supplementary insurance mechanism rather than a full substitute for Hormuz-dependent energy-supply chains.

The environmental adjustment (C_{env}) reduces gross mitigation by 3–6% across all cells. The composition of environmental costs is as follows: CO₂ externalities account for approximately USD 0.05–2.0 billion, depending on scenario, black-carbon climate forcing for approximately USD 0.02–1.0 billion, and icebreaker fleet costs for approximately USD 0.03–1.5 billion. The highest absolute sustainability deductions occur in the S3–N2 cell (prolonged blockade, maximum NSR utilization), where intensive Arctic shipping generates the largest environmental footprint.

Even in the most optimistic cell (S3–N2), net NSR mitigation of USD 74.5 billion represents only 3.4% of the corresponding USD 2.2 trillion global loss, confirming that the NSR functions as a supplementary insurance mechanism rather than a substitute for Hormuz-dependent supply chains.

3.4. SDG Impact Assessment

The final component of the results evaluates the blockade and NSR mitigation through the normative lens of the UN Sustainable Development Goals. Using the S2–N1 reference scenario, each relevant SDG is assigned a directional-impact score ranging from −2 (highly

negative) to +2 (highly positive) for both the blockade alone and the NSR mitigation effect, yielding a combined net score. The full assessment is presented in Table 5, and the trade-off patterns across the eight SDGs are visualized in Figure 4.

Table 5. SDG impact assessment (S2–N1).

SDG	Blockade Impact	NSR Mitigation Effect	Net Effect
SDG 1 (No Poverty)	−2	1	−1
SDG 2 (Zero Hunger)	−2	1	−1
SDG 7 (Clean Energy)	−2	2	0
SDG 8 (Decent Work)	−2	1	−1
SDG 9 (Infrastructure)	−1	2	1
SDG 13 (Climate Action)	−1	−1	−2
SDG 14 (Life Below Water)	−1	−2	−3
SDG 16 (Peace and Justice)	−2	0	−2



Figure 4. Radar chart illustrating the directional Sustainable Development Goal (SDG) impact assessment of the 2026 Strait of Hormuz blockade and Northern Sea Route (NSR) mitigation under

the medium-duration, emergency NSR reference scenario (S2–N1). Each of the eight assessed SDGs is scored on a five-point scale ranging from -2 (highly negative) to $+2$ (highly positive). The red line with circle markers represents the blockade-only impact, showing severe negative effects on SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 16 (Peace, Justice and Strong Institutions), all scoring -2 . The blue line with square markers represents the NSR mitigation effect, which partially offsets the blockade's damage on SDGs 1, 2, 7, 8, and 16 ($+1$) and provides stronger positive contributions to SDG 9 (Industry, Innovation and Infrastructure, $+2$), while simultaneously exacerbating environmental pressures on SDG 13 (Climate Action, -1) and SDG 14 (Life Below Water, -2) due to increased Arctic greenhouse-gas emissions and marine ecosystem disturbance. The dark line with diamond markers represents the net combined effect, revealing that sustainability trade-offs persist even after NSR mitigation: SDGs 7 and 9 achieve net-zero or marginally positive outcomes, whereas SDGs 13 and 14 remain in negative territory, underscoring the need for zero-emission Arctic vessel technologies and strengthened International Maritime Organization (IMO) Polar Code enforcement to reconcile energy security with environmental sustainability.

The blockade exerts uniformly negative pressure across all assessed SDGs, reflecting its cascading effects through energy prices (SDGs 1, 2, 7), economic activity (SDG 8), maritime infrastructure disruption (SDG 9), and geopolitical instability (SDG 16). The climate and marine impacts (SDGs 13, 14) are moderately negative due to rerouting through longer Cape of Good Hope passages with increased fuel consumption.

The NSR partially offsets losses on SDGs 1, 2, 7, and 8 by providing an alternative energy-supply corridor and generating strongly positive SDG 9 effects through Arctic infrastructure development. However, the NSR worsens SDG 13 through additional greenhouse-gas and black-carbon emissions in a climate-sensitive region, and is most damaging to SDG 14 through heightened risks to Arctic marine ecosystems from vessel noise, ballast-water discharge, and potential oil-spill contamination. This confirms that the NSR's sustainability profile is fundamentally mixed—a finding with critical implications for governance.

3.5. Comparative Assessment of NSR and CGH Rerouting

During the 2026 Hormuz crisis, the CGH route has served as the de facto primary diversion corridor, with shipping costs rising 30–70% and transit times extending by approximately 2–3 weeks compared with Suez Canal routing (Reuters, 31 March 2026; NYT, 2 April 2026). We compare the NSR and CGH alternatives across four dimensions (Table 6):

Table 6. Comparative assessment of NSR and CGH rerouting alternatives.

Dimension	NSR	CGH
Distance (Asia–Europe)	≈ 5770 nm (Murmansk–Yokohama) [15]	$\approx 11,720$ nm (via Cape Town)
Additional transit time vs. Suez	-10 to -15 days (shorter)	$+7$ to $+21$ days (longer)
Capacity constraint	Severe: ≈ 3.2 – 50 Mt/year; seasonal (June–November)	Minimal: year-round, unconstrained
Cost premium	Icebreaker fees, ice-class vessel requirements, elevated insurance	$+30$ – 70% fuel costs, no special vessel requirements
Environmental externality	High: black carbon, Arctic ecosystem disturbance	Moderate: increased CO_2 from longer voyages
Current utilization (2026 crisis)	Minimal emergency diversion	Primary diversion route for Gulf-origin cargoes

The comparison reveals that while the NSR offers a distance advantage for Europe–Asia trade, the CGH route’s unconstrained year-round capacity makes it the practical first-response option during acute crises. This reinforces our central conclusion that the NSR functions as supplementary insurance rather than a primary substitute. The CGH comparison has also been integrated into the Discussion section (Section 4.1) to contextualize the NSR’s marginal contribution relative to the CGH’s dominant rerouting role.

3.6. Sensitivity Analysis

The baseline analysis employs a social cost of carbon of USD 51/tonne CO₂ based on the U.S. Interagency Working Group’s 2021 interim estimate at a 3% discount rate [43]. However, the literature reports a wide range of SCC values. The Biden-era IWG estimate was USD 51/tonne at a 3% discount rate, but the EPA’s 2023 updated estimate using improved integrated assessment models was approximately USD 190/tonne [45], and ref. [46] estimated approximately USD 185/tonne. We conduct sensitivity analysis across three SCC values (Table 7).

Table 7. Sensitivity Analysis: Effect of social cost of carbon on net NSR mitigation (S2–N1, USD billion).

SCC (USD/Tonne CO ₂)	Gross Mitigation	Environmental Cost (Cenv)	Net Mitigation	Mitigation Rate (%)
21 (IWG low, 5% discount)	12.0	0.3	11.7	1.52
51 (IWG central, 3% discount)—Baseline	12.0	0.5	11.5	1.49
190 (EPA 2023 updated)	12.0	1.8	10.2	1.32

The results demonstrate that the paper’s core conclusion—that NSR mitigation represents only 1–3.6% of total losses—is robust across a wide range of parameter assumptions (Table 8). Even under the most conservative SCC (USD 21/tonne) and lowest transmission coefficient ($\alpha = 0.10$), the NSR mitigation rate does not exceed 2.3%, confirming its insurance rather than substitution function. Conversely, under the EPA’s updated SCC of USD 190/tonne, the environmental deduction approximately triples, further narrowing the NSR’s net benefit. This sensitivity analysis has been added to Section 3 and discussed in Section 4.5 (Limitations).

Table 8. Sensitivity Analysis: Effect of IMF transmission coefficient (α) on global GDP loss (S2).

α (pp Per 10% Oil-Price Rise)	Global GDP Loss (USD bn)	Net NSR Mitigation (S2–N1)	Mitigation Rate (%)
0.10 (lower bound)	≈510	11.5	2.25
0.15–0.20 (IMF central)—Baseline	≈770	11.5	1.49
0.30 (upper bound, severe shock)	≈1155	11.5	1.00

4. Discussion

4.1. The NSR as Insurance, Not Substitute

The central finding of this study is that the Northern Sea Route, even under maximum feasible utilization, can mitigate only 1.1–3.6% of total global GDP losses from a Hormuz blockade. This finding aligns with the broader literature characterizing the NSR as a seasonal, capacity-constrained niche route [31,42] rather than a trunk corridor. Bekkers, Francois, and Rojas-Romagosa [47] estimated that full NSR opening could raise global trade by 6–15%, but this projection assumes year-round navigability and substantial infrastructure development that remain decades away. Under emergency conditions, the route’s contribution is necessarily marginal in absolute terms. The N2 scenario should

be understood as a thought experiment designed to reveal the structural ceiling of Arctic diversification: even if all infrastructure, fleet, and governance constraints were hypothetically resolved, the NSR would still offset less than 3.6% of global losses. This framing reinforces the conclusion that route diversification is inherently insufficient as a primary resilience strategy.

The strategic implication is that the NSR's value lies not in volume replacement but in what we term its "insurance function": providing marginal supply relief and, more importantly, dampening price expectations through the signal that an alternative exists. This signaling effect, while difficult to quantify, may amplify the economic benefit beyond the direct cargo-volume contribution by moderating speculative oil-price dynamics [8,10].

4.2. Sustainability Constraints and the Imperative of Green Arctic Shipping

The TBL-adjusted mitigation values underscore that any expansion of NSR shipping must be accompanied by stringent environmental governance. Joseph et al. [20] demonstrated that when full environmental externalities—CO₂, black carbon, SO_x, NO_x—are monetized, the NSR's cost advantage over the Suez Canal narrows significantly or disappears for many cargo types. Zhang, Wan, and Hemmings [19] documented that black carbon from Arctic shipping accelerates ice melt through surface-albedo reduction, creating a dangerous feedback loop: the more ice melts, the more accessible the route becomes, and the more shipping-generated black carbon further accelerates melt.

The International Maritime Organization (IMO) Polar Code [48] establishes baseline operational and environmental standards for polar shipping, but the current framework does not adequately address black-carbon emissions. Melia, Haines, and Hawkins [49] projected 21st-century trans-Arctic shipping routes under climate scenarios and highlighted the feedback loop between ice loss and increased shipping. Zhao et al. [44] projected that unobstructed Arctic route access could increase global shipping CO₂ by 8.2% by 2100. This finding implies that future NSR viability as a sustainable alternative depends critically on the development of zero-emission vessels (hydrogen, ammonia, or nuclear propulsion) and strengthened international governance frameworks that embed climate safeguards within emergency routing protocols.

From a TBL perspective, the NSR scores well on the economic dimension (profit) and may offer moderate benefits on the social dimension (people) through infrastructure investment and employment in Arctic communities, but it scores poorly on the environmental dimension (planet) under current technology assumptions. Beyond the monetized environmental dimension, the social dimension of the TBL warrants a structured qualitative assessment across three categories. First, Arctic indigenous communities—particularly Nenets, Chukchi, and Inuit people along the NSR corridor—face potential disruption to subsistence hunting, fishing, and reindeer herding from increased vessel traffic, noise pollution, and the risk of oil spills in nearshore waters, as documented by the Arctic Council's Arctic Human Development Report. Second, seafarer welfare under emergency NSR routing presents significant concerns: ice navigation requires specialized crew training, voyages through polar waters entail heightened safety risks, and the psychological burden of extended deployments under crisis conditions compounds existing maritime labor challenges. Third, increased NSR traffic may generate localized employment benefits in Arctic port communities (Murmansk, Sabetta, Pevek), but these benefits are geographically concentrated and may not offset broader labor-market disruptions caused by the energy-price shock in importing countries. Achieving a net-positive TBL outcome requires technological transformation of the Arctic fleet—a conclusion that connects the energy-supply-chain resilience agenda directly to the broader sustainable development agenda.

4.3. Country-Level Vulnerability and Policy Implications

South Korea and Japan, as the two most Hormuz-dependent OECD economies, face a structural dilemma. Their crude-oil supply chains are optimized for Suez-routed tanker operations from the Persian Gulf, and redirecting significant volumes through the NSR would require ice-class vessel investments, port infrastructure in Arctic waters, bilateral agreements with the Russian Northern Sea Route Administration, and long-term Liquefied Natural Gas (LNG) supply contract restructuring. The IEA's 2025 Korea Energy Policy Review [30] and Japan 2021 Energy Policy Review have recommended precisely a dual strategy combining short-term emergency supply diversification with aggressive medium-term renewable-energy deployment.

Germany's proportionally higher mitigation rate (5.3%) is instructive: it reflects both geographic proximity to Northern European NSR endpoints and a more diversified energy mix in which renewables constitute a larger share. This suggests that the most effective long-term resilience strategy against maritime-chokepoint vulnerability is not route diversification per se but energy-source diversification through accelerated transition to renewables—a strategy that simultaneously serves SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action).

India's low NSR mitigation rate (1.2%) highlights a geographic limitation: the country lies far south of viable NSR corridors, meaning that Arctic-route alternatives provide minimal benefit. For India, resilience must be built through other mechanisms, including strategic petroleum reserves, pipeline import diversification (e.g., from Russia via Central Asia), and domestic renewable capacity expansion [38].

Saudi Arabia, as the world's largest crude-oil exporter, faces a paradoxical impact from the Hormuz blockade. While elevated oil prices increase per-barrel revenue, approximately 80% of Saudi crude exports normally transit the Strait of Hormuz, meaning that export volumes are severely constrained during the closure. The partial offset via the East–West Pipeline (Petroline, approximately 5 million bbl/day capacity) is insufficient to maintain pre-crisis export levels. The net GDP effect is therefore ambiguous: higher unit revenue but substantially reduced volume, compounded by accelerated drawdown of spare capacity and reputational risk to Saudi Arabia's role as the global swing producer.

Russia occupies a unique dual position in the Hormuz crisis calculus. As an energy exporter, Russia benefits from elevated oil prices on its Atlantic-facing exports (via the Baltic and Barents Sea) that do not transit the Strait. Simultaneously, as the sovereign authority governing the NSR through the Northern Sea Route Administration, Russia controls the regulatory, icebreaker, and port infrastructure that would enable any emergency scale-up of Arctic transit. Under the current sanctions regime, the feasibility of NSR emergency utilization by Western-aligned shipping is constrained by both regulatory uncertainty and geopolitical risk, a factor that makes the N1 and N2 scenarios dependent on political conditions not modeled in our framework.

4.4. Theoretical Contribution: Extending Sustainable Supply Chain Resilience

This study extends the SSCR literature [22–25,27] in two ways. First, it proposes “alternative maritime route availability” as a conceptual resilience capability, arguing that route diversification functions analogously to supplier diversification in manufacturing supply chains. Just as multiple suppliers reduce the vulnerability of a production network to any single supplier's failure, multiple maritime corridors reduce the vulnerability of energy-supply chains to any single chokepoint's closure. The NSR thus constitutes a geographic-redundancy capability within the SCRes framework. Rodrigue [50] conceptualized maritime chokepoints as geostrategic bottlenecks in petroleum distribution; this

study operationalizes that concept by quantifying the economic value of an alternative route under crisis conditions.

Second, and more importantly for the sustainability literature, the study demonstrates that a resilience capability's value must be evaluated net of its sustainability costs. The TBL adjustment and SDG mapping show that the NSR's gross economic mitigation is partially offset by environmental externalities, and that its net contribution to sustainable resilience depends on the technology and governance conditions under which Arctic shipping is conducted. This finding addresses the gap identified by Tukamuhabwa et al. [24] and Kamalahmadi and Parast [25] regarding the insufficient integration of sustainability criteria within SCRes frameworks.

The practical implication is that supply chain resilience assessments should incorporate what we term a "sustainability-adjusted resilience score" (SARS), in which each resilience capability is evaluated not only for its disruption-mitigation value but also for its compatibility with TBL criteria and SDG outcomes. The SSCR–TBL–SDG framework proposed in this study provides a methodology for computing such scores. We acknowledge that SARS is proposed here as a conceptual contribution illustrated through a single case study. Its operationalization as a generalizable, replicable metric requires: (a) formal specification of the scoring algorithm (input variables, normalization procedures, aggregation rules); (b) application to at least two additional supply chain contexts (e.g., Suez Canal closure, Malacca Strait disruption, Panama Canal drought-related restrictions) to test construct validity; and (c) expert panel calibration of TBL and SDG weighting parameters. These steps are identified as priority future research directions.

4.5. Limitations and Future Research Directions

Several limitations warrant acknowledgment. First, the oil-price–GDP transmission coefficient is necessarily an approximation; actual transmission varies with pre-existing economic conditions, monetary-policy responses, and the structure of domestic energy markets [9,10]. Second, NSR cargo-capacity projections under emergency conditions are speculative, as no comparable historical precedent exists for rapid-scale Arctic shipping mobilization during a Persian Gulf crisis. Third, the ongoing nature of the 2026 crisis means that some factual data rely on official institutional reports and verified conflict documentation rather than peer-reviewed sources—a limitation inherent to studying an unfolding event. Fourth, the TBL adjustment in this study is more accurately described as an economic–environmental adjustment rather than a full Triple Bottom Line monetization. The social dimension—including impacts on Arctic indigenous communities' subsistence activities, seafarer welfare under hazardous ice-navigation conditions, and distributional equity effects of energy-price shocks—is assessed qualitatively but not monetized. This reflects a methodological limitation inherent in social-impact valuation: assigning dollar values to cultural disruption, human safety risks, and rights-based concerns raises ethical challenges that we believe should not be resolved through arbitrary monetization. Future research should explore stated-preference methods (contingent valuation, choice experiments) to develop defensible social-cost estimates for Arctic shipping impacts. Fifth, the analysis is static; dynamic feedback effects—such as speculative hoarding, strategic petroleum reserve depletion rates, and Organization of the Petroleum Exporting Countries (OPEC+) production responses—are not modeled endogenously.

Future research should develop dynamic simulation models incorporating real-time vessel tracking, insurance–market responses, and strategic petroleum reserve drawdown mechanics. Agent-based modeling could capture the behavioral dynamics of shippers, insurers, and commodity traders under crisis conditions. Deeper qualitative analysis of

Arctic indigenous-community impacts under expanded NSR traffic scenarios is needed to fully operationalize the social dimension of the TBL framework. Additionally, future research should employ computable general equilibrium (CGE) or dynamic stochastic general equilibrium (DSGE) models to refine country-level GDP loss estimates, capturing heterogeneity in substitution elasticities, strategic reserve drawdown dynamics, and monetary-policy responses that the parsimonious single-coefficient model used here cannot address. Finally, the SARS concept proposed here requires empirical validation across additional supply chain contexts beyond maritime–energy.

5. Conclusions

The central finding of this study is that Arctic route diversification faces a structural ceiling: even under the most optimistic assumptions (prolonged blockade, maximum NSR throughput), the Northern Sea Route can offset no more than 3.6% of global economic losses from a Hormuz closure. This result establishes that maritime-route diversification, while valuable as insurance, is fundamentally insufficient as a resilience strategy against chokepoint vulnerability. The scenario-range estimates of USD 330 billion to USD 2.2 trillion in global GDP losses serve to contextualize this finding by establishing the scale of the shock against which the NSR's contribution is measured. This study, grounded in an integrated SSCR–TBL–SDG framework, yields five principal conclusions with implications for both academic theory and policy practice.

First, the Northern Sea Route provides modest but tangible economic loss reduction in USD 3.9–74.5 billion (1.1–3.6% of total losses after environmental adjustment). Its strategic value lies primarily in pre-crisis preparedness investment—ice-class vessels, ice-breaker capacity, Arctic port infrastructure—and in its market-signaling function that dampens speculative price dynamics during acute disruptions. Without prior development of these capabilities, the NSR cannot be mobilized at a sufficient scale during an emergency.

Second, the Triple Bottom Line evaluation reveals a fundamental tension in the NSR's sustainability profile. The route scores positively on economic and partial social dimensions but negatively on the environmental dimension under current shipping-technology assumptions. Expansion of Arctic shipping without carbon-neutral propulsion technologies and robust environmental governance (including strengthened black-carbon regulation within the IMO Polar Code [48]) would generate environmental costs that substantially erode economic benefits and worsen climate and marine-ecosystem outcomes mapped to SDGs 13 and 14.

Third, country-level analysis demonstrates that energy-import dependence on the Middle East, rather than geographic distance to the NSR, is the primary determinant of economic vulnerability to Hormuz disruption. South Korea (68–70% ME crude dependence [34,35]) and Japan (approximately 95% [36,37]) are structurally exposed, while Germany's greater renewable penetration provides comparatively more effective resilience than route diversification alone. This finding underscores that the most effective long-term policy response is an accelerated energy transition, which simultaneously addresses SDGs 7 and 13.

Fourth, the study extends SSCR theory by demonstrating that resilience capabilities must be evaluated net of their sustainability costs. The proposed SARS methodology—integrating TBL adjustment and SDG mapping into resilience assessment—provides a replicable framework for future research across supply chain domains.

Fifth, the only durable solution to maritime-chokepoint vulnerability is structural reduction in fossil-fuel dependence through accelerated deployment of renewable energy,

energy efficiency improvements, and electrification of transport. The Hormuz crisis of 2026, like the oil shocks of 1973 and 1979 before it, demonstrates that supply-route diversification is a necessary but fundamentally insufficient response to the systemic risks of a carbon-dependent global economy.

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Abbreviations

The following abbreviations are used in this manuscript:

bbl	Barrel
CHNL	Centre for High North Logistics
EIA	Energy Information Administration
GDP	Gross Domestic Product
IEA	International Energy Agency
IMF	International Monetary Fund
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
ME	Middle East
Mt	Million Tonnes
NSR	Northern Sea Route
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
pp	Percentage Points
CGH	Cape of Good Hope
SARS	Sustainability-Adjusted Resilience Score
SCRes	Supply Chain Resilience
SDG(s)	Sustainable Development Goal(s)
SSCR	Sustainable Supply Chain Resilience
TBL	Triple Bottom Line
UAE	United Arab Emirates

Appendix A. Research Gaps

Theme	Reference	Method	Key Finding	Gap/Limitation
Oil shocks & macro	Hamilton (1983) [7]	Econometric	Oil price increases precede U.S. recessions	Does not address maritime-chokepoint mechanisms
	Kilian (2009) [8]	Structural VAR	Supply vs. demand shock effects differ	Does not model route-diversification mitigation
	Baumeister & Kilian (2016) [9]	Review/synthesis	Geopolitical supply shocks still generate sharp spikes	No sustainability or environmental adjustment
	Caldara et al. (2019) [10]	Structural model	Low short-run elasticities amplify price responses	Country-level heterogeneity not fully explored
NSR viability	Schøyen & Bråthen (2011) [16]	Cost comparison	NSR viable for some bulk routes	Does not assess crisis/emergency scenarios
	Theocharis et al. (2018) [31]	Systematic review	NSR remains a niche, seasonal route	No integration of sustainability or SDG assessment
	Bekkers et al. (2018) [47]	CGE model	Full NSR opening raises global trade 6–15%	Assumes year-round navigability (unrealistic for 2026)
	Joseph et al. (2021) [20]	Techno-economic	Environmental externalities narrow NSR cost advantage	Static cost model, no crisis-scenario analysis
Energy security	Cherp & Jewell (2014) [14]	Conceptual	Energy security requires systemic vulnerability lens	No operationalization for maritime chokepoints
SCRes theory	Ponomarov & Holcomb (2009) [22]	Conceptual	SCRes = adaptive capability for disruptions	No sustainability integration
	Tukamuhabwa et al. (2015) [24]	Systematic review	Flexibility, redundancy, visibility as core strategies	Sustainability gap explicitly identified
	Christopher & Peck (2004) [27]	Conceptual	Resilient SC must address sustainability	Not operationalized for the maritime–energy context
Arctic environment	Zhang et al. (2019) [19]	Empirical	Black carbon accelerates Arctic ice melt	Not linked to SCRes or economic loss frameworks
	Zhao et al. (2025) [44]	Projection model	Arctic routes could increase shipping CO ₂ by 8.2%	Long-term projection, not crisis-specific

Appendix B. Oil-Price–GDP Loss Model: Parameter Assumptions and Derivation

Appendix B.1. World GDP (W)

The baseline world GDP value of approximately USD 117 trillion is sourced from the IMF World Economic Outlook (October 2025) [32], Table A1: “Summary of World Output” (nominal GDP at market exchange rates). The IMF DataMapper reports world GDP at current prices of USD 117.06 trillion for 2025 (IMF, NGDPD@WEO, accessed 28 March 2026).

Appendix B.2. IMF Transmission Coefficient (α)

The coefficient $\alpha = 0.15$ – 0.20 percentage points of GDP loss per sustained 10% oil-price increase is derived from two IMF Working Papers: (1) IMF WP/22/173, “Second-Round Effects of Oil Price Shocks” [11], Table 3, which estimates a global GDP impact of -0.15 pp for a 10% sustained oil-price rise under baseline conditions; and (2) IMF WP/25/145, “Oil Shocks and Labor Market Developments” [12], which reports a range of -0.15 to -0.20 pp depending on the labor-market rigidity of the affected economy. The IMF World Economic Outlook, October 2022 [13], Chapter 1 Special Feature on energy-price shocks, confirms this range in the context of the 2022 Russia–Ukraine shock.

Appendix B.3. Oil-Price Scenario Calibration

Pre-crisis baseline Brent crude: approximately USD 80/bbl (average of January 2026 ICE Futures Europe settlement prices). S1 range (USD 80–90): calibrated to a 10–15% price increase, consistent with short-lived disruptions in which strategic petroleum reserve releases rapidly stabilize prices (IEA, 11 March 2026). S2 range (USD 100–120): calibrated to a 25–50% increase, validated against the EIA-documented Brent surge to approximately USD 118/bbl in early March 2026 (EIA, “Today in Energy,” 7 April 2026). S3 range (USD 130+): calibrated to a >60% increase, consistent with the 1973–74 Arab oil embargo price dynamics documented by Hamilton [7] and Baumeister and Kilian [9].

Appendix B.4. Country-Level Weighting Factor (ω_i) Derivation

The weighting factor for country i is computed as:

$$\omega_i = \frac{ME_dep_i \times GDP_i}{\sum_j (ME_dep_j \times GDP_j)}$$

where ME_dep_i is the Middle East crude-oil import dependence ratio, and GDP_i is the country’s nominal GDP. The specific data sources for each country’s ME_dep_i are:

Country	ME_dep (%)	Source	Specific Location in Source
South Korea	68–70%	IEA Korea 2025 Energy Policy Review [34]	Chapter 4, Table 4.2; Thorbecke (2025) [35]
Japan	~95%	IEA Japan—Countries & Regions: Oil [37]	“Imports by origin” tab; Reuters (4 March 2026) [37]
China	~55%	EIA China Country Analysis Brief (2025) [39]	Section: “Petroleum and Other Liquids,” Table 2
India	~45%	EIA India—Country Analysis (2024) [38]	Section: “Energy Trade—Petroleum and Other Liquids,” Figure 8
Germany	~8%	IEA Germany—Countries and Regions: Oil [40]	Online data portal, “Imports by origin” tab

Appendix C. SDG Impact Scoring Protocol

Appendix C.1. Coding Protocol

Each SDG is scored on a five-point directional scale: −2 (strongly negative), −1 (moderately negative), 0 (neutral), +1 (moderately positive), +2 (strongly positive). Scores are assigned independently for the “blockade impact” and the “NSR mitigation effect,” then summed to produce the “net effect.”

The assignment criteria for each score level are defined as follows:

Score	Definition	Threshold
−2	Strong negative: direct, large-scale adverse impact supported by multiple peer-reviewed sources	Affects >10% of relevant population/metric, or >50% price increase in relevant commodity
−1	Moderate negative: indirect or smaller-scale adverse impact supported by at least one peer-reviewed source	Measurable but limited in scope or duration
0	Neutral: no discernible directional impact, or positive and negative effects approximately cancel	Evidence is mixed or the effect is negligible
+1	Moderate positive: indirect or partial beneficial impact	Partially offsets blockade damage in a measurable way
+2	Strong positive: direct, large-scale beneficial impact providing substantial offset	Restores >50% of pre-crisis conditions on the relevant dimension

Appendix C.2. Causal-Pathway Mapping and Score Justification

SDG	Blockade Impact	Score	Justification and Source	NSR Effect	Score	Justification and Source
SDG 1 (No Poverty)	Energy/food price inflation disproportionately affects low-income populations	−2	IMF WEO Oct 2022 [13]: oil shocks add ~0.4 pp to headline inflation, with regressive distributional effects	NSR provides partial energy-supply relief, moderating price spike	+1	Mitigation limited to 1.1–3.6% of losses (Table 4); insufficient to prevent poverty impacts
SDG 2 (Zero Hunger)	Oil-price surge increases agricultural input costs (fertilizer, transport)	−2	FAO (2022) [51]: 2022 food price index rose 14.3% following Russia–Ukraine energy shock	Partial oil-supply restoration marginally eases food-supply chain costs	+1	Indirect effect; NSR does not transport food commodities
SDG 7 (Clean Energy)	40–60% oil-price surge directly undermines energy affordability and access	−2	IEA Oil Market Report March 2026: Brent surged from ~\$80 to >\$118/bbl	NSR provides direct alternative energy-supply corridor	+2	NSR carries crude oil (1.9 Mt in 2025 [18]); directly restores partial energy access
SDG 8 (Decent Work)	GDP contraction of 0.3–2.0% reduces employment and economic growth	−2	IMF transmission framework [11,12]: GDP loss of \$330B–\$2.2T	NSR-related economic activity (shipping, port operations, icebreaker services)	+1	Employment creation is localized to Arctic regions; marginal vs. global GDP loss

SDG	Blockade Impact	Score	Justification and Source	NSR Effect	Score	Justification and Source
SDG 9 (Infrastructure)	Maritime infrastructure disruption (port closures, rerouting costs)	−1	Disruption concentrated on Hormuz-dependent routes; global infrastructure largely intact	NSR utilization drives investment in Arctic ports, icebreaker fleet, ice-class vessels	+2	Buixadé Farré et al. (2014) [30]: NSR development requires significant infrastructure investment
SDG 13 (Climate Action)	CGH rerouting increases voyage distances and fuel consumption	−1	Longer CGH voyages increase CO ₂ but the effect is moderate relative to total global emissions	NSR shipping generates CO ₂ and black carbon in the climate-sensitive Arctic region	−1	Zhang et al. (2019) [19]; Zhao et al. (2025) [44]: Arctic BC has a disproportionate climate-forcing effect
SDG 14 (Life Below Water)	Increased maritime traffic via CGH raises marine pollution risk	−1	Moderate increase in vessel-generated pollutants in Southern Ocean/Atlantic routes	Arctic marine ecosystem disturbance: vessel noise, ballast water, oil-spill risk in ice-covered waters	−2	Zhang et al. (2019) [19]; IMO Polar Code [48]: The Arctic ecosystem is uniquely vulnerable
SDG 16 (Peace and Justice)	Military conflict destabilizes the regional and international order	−2	Direct: Hormuz crisis is a military conflict with geopolitical escalation risks	NSR provides no direct contribution to conflict resolution	0	Route diversification does not address root cause of geopolitical instability

Appendix C.3. Inter-Rater Reliability

Scores were independently assigned by two co-authors (S.-J.L. and J.-S.K.) using the protocol in Appendix C.1. Cohen’s Kappa was calculated across all 16 score assignments (8 SDGs × 2 dimensions): $\kappa = 0.78$ (substantial agreement). Three discrepancies (SDG 2 NSR effect: one rater scored 0, the other scored +1; SDG 8 blockade impact: one rater scored −1, the other scored −2; SDG 9 blockade impact: both initially agreed at −1) were resolved through discussion and reference to the evidence base.

Appendix C.4. Robustness Check: Three-Point Scale

To test scale sensitivity, all scores were collapsed to a three-point scale: negative (original −2 and −1 → −1), neutral (0 → 0), positive (+1 and +2 → +1).

SDG	Blockade (3-pt)	NSR Effect (3-pt)	Net (3-pt)	Directional Consistency with 5-pt
SDG 1	−1	+1	0	Yes (negative → partially offset)
SDG 2	−1	+1	0	Yes
SDG 7	−1	+1	0	Yes
SDG 8	−1	+1	0	Yes
SDG 9	−1	+1	0	Yes
SDG 13	−1	−1	−2	Yes (both negative)
SDG 14	−1	−1	−2	Yes (both negative)
SDG 16	−1	0	−1	Yes

All directional conclusions are preserved: SDGs 13 and 14 remain net-negative under NSR mitigation, while SDGs 7 and 9 show partial or full offset. The fundamental trade-off structure is scale-invariant.

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