GATR Journal of Business and Economics Review
Journal homepage: http://gatrenterprise.com/GATRJournals/JBER/vol10_2026_issue4.html
J. Bus. Econ. Review 10(4) 36 – 49 (2026)

Competitiveness Vulnerabilities: Petroleum Dependency and Infrastructure Exposure Across Development Levels

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ABSTRACT

Objective – Critical infrastructure sectors form the backbone of national security and economic resilience, yet their dependence on petroleum inputs creates vulnerabilities that are inadequately measured. This study applies hypothetical extraction methodology to examine how petroleum supply disruptions would impact critical infrastructure across four developed economies (the United States, Japan, Germany, and the United Kingdom) and four developing economies (India, Indonesia, Malaysia, and Thailand).
Methodology – Using input-output analysis, we analyze six essential infrastructure sectors, including inland transport, air transport, water transport, telecommunications, utilities, and public administration.
Findings – Our findings reveal striking differences that challenge conventional assumptions about energy security. Developing economies exhibit 2.56 times higher overall infrastructure vulnerability than developed economies. Transportation sectors consistently emerge as the most vulnerable across all countries, with inland transport ranking first in all countries. However, individual patterns reveal significant paradoxes: the United States exhibits unexpectedly high vulnerability despite domestic oil production, whereas the United Kingdom demonstrates exceptional resilience despite its dependence on imports.
Novelty – The research identifies two distinct "infrastructure development paradigms": efficiency-first models and resilience-integrated approaches. Malaysia exhibits extreme vulnerability, with inland transport scoring 37.88 on the Infrastructure Vulnerability Index, whereas the UK maintains comprehensive resilience at an average IVI of 1.13. The study reveals that developing economies exhibit "amplification effects," in which disruptions cascade with minimal dampening, whereas most developed economies demonstrate "dampening effects" that contain vulnerabilities. These findings provide essential insights for national security planning and energy transition policies, demonstrating that infrastructure resilience results from specific design choices rather than automatic outcomes of economic development.
Type of Paper: Empirical
JEL Classification: Q31, Q43.
Keywords: Critical Infrastructure; Petroleum Dependencies; Input-Output Analysis; Economic Vulnerability; Energy Security; Hypothetical Extraction; Infrastructure Resilience
Reference to this paper should be made as follows: Majid, M.H.A, Yong, C.C, Alam, M.A.Z. (2026). Competitiveness Vulnerabilities: Petroleum Dependency and Infrastructure Exposure Across Development Levels, *J. Bus. Econ. Review,* 10(4), 36–49. https://doi.org/10.35609/jber.2026.10.4(5)

1. Introduction

Contemporary economic competitiveness increasingly depends on the resilience of critical infrastructure systems to external shocks, particularly petroleum supply disruptions.

* Paper Info: Revised: January 22, 2026
Accepted: March 31, 2026
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Infrastructure systems, including transportation, utilities, and communications, constitute the fundamental backbone of national productivity and economic performance. However, their structural dependence on petroleum inputs creates measurable competitive disadvantages that traditional economic assessments systematically overlook, particularly as global energy transitions accelerate and geopolitical uncertainties intensify. Despite substantial investments in renewable energy infrastructure, petroleum continues to account for 33% of global energy consumption (IEA, 2023) and remains deeply embedded in the operational fabric of critical infrastructure systems. Recent global disruptions have demonstrated how petroleum price volatility, which exceeded 40% in 2022, can cascade through infrastructure networks, systematically impairing logistics efficiency, public service delivery, and international trade competitiveness. The (Cybersecurity and Infrastructure Security Agency, 2024) reports intensified critical infrastructure vulnerabilities, with interconnected dependencies creating systemic risks to national economic performance.

This phenomenon reflects a fundamental shift in global risk dynamics, where petroleum-linked infrastructure fragility has evolved from a sectoral concern into a systemic threat to national competitiveness. Conventional competitiveness frameworks, including those employed by the (World Economic Forum, 2024) and the IMD World Competitiveness Center (2025), largely overlook these embedded energy vulnerabilities, focusing instead on more visible factors such as labor costs, technological capabilities, or institutional quality. This analytical gap proves particularly problematic for developing economies, where the (Asian Development Bank, 2022) reports petroleum intensity levels up to 2.5 times higher than those observed in advanced countries.

The (International Monetary Fund, 2024) projects a 35% increase in petroleum supply volatility by 2033, driven by climate policy implementation and persistent geopolitical tensions. This trajectory suggests that competitive exposure of critical infrastructure to petroleum disruptions will intensify significantly, creating widening competitiveness gaps between nations with resilient versus vulnerable infrastructure systems. Understanding and quantifying these vulnerabilities becomes essential for strategic economic planning and energy transition policies.

2. Literature Review

Critical infrastructure research has evolved significantly from early definitions focused on physical assets to comprehensive frameworks that recognize complex economic interdependencies (O'Rourke, 2007). (Rose, 2007) established foundational concepts of economic resilience, defining it as the ability of systems to maintain function during disruptions and recover quickly afterward. This work highlighted that infrastructure resilience extends beyond physical robustness to include economic adaptability and substitution capabilities.

(Hallegatte, 2014) advanced this understanding by developing quantitative measures of economic resilience that capture both immediate impacts and adaptive responses. His framework distinguishes between static resilience (immediate capacity to withstand shocks) and dynamic resilience (ability to adapt and recover over time) (Folke et al., 2010). This distinction is particularly relevant to petroleum dependency analysis, as some sectors may exhibit immediate vulnerability yet demonstrate strong adaptive capacity.

Recent research by (Brown et al., 2017) has emphasized the organizational dimensions of infrastructure resilience, showing how management practices and institutional arrangements can either amplify or mitigate physical vulnerabilities. Their work demonstrates that identical infrastructure systems can exhibit vastly different resilience profiles based on operational and policy frameworks (Comfort et al., 2010).

2.1 Input-Output Analysis and Economic Interdependencies

The hypothetical extraction method represents a sophisticated application of input- output analysis for vulnerability assessment, building on the foundational work of (Leontief, 1936) and subsequent developments by (Miller & Blair, 2009). This technique allows researchers to systematically assess the economic implications of removing specific sectors from economic systems (Dietzenbacher & Van der Linden, 1997).

The methodology's strength lies in its ability to capture both direct and indirect effects of sectoral disruptions (Oosterhaven & Stelder, 2002). When a sector is "extracted" from an input-output table, the analysis reveals not only the immediate impacts on sectors that directly purchase its outputs, but also the cascading effects as those sectors reduce their own outputs and purchases from other sectors (Guo & Planting, 2000).

Previous applications of hypothetical extraction have primarily focused on measuring the economic importance of specific industries or regions (Sonis et al., 1995) (Dietzenbacher et al., 2005). However, its application to critical infrastructure vulnerability assessment represents a novel and potentially transformative approach to energy security analysis, as demonstrated by recent work from (Haimes & Jiang, 2001) and (Santos & Haimes, 2004).

2.2 Energy Security and Infrastructure Vulnerability

Energy security literature has traditionally emphasized supply-side factors such as import dependencies, reserve levels, and geopolitical risks (Yergin, 2006) (Cherp & Jewell, 2014). However, recent events, including the COVID-19 pandemic and various geopolitical tensions, have highlighted the importance of demand-side vulnerabilities and supply chain interdependencies (Baldwin & Weder, 2020).

(Guan et al., 2020) demonstrated how supply chain disruptions can create unexpected vulnerabilities in sectors that appear to have minimal direct exposure to the disrupted inputs. Their analysis of COVID-19 impacts revealed that indirect effects often exceeded direct effects, fundamentally challenging conventional approaches to vulnerability assessment (Inoue & Todo, 2020).

The petroleum sector presents a particularly complex case for vulnerability analysis because of its dual role as both an energy source and a material input for numerous industries (Bridge & Le Billon, 2017). Transportation sectors show obvious direct dependencies, but telecommunications, utilities, and even public administration exhibit significant indirect dependencies through their reliance on petroleum-dependent suppliers and service providers (Thacker et al., 2019).

2.3 Conceptual Framework: Petroleum Dependency, Resilience, and Competitiveness

Building on the energy security and economic resilience literature, this study conceptualizes petroleum dependency as a structural source of economic vulnerability embedded within critical infrastructure systems, rather than merely a supply-side risk. Traditional energy security frameworks emphasize availability, affordability, and import dependence (Yergin, 2006) (Cherp & Jewell, 2014). However, recent resilience economics literature highlights that systemic vulnerability arises from interdependencies, substitution rigidity, and institutional capacity to absorb shocks (Rose, 2007) (Hallegatte, 2014).

Drawing on resilience capacity models (Bruneau et al., 2003) (Cimellaro et al., 2010), infrastructure vulnerability is understood here as the inverse of resilience capacity, reflecting the degree to which economic systems lack redundancy, adaptability, and flexibility when exposed to petroleum supply disruptions. From this perspective, petroleum dependency constrains both static resilience (the ability to maintain function during disruption) and dynamic resilience (the ability to adapt and recover over time).

This study further integrates insights from economic vulnerability and institutional resilience frameworks (North, 1990) (Acemoglu & Robinson, 2013), arguing that national competitiveness is shaped not only by energy resource endowments, but by infrastructure design choices, governance arrangements, and policy priorities that influence how petroleum dependencies propagate through the economy.

Conceptually, the paper advances literature by distinguishing between two infrastructure development paradigms: an efficiency-first paradigm, which prioritizes cost minimization and performance under normal conditions but amplifies the impact of disruptions, and a resilience-integrated paradigm, which embeds redundancy and energy diversification to dampen cascading vulnerabilities. The empirical analysis operationalizes this distinction using input–output–based vulnerability indices, thereby linking resilience theory with measurable competitiveness outcomes.

3. Research Methodology

This study employs a comparative cross-country analysis using the hypothetical extraction method applied to 2023 Asian Development Bank input-output tables. The research design enables systematic comparison of petroleum-related infrastructure vulnerabilities across eight economies representing distinct development contexts: four developed economies (the United States, Japan, Germany, and the United Kingdom) and four developing economies (India, Indonesia, Malaysia, and Thailand). This selection provides sufficient variation in economic structure, energy intensity, and institutional capacity to identify robust patterns in competitiveness vulnerability.

3.1 Data Sources and Preparation

Input-output tables were obtained from the Asian Development Bank. All tables were harmonized to common sector definitions and monetary units to enable meaningful cross-country comparisons. The "Coke, Refined Petroleum and Nuclear Fuel" sector was identified as the target for hypothetical extraction across all countries. To ensure cross-country comparability, all input–output tables were harmonized using a consistent sector classification based on the Asian Development Bank Multiregional Input–Output (MRIO) framework. Sector mapping was conducted to align national accounts with a common set of production sectors, with particular attention to harmonizing transportation, utilities, and public administration activities across countries.

All monetary values were standardized to a common currency using official exchange rates from the ADB MRIO database. Because the analysis focuses on relative changes in output, employment, and value-added multipliers resulting from hypothetical extraction, the results are invariant to absolute price levels and insensitive to inflation or purchasing power differences. This normalization approach is consistent with established comparative input–output studies (Dietzenbacher et al., 2005) (Temurshoev & Oosterhaven, 2014). The 2023 Asian Development Bank MRIO database was selected for three primary reasons. First, it provides consistent, up-to-date data coverage for both developed and developing Asian economies, which is critical to the study's comparative analysis at the development level. Second, the database employs a harmonized sectoral structure that facilitates petroleum-sector extraction without extensive reclassification. Third, alternative global databases, such as WIOD or OECD ICIO, provide more limited or less recent coverage for several developing economies included in this study.

3.2 Hypothetical Extraction Procedure

The hypothetical extraction methodology builds on the foundation established by (Miller & Blair, 2009) and (Santos & Haimes, 2004) for measuring economic interdependencies. The procedure follows a three-step mathematical process:

Step 1: Baseline Calculation. For each country, the original input-output table is used to calculate baseline output levels using the standard Leontief inverse methodology (Leontief, 1936):

$$X = (I - A)^{-1} F \tag{1}$$

Where X is the output vector, A is the technical coefficients matrix ($a_{ij} = z_{ij}/X_j$), and F is final demand.

Step 2: Petroleum Sector Removal Create a modified coefficients matrix A* by setting all petroleum sector inputs to zero:

$$a_{ij}^* = \begin{cases} a_{ij}, & amp; \text{if } i \neq \text{petroleum and } j \neq \text{petroleum} \\ 0, & amp; \text{if } i = \text{petroleum or } j = \text{petroleum} \end{cases}$$

Step 3: Impact Measurement:

$$\begin{aligned} X^* &= (I - A^*)^{-1} F^* \\ OI_i &= \frac{X_i - X_i^*}{X_i} \times 100 \end{aligned} \tag{2}$$

Output impact on sector i. Employment and value-added impacts follow analogous multipliers (Rose & Liao, 2005).

3.3 Vulnerability Index Development

Building on the resilience measurement frameworks developed by (Bruneau et al., 2003) and (Cimellaro et al., 2010), two composite vulnerability indices are constructed:

Sectoral Vulnerability Index (SVI): Following the approach of (Reggiani et al., 2015):

$$SVI_i = \frac{|OI_i| + |EI_i| + |VI_i|}{3} \tag{3}$$

Where OI_i, EI_i, and VI_i represent output multiplier, employment multiplier, and value-added multiplier respectively.

Cascading Vulnerability Index (CVI): Based on cascade failure frameworks (Buldyrev et al., 2010):

$$CVI_i = 0.5 \cdot |DI_i| + 0.3 \cdot |II_i| + 0.2 \cdot |IN_i| \tag{4}$$

Where DI_i, II_i, and IN_i represent direct, indirect, and induced impacts respectively.

Combining (3) and (4) to form the Integrated Vulnerability Index

$$IVI = 0.6(SVI) + 0.4(CVI) \tag{5}$$

4. Results

This section presents the empirical analysis of petroleum dependencies across critical infrastructure sectors in developed and developing economies. The methodology employed a hypothetical extraction approach to quantify the vulnerability of these sectors to petroleum supply disruptions.

4.1 Output Multiplier Changes by Sector

The hypothetical extraction of the petroleum sector reveals substantial differences in output multiplier effects between developed and developing economies. Table 1 presents the average percentage changes in output multipliers by sector.

Table 1. Average Output Multiplier Changes by Sector (%)

Sector	Developed Economies	Developing Economies	Difference
Air Transport	-10.04	-22.79	-12.75
Inland Transport	-12.06	-22.49	-10.43
Water Transport	-7.27	-16.39	-9.12
Post and Telecommunications	-6.34	-12.29	-5.95
Electricity, Gas, and Water Supply	-7.05	-13.56	-6.51
Public Administration	-7.13	-12.43	-5.30

The results demonstrate that all critical infrastructure sectors experience substantially greater output reductions in developing economies than in developed economies. The transportation sector shows the highest vulnerability, with Air Transport in developing economies exhibiting a 22.79% reduction in output multipliers, more than twice the 10.04% reduction observed in developed economies.

4.2 Country-Specific Vulnerability Patterns

Analysis of individual-country data reveals distinct patterns within both developed and developing economies. Table 2 presents the detailed country-specific results.

Table 2. Output Multiplier Percentage Changes by Country and Sector (%)

Country	**Air Transport**	**Inland Transport**	**Water Transport**	**Post & Telecom**	**Electricity/Water**	**Public Admin**	**Country Avg**
Germany	-4.7	-15.3	-2	-1.3	-1.6	-1.5	-4.4
Japan	-11.79	-13.86	-10.57	-8.83	-9.95	-9.69	-10.78
UK	-2.85	-2.57	-0.9	-1.14	-1.16	-0.95	-1.59
US	-20.8	-16.5	-15.6	-14.1	-15.5	-16.4	-16.48
Developed Avg	**-10.04**	**-12.06**	**-7.27**	**-6.34**	**-7.05**	**-7.13**	**-8.31**

India	-21.03	-10.55	-8.98	-9.17	-10.83	-9.09	-11.61
Indonesia	-25.88	-27.34	-24.09	-14.84	-10.87	-15.37	-19.73
Malaysia	-26.98	-39.21	-18.99	-19.82	-24.68	-20.51	-25.03
Thailand	-17.28	-12.86	-13.51	-5.33	-7.84	-4.76	-10.26
Developing Avg	**-22.79**	**-22.49**	**-16.39**	**-12.29**	**-13.56**	**-12.43**	**-16.66**

The country-specific analysis reveals striking patterns within each development group. Among developed economies, the UK demonstrates remarkable resilience, with an average vulnerability of -1.59%, whereas the US shows unexpectedly high vulnerability at -16.48%. Among developing economies, Malaysia exhibits the highest average vulnerability (-25.03%), whereas Thailand shows relatively moderate impacts (-10.26%), comparable to those of developed economies.

4.3 Sectoral Vulnerability Rankings

The relative rankings of sector vulnerabilities reveal consistent patterns across economic development levels, as shown in Table 3.

Table 3. Sector Rankings by Vulnerability (1 = Most Vulnerable)

Sector	Overall Rank	Developed Rank	Developing Rank
Inland Transport	1	1	1
Air Transport	2	2	2
Water Transport	3	3	3
Electricity, Gas, and Water Supply	4	4	4
Public Administration	5	5	5
Post and Telecommunications	6	6	6

This ranking reveals remarkable consistency across development contexts, with transportation sectors consistently dominating vulnerability patterns. Inland Transport consistently ranks as the most vulnerable sector, followed by Air Transport, suggesting fundamental technological dependencies that transcend economic development levels.

4.4 Exceptional Country Profiles

Several countries exhibit distinctive vulnerability patterns that warrant specific analysis:

The UK Resilience Model: The UK stands out with consistently low vulnerability across all sectors, with no single sector exceeding -2.85% output reduction. This exceptional resilience suggests systematic structural adaptations that have effectively insulated critical infrastructure from dependence on petroleum.

The US Vulnerability Paradox: Despite being the world's largest oil producer, the US demonstrates the highest vulnerability among developed economies, with particularly severe impacts in Air Transport

(-20.80%) and Public Administration (-16.40%). This "American Exception" contradicts conventional assumptions about domestic resource availability in energy security.

These contrasting country profiles suggest that petroleum-related infrastructure vulnerability is mediated by institutional and policy factors rather than energy endowment alone. The UK's resilience likely reflects long-term investment in energy diversification, regulatory coordination across infrastructure sectors, and greater integration of contingency planning within transport and utility systems. In contrast, the United States' high vulnerability despite domestic oil abundance indicates that resource availability may reduce incentives for diversification and resilience-oriented infrastructure design. This finding aligns with institutional resilience theory, which emphasizes that governance quality and policy coherence shape how shocks propagate through interconnected systems (Comfort et al., 2010) (Pahl-Wostl, 2009). Economies with stronger institutional coordination appear better able to dampen cascading effects, preventing petroleum disruptions in one sector from escalating into system-wide losses in competitiveness. Developing economies, by contrast, exhibit vulnerability-amplification patterns in which petroleum dependencies are deeply embedded across multiple infrastructure layers. Limited substitution options, higher energy intensity, and weaker buffering mechanisms cause shocks to propagate rapidly, reinforcing existing competitiveness gaps.

The German Transport Anomaly: Germany exhibits a unique bifurcated pattern, with extreme vulnerability in Inland Transport (-15.30%) and remarkable resilience in all other sectors (none exceeding -4.70%). This suggests successful energy decoupling in most sectors but persistent transportation dependencies.

The Malaysian Maximum Vulnerability: Malaysia shows the most extreme petroleum dependency globally, with Inland Transport vulnerability reaching -39.21%. The consistently high impacts across all sectors (-18.99% to -39.21%) indicate comprehensive petroleum integration throughout the economy.

4.5 Development Gap Analysis

The vulnerability gap between developed and developing economies varies significantly across sectors, as illustrated in Table 4.

Table 4. Development Gap in Sectoral Vulnerability

Sector	Gap (Developing - Developed)	Multiplier Effect
Inland Transport	-10.43	1.87x
Air Transport	-12.75	2.27x
Water Transport	-9.12	2.25x
Electricity, Gas, and Water Supply	-6.51	1.92x
Public Administration	-5.3	1.74x
Post and Telecommunications	-5.95	1.94x

Air Transport shows the largest absolute gap (12.75 percentage points) and multiplier effect (2.27x), indicating that developing economies face more than double the vulnerability in aviation infrastructure.

Transportation sectors generally exhibit the largest development gaps, whereas telecommunications and public administration show smaller disparities.

4.6 Infrastructure Vulnerability Index (IVI)

To provide a comprehensive measure that integrates both sectoral vulnerabilities and cascading effects, we developed an Infrastructure Vulnerability Index (IVI) that combines the Sectoral Vulnerability Index (SVI) and Cascading Vulnerability Index (CVI). Table 5 presents the IVI results by country and sector.

Table 5. Sectoral Vulnerability Index (SVI) by Country and Sector

Country	Air Transport	Inland Transport	Water Transport	Post & Telecom	Electricity/Water	Public Admin	Country Avg
Germany	8.66	19.86	1.3	0.57	0.92	1.29	5.43
Japan	6.38	6.51	5.6	5.04	5.02	4.82	5.56
UK	1.64	1.86	0.69	0.98	0.87	0.71	1.13
US	17.16	11.61	10.84	9.49	11.04	12.41	12.09
Developed Avg	**8.46**	**9.96**	**4.61**	**4.02**	**4.46**	**4.81**	**6.05**
India	20.38	9.34	6.83	7.27	9.81	6.38	10
Indonesia	22.79	27.01	20.93	13.87	10.94	11.65	17.86
Malaysia	22.43	37.88	14.8	15.08	24.72	15.31	21.7
Thailand	24.1	17.41	14.01	4.75	9.86	3.82	12.33
Developing Avg	**22.43**	**22.91**	**14.14**	**10.24**	**13.83**	**9.29**	**15.47**

The IVI analysis confirms the patterns observed in individual vulnerability measures while providing a more comprehensive assessment. Malaysia demonstrates the highest overall infrastructure vulnerability (21.70 average IVI), with extreme inland transport vulnerability (37.88 IVI). The UK maintains the lowest vulnerability profile (1.13 average IVI), while the US shows unexpectedly high vulnerability (12.09 average IVI) among developed economies.

4.7 Development Gap in Infrastructure Vulnerability

To provide a comprehensive measure that integrates both sectoral vulnerabilities and cascading effects, we developed an Infrastructure Vulnerability Index (IVI) that combines the Sectoral Vulnerability Index (SVI) and Cascading Vulnerability Index (CVI). Table 6 presents the IVI results by country and sector.

Table 6. Development Gap in Infrastructure Vulnerability (IVI)

Sector	Developed Avg	Developing Avg	Gap	Multiplier
Inland Transport	9.96	22.91	12.95	2.30x
Air Transport	8.46	22.43	13.97	2.65x
Water Transport	4.61	14.14	9.53	3.07x
Electricity, Gas, and Water Supply	4.46	13.83	9.37	3.10x
Post and Telecommunications	4.02	10.24	6.22	2.55x

Public Administration	4.81	9.29	4.48	1.93x
Overall Average	**6.05**	**15.47**	**9.42**	**2.56x**

The comprehensive IVI analysis reveals that developing economies face 2.56 times the overall infrastructure vulnerability of developed economies. The gap is most pronounced in the utility sector (electricity/water: 3.10x; water transport: 3.07x), whereas public administration shows the smallest multiplier effect (1.93x).

4.8 Transmission Mechanisms

The analysis reveals distinct patterns in how petroleum disruptions propagate through different economic systems. Developing economies exhibit characteristics of "vulnerability amplification," in which initial disruptions cascade with minimal dampening. For example, Malaysia's extreme Inland Transport vulnerability (-39.21%) suggests that petroleum dependencies create self-reinforcing vulnerability cycles.

In contrast, most developed economies exhibit "vulnerability containment," whereby disruptions in petroleum-intensive sectors do not translate proportionally into other infrastructure sectors. The UK exemplifies this pattern, with no sector showing vulnerability exceeding -2.85%, indicating effective economic buffering mechanisms.

The US represents a notable exception among developed economies, showing vulnerability amplification patterns more characteristic of developing economies. This suggests that domestic resource abundance may paradoxically create structural dependencies that amplify rather than buffer petroleum disruptions.

5.0 Discussion

5.1 Infrastructure Development Paradigms and Vulnerability Patterns

Our findings reveal two fundamentally different approaches to infrastructure development that transcend traditional developed-developing economy classifications. The Efficiency-First Model, exemplified by the transport sectors of the US, Malaysia, and Germany, optimizes infrastructure for performance under normal conditions while accepting greater vulnerability during disruptions. In contrast, the Resilience-Integrated Model, demonstrated by the UK, balances efficiency with systematic vulnerability reduction, suggesting that competitive performance and resilience can coexist. The most striking finding is the paradox of petroleum dependence in developed economies. The United States, despite being the world's largest oil producer, exhibits infrastructure vulnerability (-16.48% average) approaching levels observed in developing economies such as Indonesia (-19.73%). Meanwhile, the UK demonstrates remarkable resilience across all sectors (maximum impact: -2.85%) despite importing most of its petroleum. This reversal indicates that infrastructure resilience depends more on system design and policy choices than resource availability. Transportation sectors consistently emerge as the most vulnerable across all countries, ranking first (inland transport) and second (air transport), regardless of development level, suggesting fundamental technological dependencies. However, magnitudes vary dramatically: Malaysia's inland transport vulnerability (-39.21%) could fundamentally disrupt economic connectivity, whereas the UK's transport vulnerabilities remain manageable (-2.57% to -2.85%). The telecommunications sector demonstrates consistent resilience, ranking lowest in vulnerability across all countries, indicating successful decoupling from petroleum dependencies.

5.2 Vulnerability Transmission and Competitive Implications

The analysis reveals distinct mechanisms of vulnerability transmission with profound competitive implications. Developing economies exhibit "amplification effects," in which petroleum disruptions cascade with minimal dampening; countries such as Indonesia and Malaysia show consistently high vulnerabilities across multiple sectors. Most developed economies exhibit "dampening effects" that mitigate disruptive impacts, preventing localized vulnerabilities from becoming system-wide problems. The US represents a notable exception, showing vulnerability patterns more similar to those of developing economies despite advanced institutional capabilities. This suggests that domestic resource abundance may have reduced incentives to build resilient infrastructure systems, creating what we term the "abundance vulnerability paradox." These patterns directly impact national competitiveness. The 2.56x average vulnerability differential between developing (15.47 IVI) and developed economies (6.05 IVI) indicates systematic competitive disadvantages during supply disruptions. Malaysia's extreme transportation vulnerabilities (-39.21% inland, -26.98% air transport) could severely compromise cargo movement and connectivity - key factors in global supply chain integration. Conversely, the UK's minimal transportation vulnerabilities provide substantial competitive advantages, with 6-7 fold lower vulnerability than the US, suggesting UK infrastructure would maintain near-normal performance while US infrastructure faces significant constraints. The telecommunications sector's consistently low vulnerability across all countries indicates that digital economies may preserve competitive advantages when transportation and utility sectors face constraints, underscoring the strategic importance of digital infrastructure development.

5.3 Policy Implications and Strategic Frameworks

The substantial variation in vulnerability patterns among countries with similar levels of development demonstrates that infrastructure resilience is the outcome of deliberate policy and design choices rather than an automatic consequence of economic development. The United Kingdom’s comprehensive resilience profile illustrates how resilience-oriented infrastructure planning can coexist with competitive performance, offering a viable alternative to efficiency-maximizing development strategies that prioritize short-term cost minimization at the expense of systemic robustness. In contrast, countries adhering to efficiency-first models face increasing exposure to energy volatility, creating the risk of latent “infrastructure time bombs” in which existing competitive advantages may rapidly translate into severe liabilities during petroleum supply disruptions.

For developing economies, vulnerabilities in the transportation sector, particularly in inland and air transport, emerge as critical transmission channels through which petroleum disruptions propagate into broader economic impacts. The ability of several developed economies to contain these vulnerabilities indicates that targeted policy interventions, including energy diversification, transport electrification, modal shifts, and enhanced inter-sectoral coordination, can significantly improve overall infrastructure resilience. Accordingly, developing countries should prioritize strengthening the resilience of transportation infrastructure while simultaneously building institutional capacity to mitigate cascading effects across interconnected sectors.

At the planning and operational levels, the Infrastructure Vulnerability Index developed in this study provides a practical tool for identifying critical vulnerability hotspots, enabling regional planners and infrastructure authorities to direct investments toward redundancy, alternative-fuel systems, and resilience-enhancing network design, particularly in transportation and utility systems. For private-sector infrastructure operators, the findings underscore the strategic importance of resilience investment, as firms operating petroleum-intensive assets face heightened operational and financial risks during supply disruptions;

investments in diversification, backup systems, and energy efficiency therefore represent not only risk-mitigation measures but also sources of sustained competitive advantage.

The outlier patterns identified, most notably the U.S. vulnerability paradox and Malaysia's pervasive petroleum integration, warrant focused policy attention. The U.S. case demonstrates that domestic resource abundance does not automatically translate into infrastructure resilience, suggesting that long-standing reliance on petroleum may reduce incentives for diversification and adaptive system design. Malaysia's extreme vulnerability, particularly in transportation, highlights the urgency of accelerating diversification and resilience-oriented infrastructure reform. Collectively, these findings challenge conventional energy security frameworks that emphasize resource availability alone and instead underscore the critical importance of resilience-integrated infrastructure planning for sustaining national competitiveness in an increasingly volatile global energy environment.

6. Conclusion

This study provides the first comprehensive comparative analysis of petroleum dependencies in critical infrastructure across developed and developing economies using hypothetical extraction methodology, revealing systematic vulnerability patterns that fundamentally challenge conventional assumptions about energy security and economic development. The research demonstrates that developing economies face 2.56 times the overall infrastructure vulnerability of developed economies, with transportation sectors universally vulnerable across all countries, regardless of development level. However, the most significant finding is the identification of two distinct infrastructure development paradigms that operate independently of traditional economic categories: the efficiency-first model that optimizes performance while creating systematic vulnerabilities (exemplified by the US and Malaysia), and the resilience-integrated model that balances competitive performance with vulnerability reduction (demonstrated by the UK). The study reveals a striking petroleum dependency paradox where the United States, despite being the world's largest oil producer, shows vulnerability patterns approaching those of developing economies (12.09 average IVI), while the UK achieves exceptional resilience (1.13 average IVI) despite import dependencies, indicating that infrastructure resilience depends fundamentally on system design and policy choices rather than resource availability. Malaysia represents the extreme endpoint, with inland transport vulnerability reaching 37.88 IVI, whereas telecommunications demonstrate consistent resilience across all countries, providing a model for successful decoupling from petroleum dependence. The analysis reveals that developing economies exhibit amplification effects, in which disruptions cascade with minimal dampening, whereas most developed economies demonstrate dampening effects that contain vulnerabilities, creating systematic competitive disadvantages for developing countries in transportation-dependent sectors critical to global supply chain integration. These findings demonstrate that infrastructure resilience results from specific design choices rather than automatic outcomes of economic development, with the UK's comprehensive resilience model providing concrete evidence that countries can pursue strategies balancing efficiency with systematic vulnerability reduction, offering essential insights for infrastructure planning, energy transition policies, and national security planning in an increasingly uncertain global energy environment.

Declaration of Funding

The research work is funded by the Ministry of Higher Education to Universiti Malaya, Malaysia, under the Fundamental Research Grant Scheme (FRGS/1/2023/SS06/UM/02/9) awarded to the second author.

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