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Geopolitical Resilience in Global Supply Chains: Comparing Sectoral Strategies for Sustainable Risk Mitigation

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“To my mom for always saying: it will be ok”

Abstract

The dissertation examines the geopolitical resilience of four global supply chain sectors, semiconductors, energy and critical minerals, pharmaceuticals and medical supplies, agri food products. The main issue nowadays is that resilience is treated as a general corporate objective; this dissertation addresses the core problem which is that mitigation instruments are attached to sector specific economic and regulatory structures. Using a qualitative comparative research methodology the study maps these sector specific vulnerabilities relative to operational mitigation capabilities.

The findings reveal that resilience strategies are impossible to be applied universally, because each sector presents unique challenges. Semiconductor bottlenecks are capital-intensive fabrication monopolies (TSMC, Intel, Samsung), the long-term government financial support and technological alliances. Energy and critical minerals are strongly connected to geological concentration, shifting the resilience directive toward refining diversification and material circulation. Pharmaceutical products are constrained by very strict regulatory approvals (5 to 10 years for a product to be tested, approved and released to public), unexpected and quick demand spikes. Finally, Agri-food chains are extremely sensitive to real time climate impacts (drought can destroy vast agricultural land) and fertilizer reliance, requiring localized yield optimization and agile trade substitutability.

The essential insight of this study is that geopolitical resilience means adapting to global risks by creating strong local foundations, not abandoning the global market completely. The supply chain security we should pursue needs public and private actors to reject the uniform resilience models for a calibrated matrix where cost efficiency, national security and compliance coexist and create a balanced system.

Keywords

Geopolitical Risk Management, Supply Chain Resilience, Sustainable Logistics Strategy, Economic Sovereignty

“Γεωπολιτική Ανθεκτικότητα στις Παγκόσμιες Αλυσίδες Εφοδιασμού: Σύγκριση Τομεακών Στρατηγικών για τη Βιώσιμη Μετρίαση των Κινδύνων”

“Αναστάσιος Τζελέπης”

Περίληψη

Η διατριβή αυτή εξετάζει τη γεωπολιτική ανθεκτικότητα τεσσάρων τομέων της παγκόσμιας εφοδιαστικής αλυσίδας: των ημιαγωγών, της ενέργειας και των κρίσιμων ορυκτών, των φαρμακευτικών προϊόντων και ιατρικών προμηθειών, καθώς και των αγροδιατροφικών προϊόντων. Το κύριο ζήτημα σήμερα είναι ότι η ανθεκτικότητα αντιμετωπίζεται ως ένας γενικός εταιρικός στόχος· η παρούσα διατριβή πραγματεύεται το κεντρικό πρόβλημα, το οποίο συνίσταται στο ότι τα εργαλεία μετριασμού του κινδύνου είναι άρρηκτα συνδεδεμένα με τις οικονομικές και κανονιστικές δομές κάθε συγκεκριμένου τομέα. Χρησιμοποιώντας μια ποιοτική συγκριτική μεθοδολογία έρευνας, η μελέτη χαρτογραφεί αυτές τις τομεακές ευπάθειες σε σχέση με τις επιχειρησιακές δυνατότητες μετριασμού.

Τα ευρήματα αποκαλύπτουν ότι είναι αδύνατο οι στρατηγικές ανθεκτικότητας να εφαρμοστούν καθολικά, καθώς κάθε τομέας παρουσιάζει μοναδικές προκλήσεις. Οι αδυναμίες (bottlenecks) στον τομέα των ημιαγωγών εντοπίζονται στα μονοπώλια παραγωγής έντασης κεφαλαίου (TSMC, Intel, Samsung), στη μακροπρόθεσμη κρατική χρηματοδοτική στήριξη και στις τεχνολογικές συμμαχίες. Η ενέργεια και τα κρίσιμα ορυκτά συνδέονται στενά με τη γεωλογική συγκέντρωση, μετατοπίζοντας τη στρατηγική κατεύθυνση της ανθεκτικότητας προς τη διαφοροποίηση της διύλισης και την κυκλικότητα των υλικών. Τα φαρμακευτικά προϊόντα περιορίζονται από εξαιρετικά αυστηρές κανονιστικές εγκρίσεις (απαιτούνται 5 έως 10 έτη για τη δοκιμή, έγκριση και διάθεση ενός προϊόντος στο κοινό), καθώς και από ξαφνικές, απότομες εξάρσεις της ζήτησης. Τέλος, οι αγροδιατροφικές αλυσίδες είναι εξαιρετικά ευαίσθητες στις επιπτώσεις της κλιματικής αλλαγής σε πραγματικό χρόνο (όπου η ξηρασία μπορεί να καταστρέψει τεράστιες γεωργικές εκτάσεις) και στην εξάρτηση από τα λιπάσματα, απαιτώντας τοπική βελτιστοποίηση της απόδοσης και ευέλικτη δυνατότητα υποκατάστασης στο εμπόριο.

Η θεμελιώδης διαπίστωση αυτής της μελέτης είναι ότι η γεωπολιτική ανθεκτικότητα σημαίνει προσαρμογή στους παγκόσμιους κινδύνους μέσω της δημιουργίας ισχυρών τοπικών βάσεων, και όχι την πλήρη εγκατάλειψη της παγκόσμιας αγοράς. Η ασφάλεια της εφοδιαστικής αλυσίδας που πρέπει να επιδιώξουμε απαιτεί από τους δημόσιους και ιδιωτικούς φορείς να απορρίψουν τα ενιαία μοντέλα ανθεκτικότητας, προκρίνοντας ένα βαθμονομημένο πλέγμα (matrix) όπου η σχέση κόστους-αποτελεσματικότητας, η εθνική ασφάλεια και η κανονιστική συμμόρφωση συνυπάρχουν και διαμορφώνουν ένα ισορροπημένο σύστημα.

Λέξεις – Κλειδιά

Διαχείριση Γεωπολιτικών Κινδύνων, Ανθεκτικότητα της Εφοδιαστικής Αλυσίδας, Στρατηγική Βιώσιμων Logistics, Οικονομική Κυριαρχία

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1 Introduction

1.1 Research Background

Global supply chains have become a backbone of modern global economy, trade and consumption. For decades, international corporations chased cost efficiency, specialization, just-in-time logistics and access to globally distributed suppliers. This setup drove down costs and enabled global sourcing, secretly building dangerous choke points by concentrating on critical inputs, technologies and logistic paths in a very few limited firms, countries and regions. Recent pandemics (covid), trade disputes (Hormuz strains) , sanctions (European Union on Russia), export controls (US to the rest of the world), regional conflicts, climate shocks and transport bottlenecks demonstrate that efficiency alone is not enough when continuity depends on politically exposed or geographically choke points (Christopher & Holweg, 2017; Pettit et al., 2019).

Supply chain resilience has escalated from a single back office operational issue to a high stakes geopolitical mandate. Resilience demands more than recovery; it includes anticipation, adaptation, reconfiguration and the preservation of critical functions under uncertainty. In this sense, resilience depends on dynamic capabilities, visibility, redundancy, coordination and institutional support (Chowdhury & Quaddus, 2017; Wieland & Durach, 2021). Adding a geopolitical layer to the equation introduces the reality of state interventions, resource nationalisms, and weaponized interdependencies.

This dissertation compares the geopolitical resilience of four critical sectors: semiconductors, energy and critical minerals, pharmaceuticals and medical supplies, and agri-food products. These sectors perform essential economic and social functions, yet they differ sharply in capital intensity, technical complexity, substitutability, regulation, perishability and environmental exposure. Rather than evaluating the four sectors independent and offering isolated sectoral summaries it evaluates how different structural constraints change the strategic value of the same resilience instruments, such as diversification, stockpiling, relocation, friend-shoring and circularity. Right now, the study challenges the current supply chain literature. Current literature has presented generic risk management, but it treats supply chains as a structural uniform. This dissertation bridges the gap (Fan & Stevenson, 2018; Hosseini et al., 2019; Ivanov, 2021; Katsaliaki et al., 2022). The central premise of this dissertation is that resilience strategies cannot be evaluated in isolation from the structural properties of each sector. A resilience strategy used in one industry might be fast, cost efficient, environmentally approved, in another sector might be slow, costly, insufficient or ecologically problematic.

1.2 Geopolitical Instability and Global Supply Chains

Geopolitical instability affects global supply chains through multiple mechanisms: restricted access to suppliers, surging transport premiums, frozen capital investments and uncertainty over future trade relations. Trade wars, sanctions and export restrictions show that supply chains do not operate in a politically neutral global bubble but are bound to government level agendas. Geopolitical risk therefore is not a background variable, but it is a direct deciding factor of where production occurs, sourcing strategy and how global value chains are governed (Caldara & Iacoviello, 2022; Strange, 2020).

The real execution of this geopolitical risk differs by sector and is sector specific. In semiconductors, vulnerability is technology-centered and is weaponized through export controls on specialized equipment (ASML's EUV machines are not sold to Chinese manufactures) and highly concentrated fabrication monopolies (TSMC in Taiwan). In energy and critical minerals, risk is resource- and infrastructure-centered, involving extraction sites, refining capacity, shipping choke points, and the material requirements of green transitions. In pharmaceuticals and medical supplies, risk is mediated by Active Pharmaceutical Ingredients (API) dependence, regulated manufacturing, public-health demand surges and export restrictions. Finally, agri-food systems present geopolitical instability intersects with climate shocks, fertilizer dependence, energy prices, transport disruption and national food-security concerns (Béné, 2020; Bown, 2020; Sovacool et al., 2020; Spieske et al., 2022). This shifting landscape has forced boards and policy makers to abandon the holistic pursuit of lean efficiency. The resulting tactical shift toward near-shoring and strategic stockpiling is not a panacea. Building redundancy, and safety stocks tie up working capital, regionalization hurts economies of scale and friend-shoring narrow the vendor ecosystem. While circular economy models promise long term sustainability, they just demand advanced technological environments and extended funding before yielding the desired results. (Christopher & Holweg, 2017; Fan & Stevenson, 2018; Ivanov & Dolgui, 2020).

The main objective is not justifying the need for resilience but adapting without creating operating chaos or ecological damage. While the pure efficiency model damages the supply networks deeply a security driven model risks creating prohibitive costs and ecological degredation. Sustainable risk mitigation decreases these vulnerabilities of sector specific dependencies without introducing new layers of economic, ecological or strategic exposure. (Kano & Oh, 2020; Katsaliaki et al., 2022; Wieland & Durach, 2021).

1.3 Aim and Objectives of the Study

This dissertation aims to decipher how geopolitical resilience can be embedded into global supply chains. The study discards generic framework, executing a cross sector comparative analysis of vulnerabilities and sustainable risk mitigation strategies across all four sectoral networks. The research is organized in five main objectives:

First, it identifies the main structural and geopolitical vulnerabilities of each sector. Rather than treating all chains equally, the analysis isolates the technology-centric dependencies in semiconductors, resource and processing bottlenecks in energy and minerals, regulatory constraints in pharmaceuticals and localized vulnerabilities within agri-food systems.

The second objective evaluates which geopolitical shocks identify as operational failures. Investigates how major disruption such sanctions, export controls, war conflicts and climate disruptions compromise production capacity and disrupts logistical matters.

Third objective is to compare the standard mitigation instruments used across the four sectors. Evaluates how supplier diversification, friend-shoring, localized capacity, strategic stockpiling, public-private coordination, substitution, recycling and circular economy strategies are deployed by each sector to yield maximum operational resilience.

The fourth objective is to identify why the same resilience strategies produce unequal effects in every sector. This requires analyzing how structural variables such as capital intensity, multiyear regulatory approval timelines, physical perishability either enable or choke sector specific risk mitigation tools.

The fifth and final objective is to transform these comparative insights into actionable sector sensitive strategies corporate executives can use. The main achievement is to demonstrate how cost efficiency and national security directive can help and reinforce one another rather than operating as separate exclusive agendas.

1.4 Research Questions

The dissertation is structured around five central research questions:

RQ1: Which geopolitical and structural vulnerabilities define semiconductor, energy and critical mineral, pharmaceutical and medical, and agri-food supply chains sectors?

RQ2: How political disruptions such as sanctions, export controls, war conflict, translate into real world supply chain operational failures?

RQ3: Which mitigation mechanisms are universally used in all four sectors and how do their solutions (friend-shoring, stockpiling, circularity) vary in real life applications?

RQ4: Why do identical resilience strategies yield completely different outcomes across different industries?

RQ5: How can policymakers(governments) and corporate executives design resilience strategies that allow cost efficiency, national security and sustainability be reinforced?

These questions force a qualitative cross sector comparison rather than an isolated single industry study. They create a bridge between sector level evidence and macro level frameworks of global value chain governance. All comes down to one proposition: supply chain resilience is context dependent. If a strategy offers support to one industry's vulnerabilities can easily become an expensive, ecologically damaging liability in another if applied through a one size fits all model.

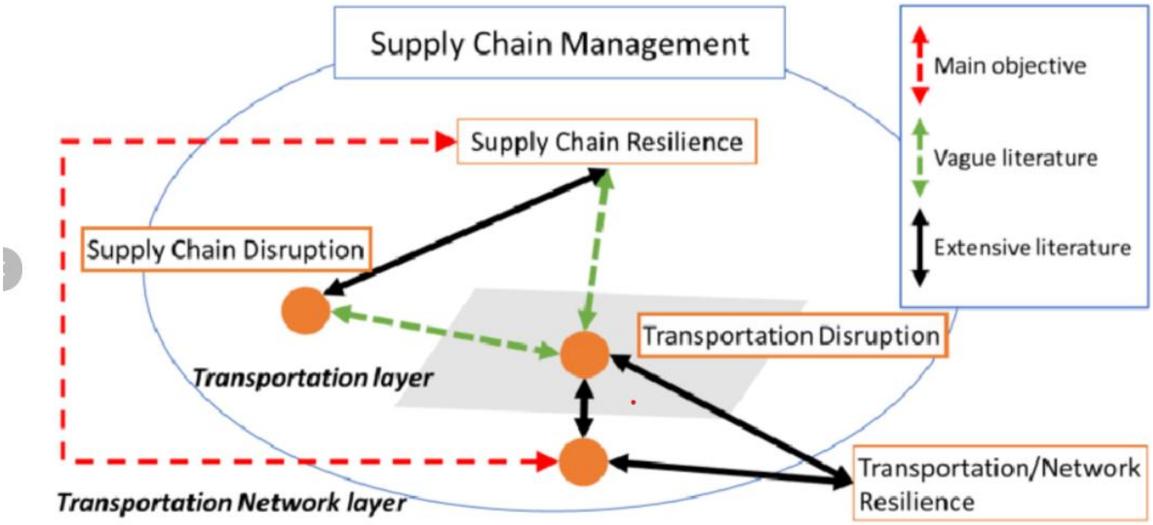

Figure 1. Relationship between supply chain disruption, transportation disruption and supply chain resilience. *Source: ResearchGate figure repository.*

1.5 Methodological Approach

The dissertation presents a qualitative comparative research design rather than presenting a mere statistical relationship between geopolitical risk and supply chain performance, focuses on explaining the specific mechanisms of the resilience strategies. To achieve this the research follows the following comparative model: each sector is questioned through the same identical analytical categories, but the evaluation and the interpretation of each category is unique to the specific sector real world operational issues.

The unit of analysis is the sectoral supply chain system itself rather than the individual corporation/firm. This approach is necessary because the examined vulnerabilities are embedded under multi-tier production layers, regulatory systems, resource geographies and international infrastructure. The four specific sectors were not randomly selected, they were selected because they present some of the most important pillars of modern economic security, technological sovereignty and ecological transition. Even though they are critical they display fundamentally different structural and geographic dependencies.

The evidence that was used consists of peer reviewed academic literature, industry reports and sectoral data selected through purposive sampling. Sources were included based on how relevant they are to the supply chain resilience, geopolitical risk and sustainable risk mitigation strategies. Most recent literature was prioritized to ensure that the analysis successfully captures post pandemic, export controls, sanctions and green energy transitions. In addition, sources from earlier years were selected for their proven definition of resilience, risk management and global value chain governance. (Christopher & Holweg, 2017; Chowdhury & Quaddus, 2017; Fan & Stevenson, 2018; Pettit et al., 2019).

The analytical procedure consists of two stages to ensure a thorough comparison. The first stage consists of a within sector analysis where each industry is evaluated separately and independently to establish clear vulnerabilities and mitigation instruments. The second stage changes to a cross-sector analysis where independent findings are compared against common sectoral criteria like implementation speed, financial costs, sustainability impacts and residual dependencies. This dual stage procedure makes it easily visible to public audiences because explains thoroughly why identical strategies yield unequal outcomes across different industries.

To ensure thorough evaluation, the research design and operational mapping are structured in Table 1.1, while the structural parameters defining each sector are displayed in Table 1.2

Table 1.1 Research design matrix

Research element	**Operationalization in this dissertation**	**Analytical function**	**Expected output**
Research purpose	Explain how sectoral structure mediates geopolitical supply-chain risk	Moves the study beyond general methodology	Strategic diagnosis rather than description
Unit of comparison	Sectoral supply-chain systems in four critical industries	Allows comparison of different forms of dependence	Common framework with sector-specific interpretation
Evidence base	Academic literature and sectoral evidence on resilience, risk, dependence and sustainability	Supports thematic coding and structured comparison	Analytical categories grounded in prior research
Coding categories	Vulnerability, disruption mechanism, mitigation strategy, governance, sustainability, implementation limits	Organizes findings consistently across sectors	Comparable evidence across Chapters 2-5
Evaluation criteria	Feasibility, speed, cost, security contribution, sustainability effect and residual dependence	Assesses the strategic value of each resilience tool	Trade-off analysis in Chapter 6

By constructing the research this way, the comparative matrix shown above is used as an analytical instrument. The study completely rejects the idea that each industry falls under the same generic problem and instead treats each sector as a distinct configuration. The goal of this study is to determine which resilience strategies are sector specific, which are universally applicable and which ones generate costly tradeoffs unable to maintain them.

Table 1.2 Sectoral differentiation criteria used in the comparison

Sector	**Dominant structural constraints**	**Why generic mitigation is insufficient**	**Strategic design implication**
Semiconductors	Capital intensity, advanced fabrication concentration, specialized equipment, intellectual property, tacit process knowledge and water/energy requirements	Alternative suppliers cannot be created quickly; relocation does not replicate process capability or ecosystem depth	Prioritize targeted redundancy in critical nodes, allied technology ecosystems and visibility beyond first-tier suppliers
Energy and critical minerals	Geological fixity, refining concentration, infrastructure dependence, long permitting cycles and exposure to sanctions or trade restrictions	Diversifying extraction alone does not reduce dependence if processing remains concentrated	Combine supplier diversification with refining capacity, recycling, substitution and credible environmental governance
Pharmaceuticals and medical supplies	API dependence, GMP compliance, regulatory approval, quality assurance, shelf-life and emergency demand surges	Stockpiles provide time but do not replace approved production capacity or qualified suppliers	Build regulated redundancy, rotating inventories, regulatory cooperation and public-private procurement mechanisms
Agri-food products	Climate exposure, perishability, seasonality, fertilizer and energy dependence, transport disruption and trade restrictions	Localization cannot fully offset climate variability, input dependence or seasonal supply gaps	Design diversified regional networks, climate-adaptive logistics, input resilience and waste-reduction capacity

This comparative analysis is interpretative rather than statistical or quantitative. The analysis uses thematic coding to identify recurring patterns and sector specific constraints, avoiding on purpose the numerical score usage. This methodological choice brings out the high dynamic of geopolitical risk and the fact that the effectiveness of mitigation measures depends on technological, environmental and institutional conditions which cannot be presented with a single quantitative indicator.

Finally, the research carries out four specific limitations. First, the study relies on secondary literature, meaning it does not incorporate original survey evidence or interviews. Second, the available literature among the four sectors is asymmetric, as pandemic academic debates favor semiconductors and of course pharmaceuticals over agri food sector. Third, although qualitative design isolates causal mechanisms and strategic tradeoffs, it is non predictive and does not produce forecasts. Fourth, this qualitative approach cannot offer financial cost-effective measurement controls. Rather than weakening the study, these limitations focus on the true contribution of the study, the strategic interpretation, structured assessment and conceptual clarification.

2 Semiconductor

2.1 Strategic Importance of Semiconductors

Semiconductors are the quiet pillar of moder global production, powering everything, digital infrastructure (data centers), vehicles, medical equipment and military equipment are among the most popular. The true value of the semiconductor industry is simply their indispensability; they cannot be replaced or substituted easily. As recent Covid and post Covid years have shown, a small shortage of low-cost chips can completely delay the production of high value goods, especially in the automotive, aerospace and military sectors. Consequently, securing a stable chip supply escalated from a routine procurement task to a critical pillar of industrial continuity, national security and technological edge (Mönch et al., 2018; Xiong et al., 2024).

Semiconductors economic weight is heavily attached to the modern on going transformation. Data processing, automation, Internet of things (IoT) rely solely on semiconductor complexity. While older chip technology keeps standard manufacturing running, cutting edge processors drive high demand growth sectors like 5G infrastructure, electric vehicles and of course artificial intelligence. As global demand keeps surging, supply chain forecasting becomes difficult and complicated due to the massive capital investments, rapid technological obsolescence and geopolitical changes. Nations or firms who looking to compete in high value markets have set as one of their main objectives securing a stable reliable chip supply, otherwise they are facing risks, like being left out of the market share or even being completely discarded (Grimes & Du, 2022; Fu et al., 2023).

2.2 Geographic Concentration of Production and Technological Dependencies

What truly defines the semiconductor industry is how heavily concentrated its critical infrastructure is within a few countries, companies and ecosystems. Advanced economies like the United States dominate high value chip design but physical manufacturing, assembly, testing and packaging its fully concentrated in East Asia (Taiwan, Korea, Japan). This highly specialized geographical concertation didn't happen overnight; are the results of decades of capital investment, workforce development, local supplier clusters and aggressive government backing. Once a certain semiconductor ecosystem settles, firms, skill and services lock in as well, creating a powerful barrier that makes relocating these supply chain difficult and cost prohibitive (Mönch et al., 2018; Grimes & Du, 2022).

This bottleneck is most fragile at the cutting edge of fabrication. Building a modern fabrication plant requires vast investments (10 – 20 billion USD), precise equipment (ASML EUV), supplier coordination and years perfecting operational processes. The entire value chain is based on super specialized inputs used only in semiconductors: software and intellectual property, advanced lithography machines, specialized chemicals and let's not forget the base where everything is taking shape on, ultra-pure silicon wafers. These deep dependencies are embedded across multiple market layers and gaining deep knowledge and access past tier one suppliers is both vital and painfully difficult to execute (Mönch et al., 2018; Fu et al., 2023).

2.3 Geopolitical Risk and Resilience in Semiconductor Supply Chains

2.3.1 The Weaponization of Interdependence at the Commercial-Security Nexus

Geopolitical risk has become a defining and almost unavoidable feature inside semiconductor supply chains. Chips are essential for economic power, military capabilities and for technological leadership in today’s global economy. Trade conflicts, sanctions, export limits, licensing restraints and strategic limitations control how governments and enterprises manage access to semiconductor technology and advanced production systems. It is an industry that lies at the nexus of commercial globalization and national security policy, fundamentally dictating how multinational corporations govern access, continuously subject to non-economic evaluations and unpredictable political shifts sometimes not even constant from one age to another. The work is difficult for firms, in many ways. Policy decisions may affect supplier relationships, market access circumstances, licensing options and investment aims incredibly quickly, and frequently without notice. Investment goals are changing fast too, with less time to prepare and less visibility for firms that need stable conditions for planning. The evaluation of geopolitical risk is helpful to understand why resilience is increasingly seen as a strategic goal not just as an operational issue anymore (Bown, 2020; Caldara & Iacoviello, 2022).

Geopolitical imperatives actively penetrate market mechanisms, directly undermining firm-level performance in ways that escape traditional corporate control frameworks in ways that are hard for organizations to control. The U.S.-China trade war makes it clear that semiconductor supply chains have become weapons and instruments of great power geopolitical strife. Access to the critical industrial processes that depend on the most innovative chips, design software and production equipment is limited by export restrictions and technical constraints. These efforts are aimed at slowing down the technological development of competitors, but they also damage the multinational firms operating in multiple places at the same time. Therefore, the impact is not rarely clear or isolated; instead, they migrate outward across wider production, investment and innovation systems in ways that are chaotic, indirect and sometimes quite costly as well. For semiconductor companies, adhering to ever-changing standards, navigating these fluid compliance mandates represents an intricate operational hurdle. The regulations are changing regularly, and the meaning of the rules may also become imprecise, disputed or politically expanded depending on the circumstances. The market is more unpredictable, and the firms are forced to shift strategies without having all the facts in front of them. At the same time, they must keep inventing, keep the supply constant, complete the contracts, retain their competitiveness and not break the law, all while maintaining absolute regulatory compliance during empirical industry execution (Bown, 2020; Grimes & Du, 2022). It is not just technical, it is regulatory and strategic and, in some cases, diplomatic in indirect ways.

2.3.2 Industrial Policy, Protectionist Subsidization, and Global Network Fragmentation

Trade restrictions can provide incentives for nations to develop their own industrial policies. Governments subsidize and encourage indigenous semiconductor capabilities via tax incentives, industrial policies and research funding initiatives designed to expand aggregate national capacity. Public-private partnerships are used to promote better domestic capacity; however, results may take several years to become apparent and, in some cases, may not be wholly successful. The measures are intended to reduce the foreign dependency and access to critical technologies and economic assets. This is a shift from a more market-led globalization to a more controlled and security-oriented administration of supply chains. Companies rethink where they produce goods in response, this strategic decoupling threatens to trigger a systemic breakdown of legacy global production networks over the longer term (Moktadir & Ren, 2024; Liu et al., 2025).

2.3.3 Geographic Hyper-Concentration and the Fragility of Advanced Nodes

Taiwan's role as a major player in advanced semiconductor manufacturing is one of the most crucial geopolitical issues facing the overall industry today. There is a significant portion of global leading-edge fabrication capacity located there, and this creates a substantial susceptibility to regional tension, strategic ambiguity and military related instability. The effects of any disruption in this industry would be global and extremely quick throughout the sectors, not confined to the local. This kind of scenario might have effects on electronics, vehicles, communication infrastructure, cloud computing, defense manufacture and current industrial equipment, would cause severe, compounding shortages across downstream sectors. This concentration makes the system efficient but also fragile, and fully exposed. The most advanced nodes have little spare capacity that can be rapidly increased when disruption unexpectedly hits. It explains the rising desire of governments to diversify and seek links with places viewed as more stable, more politically aligned or less strategically sensitive. Resilience strategies have therefore become important in corporate planning and in government policy too, since a regional risk might soon turn into a global economic worry (Liu et al., 2025; Xiong et al., 2024).

2.3.4 Inventory Distortion, Demand Asymmetry, and Self-Reinforcing Shortages

The reasoning is perhaps simple; implementation is not simple, it is quite difficult in certain areas, expensive and slow as well. Moreover, geopolitical factors also affect demand patterns and stockpiling behavior of firms throughout the semiconductor system. Facing uncertainty, firms may hoard inventory, sign long-term contracts, source from several suppliers, re-engineer their products, or stockpile more of the available components when shortages are anticipated. These procedures, although frequently increasing short term security, might increase expenses and make capacity planning more difficult than before. If several firms hoard at the same time, because of fear, the market may become increasingly distorted, generating shortages that are partly self-reinforcing and not only the result of genuine final demand. The semiconductor shortage has illustrated how fast demand may fluctuate, creating significant imbalances across the system. Advanced manufacturing is a good illustration of how market conditions may shift quicker than production capacity can respond. It takes years of research, massive capital, and highly specialized engineering competencies to build advanced manufacturing capability. It generates shortages and delays in more than one sector, not only the original one where the demand changed in the first place. The experience demonstrated the need for better forecasting, better interaction with suppliers and more flexible planning systems even if perfect prediction is not possible in such a complex situation (Ramani et al., 2022; Fu et al., 2023).

2.3.5 Systemic Viability and Holistic Network Governance

Risk can be better managed, but it can never be totally, or permanently, removed. Controlling increasingly complicated networks is critical for the durability of semiconductor supply chains. The production process is characterized by many tiers of suppliers, cross-border knowledge transfers, geographical clusters of specialization and technical interdependence among multiple actors and organizations. Limiting one business, one technology, or one category of exports may affect several related firms, frequently indirectly; therefore, the effects cannot be traced quickly, or even at all. This means that although it seems that just a single point is attacked, the whole network might saturate and overload. This results in the necessity for approaches considering the network as a complete system rather than the performance of the single firm in isolation. Viability, in this sense, is the ability of the supply chain to adapt, survive and continue to function under stress conditions and unstable environments. "This must be flexible, redundant and coordinated." These are difficult to coordinate across numerous regulatory systems, business interests and national goals (Ivanov & Dolgui, 2020; Hosseini et al., 2019). It is seldom a matter of unawareness. It is an alignment failure, a trust failure, a shared-incentives failure amongst actors who depend on each other but do not coordinate well. Sustainable risk reduction in semiconductor supply chains requires a balance between variety, investment and interaction with trusted partners. An over-reliance on a hyper-concentrated supplier bas increases considerably the risk whilst an excessive fragmentation may reduce efficiency, economies of scale and innovation capacity over time. It is a challenging element to find a fit balance. There are serious compromises in cost, security, flexibility, and long-term performance. The most effective initiatives have been on increasing attention, developing alternative capability and keeping access to critical technologies and resources. In a more competitive geopolitical environment than in the past, working with reliable partners is essential. Resilience in this area is no longer an optional strategy; it is a foundational capability developed through repeated, capital-intensive by repeated, coordinated and expensive decisions across business and policy domains (Wieland & Durach, 2021; Xiong et al., 2024).

2.4 Diversification Strategies and Friend-shoring

Even if diversification is a core value of supply chain resilience, implementing it within the semiconductor industry is difficult. Diversification in the semiconductor industry goes beyond onboarding new vendors; it demands discovering alternative channels for specialized manufacturing equipment, design methods, testing, packaging and raw materials. The strategic goal is to minimize dependency on any single county, firm or academic institution without losing access to cutting edge technology. However, excessive fragmentation can backfire, increase costs, and overcomplicate quality control. For supply chain leadership, diversification must be like a surgical strike rather than an indiscriminate policy (Chowdhury & Quaddus, 2017; Hosseini et al., 2019).

Friend shoring is a commonly used geopolitical strategy used to mitigate political risks by tightening aligned nations relations, even when these relations form a strong bond, they don't magically create new manufacturing capacities overnight. Deeply closely allied countries still find themselves facing the exact same bottlenecks of raw materials, equipment monopolies and East Asian fabrication clusters. The real value of friend shoring is not in the assumption that political ties solve deep structural supply chain dependencies but found in shared capital investments, technology and crisis aversion.

2.5 Industrial Policy and Strategic Investment

Industrial policy has re-surfaced as a core driver of supply chain resilience, because focusing solely on market efficiency has created strategic dependencies that governments see as a liability. Policymakers no longer see chips as commodities; they see them as a critical national infrastructure vital to economic growth, communications, aerospace and defense systems. To reform these networks, countries are aggressively subsiding, tax reducing, investing and creating partnerships. The overall goal of these incentives is to onshore fabrication capacity and insulate local industries from politically volatile nodes (Bown, 2020; Liu et al., 2025).

However, creating effective industrial policy introduces friction. Building regional capacity is a slow, cost-effective process that can easily hit a brick wall without access to highly specialized labor and/or deep supplier networks. In addition, aggressive export controls might protect immediate national security interests, but the real risk is fragmenting global markets and escalating geopolitical friction. The real strategic move for governments is using public funding to build domestic self-reliance without undermining international coordination which semiconductor manufacturing depends on.

2.6 Sustainability and Long-term Supply Chain Resilience

2.6.1 The Dual-Commitment Paradox: Technological Enablement vs. Manufacturing Footprint

Governmental discussion, research studies and business strategies alike are increasingly tying the two together, as sustainability is increasingly associated with long-term semiconductor supply chain stability. The semiconductor industry is a crucial facilitator of technologies such as digitalization, energy efficiency, renewable systems and low-carbon transitions. However, the semiconductor business requires exceptionally vast volumes of electricity, water and chemicals in its manufacturing. This creates a double commitment which creates a structural dual-commitment paradox. The industry supplies key ingredients for the sustainable transition, but it must also cut down its own environmental footprint in tangible and visible ways. For this conflict to persist, and not only swiftly go away, but it is also not enough that firms say sustainability is crucial. Though implementation continues to be uneven among firms, regions and governments, sustainable resilience requires secure supply chains, cleaner manufacturing and responsible resource usage throughout the system (Fu et al., 2023; Xiong et al., 2024).

2.6.2 Biophysical Constraints and Water Risks

Water consumption is a critical issue in semiconductor manufacture, probably the biggest operational hurdle in certain locations. For chip fabrication, ultra-pure water is necessary. This is for wafer cleaning and quality standards in highly sensitive operations. Water-stressed sites place fabrication facilities at operational hazards and reputational criticism from authorities, communities and environmental groups. Climate change intensifies these pressures, and makes water less predictable over time, sometimes quite substantially. Water recycling and efficiency improvements may mitigate certain risks but need investment, law and technology adaption that not all firms are able to embrace equitably. Site selection is important, too, but not all firms have the flexibility to relocate operations after they have built factories and entrenched themselves into region ecosystems. Here sustainability becomes a resilience concern, since environmental limits may directly influence the continuity of production, raise costs and reduce long-term capacity utilization (Mahachi et al., 2022; Davis et al., 2021).

2.6.3 Energy Intensity, Yield Dynamics, and Micro-Grid Infrastructure

Another essential factor is energy consumption, which is directly related to the prices and the production stability of the semiconductor manufacture. Semiconductor manufacture is an energy intensive process, and interruptions may wreak havoc on batches of production in costly and technically difficult ways. A short power cut may have a major impact on yield because once disruption occurs there is no rapid recovery. The increase in demand for semiconductors also increases energy use which causes longer term difficulties for resilience and environmental policy goals. Sustaining operational continuity requires. However, the institutional coordination required... is rarely seamless or sufficiently unified (Vakulchuk et al., 2020; Sovacool et al., 2020).

2.6.4 Sub-Tier Material Specialization and Circular Economy Trade-Offs

Material sustainability plays an important role, although it is less apparent than the water and energy issues. Semiconductor production is dependent on specialty chemicals, industrial gases, silicon wafers and rare materials since they are critical to the accuracy of the manufacturing processes and consistency of quality. Many of these commodities are supplied by a limited number of vendors, creating both environmental and geopolitical concerns that overlap. Sourcing and recycling responsible may mitigate some of these concerns, but not all materials can be economically replaced, recovered or reused. However, the adoption of circular economy solutions is limited by technical complexity, quality requirements, purity standards and cost structures. The sector is still driven by upstream resource flows. The dependency needs to be handled carefully across long time periods and various supply levels (Habib et al., 2016; Helbig et al., 2018).

2.6.5 Multi-Tier Shocks and Strategic Trade-Off Matrix

Resilience in the long run is not just about short-term recovery from isolated operational shocks. It is about surviving throughout time and changing situations. A resilient supply chain is one that can adapt, reconfigure and continue to operate in the face of recurrent pressures, shocks and structural changes. For semiconductors, it means innovation, continuity of production and environmental responsibility at the same time, a difficult target, not always internally consistent. At times there are conflicting goals between the reduction of expenses, security objectives, sustainability purposes and speed of expansion. Resilience is learning and planning, not simply reacting to the disruption after it has happened and the damage has already done. Companies and governments need to be prepared for a barrage of shocks including pandemics, trade restrictions, climate calamities, cyber threats and demand instability. These pressures are interconnected and make management more difficult than if each risk was treated independently of the others (Ivanov & Dolgui, 2020; Ivanov, 2021).

2.6.6 Collaborative Ecosystem Governance and Buffer Optimization

Sustainability resilience requires collaboration across the supply chain, which is not always easy to do in practice. Semiconductor firms, suppliers, regulators and governments are tightly interconnected networks where dangers may quickly cross borders and sectors. Such networks might be vulnerable to environmental and geopolitical upheavals that can move quickly, sometimes quicker than response mechanisms are fully prepared or even well understood. While collaborative planning and information sharing increase capacity to respond, they need trust, openness and incentives to collaborate that are often absent. Suppliers may work together on emissions reduction, contingency planning and ethical sourcing, but sometimes co-ordination breaks down or delays happen for economic or institutional reasons. However, these practices contribute to resilience by enhancing system-level awareness, visibility and collective response capabilities (Pettit et al., 2019; Wieland & Durach, 2021).

The connection between sustainability and resilience is a trade-offs issue. There are no simple, neat or easily resolved trade-offs. Building capacity and maintaining larger safety stocks and keeping larger stockpiles may improve security, but they can also increase resource consumption, energy demand and operating expenditure. If not well managed, such actions might generate waste rather than resilience and at the same time undermine sustainability goals. The difficulty for companies is where buffers are genuinely required. This is not always clear in uncertain conditions with imprecise information and fluctuating risks. Digital solutions help anticipate, monitor and plan but depend on data quality and system integration that are not optimal in supply chains. In general, specific resilience measures are better than generic ones, especially if they are focused on critical nodes and high-risk inputs, rather than implementing the same solution everywhere without difference (Christopher & Holweg, 2017; Fan & Stevenson, 2018).

2.6.7 Technological Capability vs. Simple Supplier Diversity

Semiconductors also need to be strong in the long run, which means they need to be matched with bigger industrial and geopolitical objectives, which may not be viable in the long term. Sustainable risk reduction relies on diversification, strategic alliances and ethical sourcing processes, with continuous innovation and a steady policy. Finance, institutional support and policy stability are necessary for continuous innovation but are not always available in suitable form. Governments should assist companies in infrastructure, research systems, workforce development and regulatory uniformity to improve flexibility and sustainability. Coordinated investment, environmental responsibility, and geopolitical awareness create a robust semiconductor supply chain. It is not easy to maintain this blend since sometimes priorities conflict in ways that do not have obvious solutions. However, semiconductor industries have been facing a variety of problems over the past years, and most of the issues have not been solved yet (Moktadir & Ren, 2024; Xiong et al., 2024).

In the semiconductor case, diversity has severe limitations in capital-intensive, knowledge-intensive production and specialized supplier network. Stockpiling in downstream firms will be a short-term hedge, particularly for conventional chips, yet not against the scarcity of advanced nodes or the loss of production capacity. Friend-shoring, governmental investments, and collaborations are more protracted, time-consuming, and require collaboration between firms, the government, equipment makers, and academic institutions. Friend-shoring and public investment are also less immediate and require cooperation among firms, governments, equipment manufacturers and research institutions. The main lesson from answering RQ3 and RQ4 is that semiconductor supply chain resilience is not a function of speed of replacement but the ability to build long-term skills in areas of the supply chain deemed critical. This sector illustrates why the chip sector cannot be reduced to a mere supply diversity problem, as far as geopolitical resilience is concerned (Ivanov & Dolgui, 2020; Bown, 2020; Moktadir & Ren, 2024).

Sector-specific structural constraint. Semiconductor resilience is constrained less by the number of nominal suppliers than by the depth of the technology stack. Advanced fabrication requires capital-intensive facilities, photolithography equipment, electronic design tools, qualified materials, process know-how, intellectual property and accumulated yield-learning. These dependencies cannot be duplicated through short-term procurement decisions. The strategic implication is that resilience in this sector should focus on protecting and diversifying critical nodes, not on attempting to recreate the full value chain in ejurisdiction (Bown, 2020; Mönch et al., 2018; Xiong et al., 2024).

3 Energy and Critical Minerals

3.1 Strategic Role of Energy and Critical Minerals

Energy and critical minerals form the most important foundation of modern global supply chains. Stable energy grids power everything the world is running on, from industrial manufacturing to digital infrastructure, while critical minerals are required for batteries and renewable energy hardware. Because these sectors are deeply interconnected, a single operational issue can hardly be contained; it quickly infects logistics, reshapes public policy and/or drives up manufacturing costs (Bazilian, 2018; Sovacool et al., 2020).

Global push toward a green energy transition increases the strategic value of rare minerals like copper, nickel, cobalt, and lithium. These recourses are vital for decarbonization but at the same time introduce new vulnerabilities tied to highly geographically concentrated extraction and refining sites. The shift toward renewables does not eliminate resource dependence just changes its geography and form. Building a truly ecologically sustainable energy system requires solving the low carbon technology problems, even eliminating them completely and securing the volatile complex material supply chains supporting it (Vakulchuk et al., 2020; Watari et al., 2020).

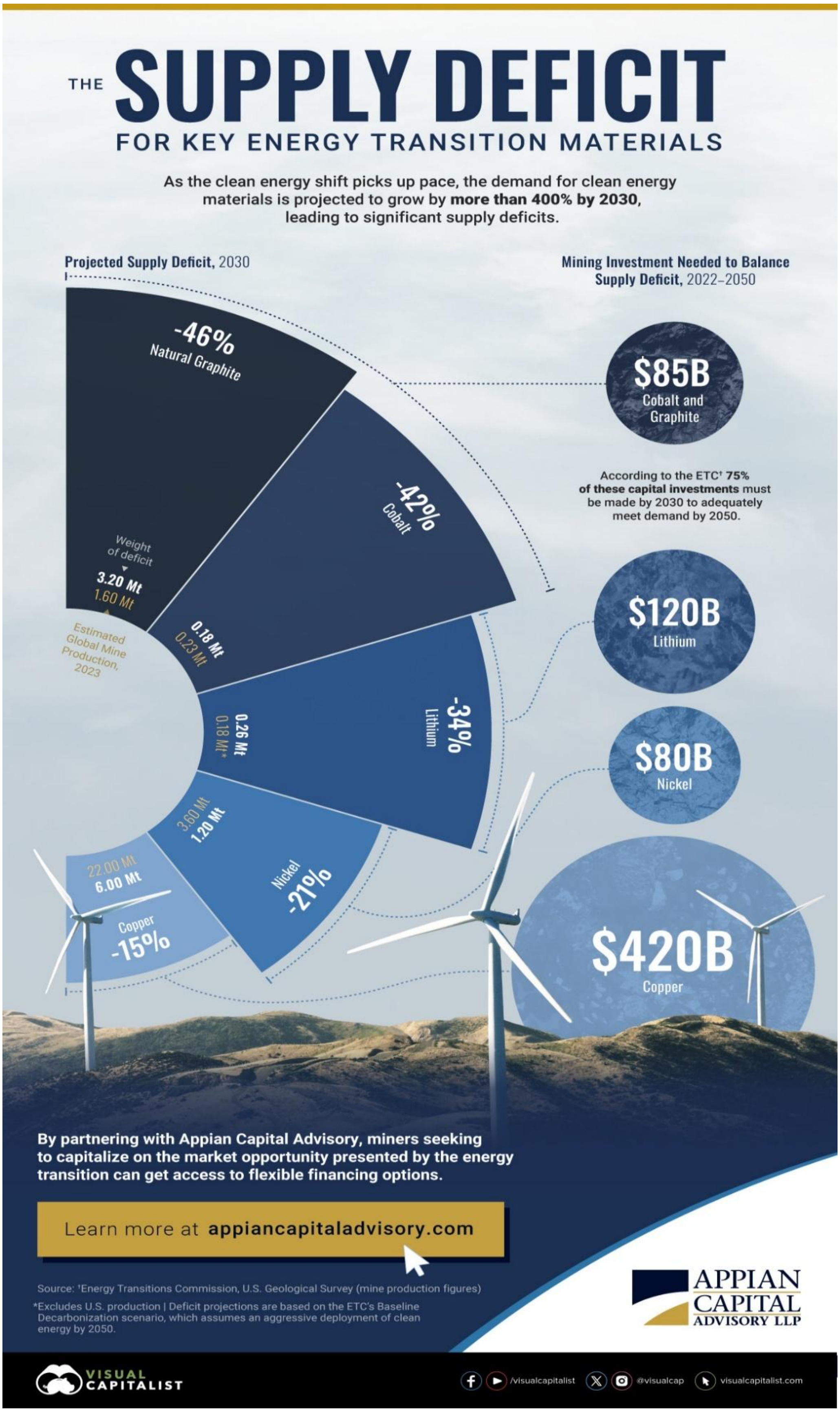

Figure 2. Projected supply deficits for key energy transition materials by 2030. *Source: Visual Capitalist / Appian Capital Advisory.*

3.2 Resource Concentration and Dependence on a Few Supplier Countries

Lithium-ion batteries present the perfect example of how fragile critical mineral supply chains are. While materials like lithium, cobalt, nickel, manganese and graphite are essential for electric vehicles and energy storage the mining and refining are geographically distributed uneven. The real bottleneck is the refining stage is far more concentrated than the mining itself. That means, owing a mineral deposit doesn’t necessarily give a country strategic independence. Countries (mostly African countries) sit on massive raw ore reserves but still can’t completely refined it on their own and they are forced to ship it overseas. This leads to narrow supply base, wild price changes and the inability to scale up when is demanded (Helbig et al., 2018; Valero et al., 2018).

Diversification for policymakers must be more than just digging holes in the ground. Opening a new mine only lowers the risk if there are local processing plants, environmental approvals, reliable transportation to support it. In case those capabilities are missing, policymakers haven’t solved the problem they just pushed it a few steps down the line.

3.3 Energy Security, Sanctions and Geopolitical Tensions

3.3.1 Institutional Vulnerabilities and Systemic Shock Transmission

Geopolitical instability directly reshapes the energy and critical mineral supply chains. Impacts are often rapid, widespread, uneven, expensive, and possibly politically amplified. These resources are closely tied to state power, industrial capacity and strategic autonomy, and are thus far more vulnerable to conflict, coercion, sanctions and political choice than are many ordinary commercial products. Sanctions, commercial, diplomatic and security restrictions may limit access to energy and minerals, but also to infrastructure, banking, transportation systems, insurance, technology and shipping routes. Energy markets are sensitive to any disturbance and prices can be transmitted across the economy quickly, with a velocity that outpaces reactive policy interventions The problem is further complicated by the fact that the critical minerals are needed for batteries, renewable technologies, power grids, storage systems, and clean energy systems in general and not only in specialized sectors (Caldara & Iacoviello, 2022; Vakulchuk et al., 2020).

3.3.2 Weaponized Interdependence, Economic Sanctions, and Market Logic

Sanctions are powerful tools and they can disrupt supply chains in big ways. Export controls, financial sanctions, restrictions on shipping and insurance, and limits on technology transfer may force firms to look elsewhere. Moreover, that is not always easy, rarely cheap, rapid or technically equivalent in the short term. Sanctions in energy markets impact flows of oil and gas, but also infrastructure such as pipelines, terminals, storage, refineries and ports. Sanctions could block access to processing methods, specialist chemicals, equipment, software or critical minerals in mineral supply chains, creating bottlenecks that are difficult to bypass quickly or cheaply. The result is a more fragmented system in which political alignment matters more for economic ties than it did before and market logic is blending commercial efficiency with state strategic imperatives (Strange, 2020; Kano & Oh, 2020).

3.3.3 The Policy Trilemma: Securing Legacy Sourcing while Financing Transitions

The contemporary energy crisis extends far beyond the secure procurement of fossil fuels, reflecting a highly complex dual mandate. Countries need to reduce their reliance on fossil fuels but also need access to the resources, equipment and technology that are needed for sustainable energy systems. The mix of issues is a difficult one, not least with geopolitical instability, changing policies and lumpy, uncertain investment incentives. We need to strike a balance between short-term energy security and long-term transition goals, but these are often at odds with each other. We need a strong energy strategy that connects, rather than divides into distinct policy compartments, without interaction or friction, fuel security, electricity reliability, access to minerals, industrial capacity, and infrastructure resilience (Bazilian, 2018; Sovacool et al., 2020).

3.3.4 Coordinated Ecosystems and the Paradox of Diversification

Geopolitical tensions are a big factor in investment decisions and hugely important for the long-term growth of supply, not just at the margin. Even if companies relocate from risky regions to safer countries, this may mean greater concentration elsewhere and new bottlenecks rather than a holistic reduction of vulnerability. Governments support domestic manufacturing through subsidies, industrial strategy and strategic alliances. This juxtaposition of supplier diversification and trade-flow balance reveals the underlying strategic contradiction in this industry. Diversification reduces dependence on a single supplier but may create new dependencies if alternative partners lack infrastructure, processing capacity, funding or regulatory stability. Therefore, rebalancing trade flows is not just a business decision. It needs ports, rail links, storage, grid connections, environmental permits, financial assurances and long-term political confidence, which directly addresses the core operational dynamics of Research Question 3 (RQ3) and Research Question 4 (RQ4): Resilience in energy and critical minerals depends on the formation of coordinated ecosystems. New suppliers are important but not enough until extraction, processing, infrastructure and recycling grow together (Christopher & Holweg, 2016).

3.4 Supplier Diversification and Restructuring of Trade Flows

3.4.1 Architectural Dimensions of Multi-Sourcing in Strategic Resources

Supplier diversity is a major strategic structure to minimize exposure in global energy and critical mineral supply network. To build up resilience in the face of these potential risks, there needs to be an expansion of the nation-states where goods are produced, alternative locations for production, new refining capacity, and alliances within institutions are required. Through diversifying on an external array of suppliers, nations and firms can make themselves better equipped to deal with abrupt geopolitical or biological disruptions.

To implement this strategy of diversification in the macro-energy supply chain, this can be done through sourcing more from other forms of alternative fuels, more investment in renewable energy infrastructure, expanding the grid and interconnecting the power grid between the case of critical minerals, this diversification may imply building new mines, forming processing partnerships, increasing recycling, and concluding inter-regional trade agreements (Helbig et al., 2018; Watari et al., 2020).

3.4.2 Geopolitical Re-Alignment and Network Translocation Costs

The changing geography of energy and resource supplies is already impacting the patterns of trade. Geopolitical tensions, sanctions and industrial policies are driving governments to diversify their import sources and deepen relationships with politically aligned partners, potentially rerouting flows of oil, gas, minerals, batteries and clean-tech components to new corridors and economic partnerships. Reconfiguration can open up opportunities for new supplier nations, but it requires logistical capacity, financing, regulatory alignment, quality assurance and institutional confidence. The transition costs, coordination difficulties and operational complexity of moving from well-known supply patterns to new networks tend to be greater than first thought, consequently, sovereign states and multinational enterprises execute these structural pivots with highly variable degrees of efficiency and velocity (Strange, 2020; Kano & Oh, 2020).

3.4.3 Vertical Integration and the Upstream-Midstream Dependency Paradox

We need to move upstream and midstream for critical minerals diversification. If refining and processing is still concentrated elsewhere, then mining more only fixes part of the vulnerability. That means alternate capacity in extraction, refining, chemical processing, component manufacture and recycling for a resilient supply chain. Supplier diversification also cannot be accomplished merely by expanding access to raw materials but requires investment along the full value chain to avoid concentration of control while still creating interdependencies that do not eliminate the dependency (Bazilian, 2018; Sovacool et al., 2020).

3.5 Rebalancing of Trade Flows and Diversification of Suppliers

3.5.1 Multidimensional Sourcing Architecture and Infrastructure Integration

Today, supplier diversity is increasingly being used as an important strategic tactic to help mitigate the vulnerability of energy and critical mineral supply chains. This will require the development of additional manufacturing locations, the diversification of supply nations and the increase of refining capacity in other areas. This reduces dependence upon one source, reduces their exposure to single-source disruptions that manifest without warning. Diversification in the energy system could be buying fuel from different sources or more investment in renewable energy. It could also mean links in infrastructure to allow energy flows between areas. Diversification of critical minerals entails mining ventures and partnerships, but also agreements between governments, which are not necessarily stable (Helbig et al., 2018; Watari et al., 2020).

3.5.2 Friend-Shoring, Geopolitical Friction, and Trade Flow Diversion

"Macroeconomic trade patterns are undergoing a profound realignment driven by." Countries are changing where they get their imports due to political friction and sanctions, and a strategic pivot toward 'friend-shoring', the practice of anchoring supply chains within politically aligned nations. This diversion is moving oil, gas, minerals and clean tech items that over time change global trade patterns. This opens new possibilities for suppliers, but it needs logistics systems and funding. Convergence of regulations is also needed but not necessarily feasible across nations. The transition from old to new supply networks is a costly and slow process, and enterprises need to be well prepared to deal with this (Kano & Oh, 2020; Strange, 2020).

3.5.3 The Midstream Bottleneck: Processing, Refining, and Industrial Ecosystems

Diversification of key minerals should not stop at the extraction level but needs to extend to upstream and midstream activities. Just increasing the amount of mining will not be enough if refining and processing are concentrated in a few places. Building a robust supply chain requires industrial capacity at every stage. Resource-endowed nations must therefore build integrated, end-to-end domestic industrial ecosystems. You don't have to have multiple projects. Countries rich in natural resources need to build complete industrial ecosystems, or they will continue to be dependent (Bazilian, 2018; Sovacool et al., 2020).

3.5.4 Logistical Inelasticity and the Infrastructure Deficit

Infrastructure is another key factor in the reconfiguration of flow of commerce that is often overlooked. The diversification of energy grids demands highly specialized pipelines. Critical resources require infrastructure – ports, railroads and processing facilities – and these take years to build. You do not have the infrastructure, but you have the resources. Absent this foundational infrastructure, a sovereign nation may possess vast natural deposits yet remain structurally incapable of engaging with global markets. Even if a country discovers new sources, it may be hampered by poor logistics or the lack of certification systems. However, resilience is not only about the ability to receive materials, but also to move and process them efficiently (Christopher & Holweg, 2017; Katsaliaki et al., 2022).

3.5.5 Bilateral Strategic Partnerships and Coordination Friction

Another important factor is the growing popularity of strategic partnerships. Moreover, governments and firms make deals with countries that have the resources to make sure they get it out and have a steady supply. The collaborations could be in finance, transfer of technology and environmental criteria but these transnational arrangements vary significantly in institutional quality... While optimally designed partnerships provide importing nations. This approach involves both resilience and development, but suffers from coordination problems (Sovacool et al., 2020; Habib et al., 2016).

3.5.6 Demand-Side Risk Management and Predictive Modeling

While supply-side diversification dominates resilience discourse, demand-side optimization represents an equally important but frequently neglected strategic lever. Rapid growth of sustainable technologies is putting pressure on mineral markets and competition among buyers. Better forecasting and long-term contracts can help firms hedge risk. But forecasts are not always correct. Governments can help with planning and transparency, but if interests are not aligned, it is hard to collaborate. Demand-side approaches may be effective when supply expansion is slow, which is often the case in mining sectors (Valero et al., 2018; Watari et al., 2020).

3.5.7 The Sustainability Paradox of Reconfigured Supply Networks

The re-structuring of trade flows raises many sustainability concerns, and not always in a positive way. New supply chains might reduce geopolitical risk but create environmental or social problems elsewhere. Poor standards create sustainability problems and undermine long-term resilience. Diversification must mean responsible sourcing, traceability, however difficult that is to implement. Long-term success will be achieved through sustainable variety, more stable and socially acceptable supply chains (Sovacool et al., 2020; Pettit et al., 2019).

3.6 Material Replacement, Reuse and Circular Economy

Turning to a circular economy sounds like an easy way to fix the dependence on raw mining issue but their contribution is not immediate. Sure, recycling, reusing and remanufacturing can reclaim valuable minerals from old batteries and discarded electronics(gold) which helps primary suppliers in the long run. But setting up a circular system is an operational nightmare. You need massive collection networks, clear environmental regulations, advanced chemical processes and enough supply of worn-out products to create a steady stream. At least for the foreseeable future recycling is just a minor addition to mining and refining not a replacement. (Watari et al., 2020; Valero et al., 2018).

Trying to swap out materials entirely faces the exact same problem, engineers can change the chemistry and the design of a battery to remove cobalt to lower the geopolitical risk, but the new designs still need to be safe, cost efficient and rare metals free. Long term circularity and substitution are excellent for building supply chain resilience but treating them as an immediate solution to our raw material shortages is a clear strategic mistake (Helbig et al., 2018; Sovacool et al., 2020).

3.7 Circular Economy, Material Substitution and Recycling

Circular economy strategies offer a pillow for a safe land from critical mineral shortages mainly because long term dependence shrinks on highly volatile mining hubs. By recycling electronics and batteries, we can reclaim rare minerals like lithium, cobalt, nickel, and graphite while extending product lifespan can ease the pressure of global demand. The real strategic value hides behind compounding, while more green technologies reach their end life and more recycling systems mature (Watari et al., 2020; Valero et al., 2018). From planning to executing a circular strategy requires governance, you cannot just create a recycling network out of thin air; it demands coordinated collection systems, special processing facilities and of course environmental safeguards. Without laying the groundwork circularity means nothing more than a good corporate presentation about how much we care for the environment and recycling rather than operational sources of raw materials. To be able to make a difference, recycling initiatives must be embedded directly into early product design and long-term infrastructure investments (Helbig et al., 2018; Sovacool et al., 2020).

3.8 Sustainable Transition and Securing Supply

At the end we cannot achieve a sustainable green energy transition without building resilient supply chains to support it. Moving to renewable energy, massive battery storage and digital grid infrastructure requires massive amounts of raw materials and advanced tech. If geopolitical friction strips out the access to these foundational inputs, decarbonization will become so expensive leaving it exposed to political blows (Vakulchuk et al., 2020; Sovacool et al., 2020). That’s why there’s a need for cross-functional policy integration. Governments can no longer isolate climate goals from industrial strategy. Pursuing actively emission targets without securing the required material pipeline is an operational failure. A smarter strategy would be to link decarbonization directly to secure sourcing partnerships, infrastructure capital and R&D into material substitution. Lastly, long term resilience is a dynamic goal; it demands adaptation that allows the supply chains to pivot as new technologies emerge and new geopolitical risks emerge over time (Bazilian, 2018; Ivanov, 2021; Ivanov & Dolgui, 2020; Hosseini et al., 2019).

Sector-specific structural constraint. Energy and critical mineral supply chains are constrained by the physical location of resources, the concentration of refining capacity and the slow expansion of infrastructure. Unlike manufactured components, mineral deposits cannot be relocated, and new mining, processing or transport capacity requires long permitting, financing and construction cycles. Resilience therefore depends on a combined strategy: diversification of suppliers, development of processing capacity, recycling, material substitution and environmental legitimacy. A security strategy that ignores social and ecological impacts may undermine the sustainability objectives that created demand for these materials in the first place (Bazilian, 2018; Sovacool et al., 2020; Watari et al., 2020).

4 Pharmaceutical and Medical Supplies

4.1 Importance of Pharmaceuticals and Medical Supplies

The critical nature of pharmaceuticals and medical supply chains derives from their direct impact on public health, human security and the healthcare systems stability. When a disruption occurs most ordinary commercial goods face an inconvenience, a shortage of medicines or vaccines or diagnostics or protective equipment can put patients' life on serious risk and can compromise social stability. During covid-19 pandemic this vulnerability clearly came to the surface; demand surges overnight, export restrictions and manufacturing bottlenecks strangled even the most advanced healthcare systems (Shukar et al., 2021; Spieske et al., 2022). Because this sector is bound by high quality standards, strict safety regulations, building resilience is not as simple as switching to a different supplier. True supply security requires cooperation of qualified production facilities, Active Pharmaceutical Ingredient (API) sourcing, proven processes and coordinated procurement strategies.

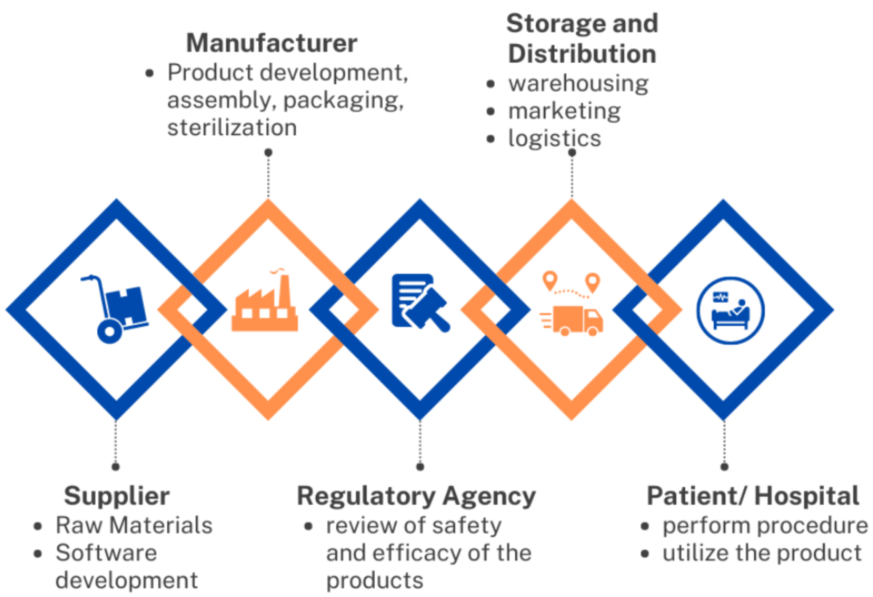

Figure 3. Medical device supply chain structure. *Source: Qualtechs.*

4.2 Dependence on Active Pharmaceutical Ingredients, Raw Materials and Manufacturing Facilities

4.2.1 Upstream Concentration Risks: Active Pharmaceutical Ingredients (APIs)

APIs are the active ingredients that make medication and without APIs there is no manufacturing. APIs are a key dependence of the pharmaceutical supply chains. Concentration risk: A high percentage of finished medicines is dependent on APIs made in a small number of countries. This means that even if there is manufacturing capacity elsewhere, interruption in production of APIs might affect the supply of finished medicines.

The supply chain is a multi-step process and a systemic failure at any individual upstream stage instantly compromises the integrity of the entire supply architecture (Shukar et al. 2021; Tucker & Daskin 2022). Production of pharmaceuticals is also about global sourcing of excipients, chemical intermediates and packaging materials. Such inputs are not always available locally and enterprises rely on overseas suppliers. Production schedules can also be disrupted by quality concerns or logistics which disrupt supply. The dependency structure is therefore complex and hard to manage in its totality. They require special production facilities and strict regulatory standards. This operational example inherently creates hyper-localized manufacturing clusters.

One key concern is dependency on API manufacturing, especially for healthcare resiliency. Many organizations employ global sourcing to save costs, but that implies certain places will be the center of manufacturing. Disruptions mean downstream firms cannot keep up with production and there are shortages. This is especially true for generic drugs, which have thin margins and a restricted base of suppliers. There are many buyers and they trade with the same providers. This market-driven supplier consolidation creates extreme vulnerability... inadvertently amplifying the systemic fragility of the entire pharmaceutical delivery network (Tucker & Daskin, 2022; Vann Yaroson et al., 2024).

4.2.2 Product-Specific Risk Profiles and Cross-Sector Disparities

A defining structural characteristic is that supply network resilience is fundamentally product-specific and cannot be accurately quantified by simply aggregating the absolute number of suppliers. A pharmaceutical that needs sterile production, cold chain distribution or thorough regulatory validation has a significantly different risk profile than a simpler oral product, which directly addresses Research Question 1 (RQ1) and Research Question 4 (RQ4). The fragility of the industry is a product of the interplay between dependency on APIs, quality standards, permitted facilities and emergency demand. Alternative supply may be beneficial only when the alternative is technically qualified and legally authorized. This distinguishes medicines from industries where companies may change suppliers largely via commercial agreements (Shukar et al., 2021; Tucker & Daskin, 2022; Pathy & Rahimian, 2023).

4.2.3 Sub-Tier Visibility Deficits in Secondary Materials and Excipients

Raw materials and excipients provide a huge supply risk in pharmaceutical supply chains. While these secondary inputs are often less apparent in macro-level supply chain assessments, they introduce significant operational risk. Medicine needs solvents, reagents, stabilizers, fillers, preservatives and packaging, all of which demand exceptionally strict quality standardizations across vendor networks. If any of these inputs are missing or fail quality tests, production might be delayed, even if the API is available. This demonstrates that pharma production is reliant on a wide network of specialist suppliers and not only the more obvious key companies in the research. It is a complicated network and sometimes it is improperly mapped. Proactive resilience planning demands end-to-end telemetry across all tiers of the supply network. Yet many firms still do not have complete visibility into second- or third-tier suppliers. Without this awareness, a bottleneck is only detected upon interruption, too late to react effectively. However, the procedure is tedious, resource intensive and not always effective in urgent circumstances, and organizations need to discover alternate sourcing possibilities in advance (Fan & Stevenson, 2018; Katsaliaki et al., 2022).

4.2.4 Technical Inelasticity and Regulatory Structural Rigidity

They are heavily reliant on the production facilities, and they give structural rigidity to the system. The pharma sector needs approved factories, validated procedures and must be compliant with stringent regulations, all of which cannot be changed in a hurry. "Moving medicines from one clinic to another is not as easy as moving them around. The approvals and process validation can take months or more. This reduces flexibility, which is a serious problem when you are faced with disruptions." A key facility may become contaminated or fail inspection or there could be political disruption, and the supply could be interrupted for a long period of time. Shortages systematically manifest in downstream markets long before alternative facilities can be legally cleared to resume production. Production resilience is therefore dependent on back-up facilities and regulatory pathways that allow for controlled flexibility which isn't always fully developed (Tucker & Daskin, 2022; Pathy & Rahimian, 2023).

4.2.5 Market Structure, Consolidations, and Procurement Fragility

Supply chains are not just complex. Dependence depends on characteristics of the product. Manufacturing systems for sterile injectables, biologics, and vaccines are more complex, requiring tighter temperature control in distribution. These products are reliant on cold-chain infrastructure and specialized equipment and are susceptible to disruption. Manufacturing systems for sterile injectables, biologics, and vaccines are more complex. These products are also more subject to demand uncertainty, in particular in the event of public health emergencies, when consumption can unexpectedly spike. This means that the production and inventory systems may not be prepared for a fast scale-up. Pharmaceutical resilience should be based on product specific risks and not on one size that fits all (Pathy & Rahimian, 2023; Spieske et al., 2022). Nor is the relationship between the concentration of production facilities and the economics of markets always clear. Essential medicine has low prices, which may give disincentives to invest in extra capacity because the profit margins are narrow. The companies may merge and become more efficient and the number of producers in the market will shrink. Less suppliers also mean a higher risk of disruption and therefore more vulnerability. Natural incentives for reliability and capacity are not always provided by market structures but are needed for a resilient supply chain. Procurement systems and reimbursement policies influence firm behavior and may inadvertently increase fragility. (Shukar et al., 2021; Vann Yaroson et al., 2024).

4.3 Pandemics, export controls and regulatory pressure

4.3.1 Asymmetric Demand Spikes and Macro-Capacity Constraints

Pandemics immediately and globally stress pharmaceutical and medical supply chains. Demand for medicines, protective equipment, and diagnostic tools can surge rapidly, often within weeks or even days. Meanwhile, restrictions, labor shortages, and transportation delays at manufacturing sites and within logistic networks are limiting available capacity. engineers an acute structural mismatch... that cannot be resolved through conventional, short-term market corrections. Even robust economies face shortages, with health systems struggling to secure basic goods. Pandemic preparedness requires flexible production and strong coordination, yet many systems were not built for such a level of disruption (Spieske et al., 2022; Zamiela et al., 2022).

4.3.2 Protectionism, Export Restrictions, and Sovereign Vulnerability

Export controls are another significant vulnerability, frequently used in times of crisis. Governments may limit the export of pharmaceuticals and medical supplies to safeguard their own citizens, immediately creating manufacturing and downstream distribution in importing nations. Supply chains are globally interconnected. Therefore, restrictions in one country can affect production and distribution in others. There is some uncertainty for companies that operate across multiple jurisdictions, and they must be able to pivot quickly, which is not always possible. This situation highlights some tension between national policies and global supply networks which can be difficult to reconcile at times of emergency (Strange, 2020; Kano & Oh, 2020).

4.3.3 Regulatory Friction and the Speed-Quality Paradigm

Regulatory pressures are also important only to add to the complexity of disruption. Pharmaceutical products are subject to strict safety and quality standards and are only marketed after approval. But the rules, while protecting patients, also slow the response when alternative suppliers are needed. Emergency flexibility is useful but must be controlled; therefore, as not to jeopardize safety. Balancing regulatory velocity with rigorous quality control represents a primary institutional trade-off. Regulatory systems need to evolve, but not at the expense of trust in medicines, which is essential for health care systems (Tucker & Daskin, 2022; Shukar et al., 2021).

4.3.4 Data Asymmetry and Supply Chain Visibility Deficits

The pandemic also highlighted the need for supply chain visibility, which was often missing (Tucker & Daskin, 2022). Procurement decisions in healthcare systems were made without real-time data on inventory and supplier capacity. Absent high accuracy data, supply chain vulnerabilities are difficult to predict, and scarce medical assets cannot be efficiently allocated. Digital tracking systems and forecasting tools can improve visibility but require data sharing and coordination. Transparency is especially important when many actors compete for the same products but is not always achieved (Zamiela et al. 2022; Fan & Stevenson 2022).

4.3.5 Quality Failures, Concentration Risks, and Regulatory Delays

Quality failures are driven by regulatory pressures. These events have a strong effect. A single production site can take a ton of medicine off the market and shortages can occur quickly. The problems take time to solve and require regulatory approval which extends the period of disruption. The contingency plans and quality management systems are critical to prevent failures when elements go wrong. The supply disruptions may take longer to be worked out if there are no such measures in place (Tucker & Daskin, 2022; Vann Yaroson et al., 2024).

4.3.6 Transnational Governance and the Failures of Multilateral Cooperation

International cooperation is also important in the case of pandemics and export restrictions, but the strength of this cooperation is not always strong. Health crises do not respect borders, and no country can solve such problems on its own, specifically, through synchronized information-sharing and joint procurement frameworks, which improves our ability to respond. At the same time, the conditions of crisis tend to produce protectionist measures that undermine cooperation. However, a resilient pharmaceutical supply chain needs cooperation mechanisms before the crisis, not only during the crisis, but developing such mechanism is difficult in practice (Kano & Oh, 2020; Ivanov & Dolgui, 2020).

4.4 Strategic stockpiling, boosted domestic production

4.4.1 Dynamics and Structural Constraints of Strategic Stockpiling

Strategic stockpiling is an important resilience strategy for pharmaceutical and medical supply chains and serving as a critical buffer during macroeconomic or biophysical shocks where demand spikes rapidly and production capacity cannot scale elastically. Stockpiles can consist of life-saving medicines, vaccines, personal protective equipment, diagnostic reagents and other health supplies required for an emergency response. They are mainly intended as a buffer for times of abrupt disruption and or prolonged procurement lags, optimizing their design remains highly complex. While stockpiles provide a vital buffer during abrupt market disruptions. However, optimizing their design remains highly complex. Demand during public health crises is inherently non-linear and volatile. A well-designed stockpile can alleviate immediate pressure on the health system and provide a wider range of response actions, while a poorly designed stockpile can create waste or inefficiency. Pharmaceutical products have expiry dates, and some require special storage conditions e.g. temperature control, making it more complex to manage. Failure to implement rotation systems properly may lead to stock expiring before it can be used, resulting in financial losses causing substantial capital losses and compromised systemic preparedness. Some items may become obsolete as medical practices or treatment protocols change. Not all items are used at the same rate. Stockpiling needs to be coordinated with healthcare providers and carefully prioritized, not just a collection of products without a clear strategy, effective stockpiling requires deep coordination... rather than the passive accumulation of medical commodities (Pathy & Rahimian, 2023; Christopher & Holweg, 2017).

4.4.2 Domestic Manufacturing Capacity vs. Strategic Stockpiling

Another major strategy is ‘building up local production. This is often described as stockpiling but the two have different roles in resilience planning. Local production can help increase access to essential medicines during disruption when export restrictions or logistical breakdowns prevent imports, which are particularly when protectionist export restrictions or cross-border logistical failures collapse international supply channels. But the total localization of pharmaceutical manufacturing is economically unviable and structurally impractical, and many geographic regions lack the specialized industrial ecosystems. Investing in domestic production means investing in infrastructure, workforce, regulatory systems. These high-fixed-cost investments cannot be mobilized reactively once a crisis materializes. It also needs a stable demand to justify the investment otherwise the capacity could be underutilized, which is not economically sustainable. A targeted approach is therefore needed targeting the most critical and vulnerable products, but identifying those priorities is not always straightforward and can change over time (Bastani et al., 2021; Ivanov, 2021).

4.4.3 Procurement Mechanisms, Incentives, and Institutional Alliances

Strategies for domestic production closely tied to procurement systems are central to shaping firm behavior in volatile market settings. Historically, public healthcare procurement models have prioritized cost-minimization, this hyper-focus on low unit pricing disincentivizes private actors to maintain redundancy or to invest in resilience as firms compete on razor-thin margins. Procurement models that incentivize reliability and security of supply can incentivize firms to maintain capacity and to diversify their sources of supply. But such models are difficult to implement and may be constrained by budgetary considerations. Public-private partnerships can help and may, if well-designed, support domestic production capacity, but cross-sector collaboration frequently introduces friction due to diverging institutional objectives and misaligned incentives. Governments can provide financing or guarantees, and firms can bring technical know-how. But when roles are not clearly defined, governance problems can arise. Partnerships can work well for vaccines or emergency products, but their success depends on realistic planning and integration with wider health systems, which remains a primary managerial challenge (Zamiela et al., 2022; Pettit et al., 2019).

4.4.4 The Hybrid Resilience Model: Synchronizing Inward and Outward Sourcing

International sourcing is not a comprehensive solution, but it should be part of a combined approach with strategic stockpiling and domestic production. Resilient systems require domestic capacity in critical areas but also access to innovation and scale through a diverse set of global suppliers. The hybrid model reduces dependence on single sources, but it is not always easy to synchronize domestic and international strategies, and policies may sometimes conflict or create inefficiencies. Nevertheless, the mix of stockpiles, local production and global sourcing results in a higher level of preparedness, although introduces significant coordination friction (Kano & Oh, 2020; Ivanov & Dolgui, 2020).

4.5 International collaboration, public policy and market access

Governments control for the most part medical supply chains because they act as the main regulator, the primary financier and the sole buyer. This triple role allows governments to make policy decisions affecting everything, supplier selection, pricing, how the supplies should be distributed. When governance fragments, national preparedness collapses, on the other hand when policy is coordinated, the systems can hold severe crises (Fan & Stevenson, 2018; Katsaliaki et al., 2022). With that in mind, there is a bottleneck introduced, market penetration. A lifesaving drug for child cancer can be fully approved and sitting in an abandoned warehouse cannot be distributed. Ironically, procurement strategies usually choose the lowest price which often backfires by ousting viable, credible suppliers and triggering shortages. In order to achieve a truly resilient supply chain we require some balancing act, we need to put on a scale the short-term affordability on one side and the long-term supplier survivability on the other, we also need to balance together strict quality controls and emergency preparedness (Tucker & Daskin, 2022; Vann Yaroson et al., 2024).

Sector-specific structural constraint. Pharmaceuticals and medical products have a regulatory qualification constraint as much as a physical manufacturing constraint. During a crisis management cannot simply switch vendors; every supplier must be cleared by infinite Good Manufacturing Practice (GMP) compliances and strict quality assurance protocols. Building inventory offers a small temporary safety net, it is not a permanent fix because those inventories must be rotated (medicine expires), they get outdated by newer technological advanced medicine. The strategic goal in this case is clear and remains the same: real resilience cannot be achieved by holding inventory, it demands strong regulatory cooperation, private and public procurement partnerships and visibility of everything that happens before the product reaches the final factory (Bastani et al., 2021; Shukar et al., 2021; Tucker & Daskin, 2022).

5 Agri-food products

5.1 Strategic goods: agri-food products

Agricultural production, logistics, public welfare and political stability are tied together by food systems because agri-food products carry extreme strategic weight for any country (they must feed their own people). Unlike standard manufacturing goods, food production cannot be stopped or postponed or substituted when a crisis hits, a sudden break in the agricultural production, transport and processing will impact households immediately and sometimes trigger social and economic ripple effects. This quickness transforms agri-food supply chains into a critical infrastructure even if standard commercial analyses fail to identify as such (Béné, 2020; Davis et al., 2021). What makes the agri-food sector vulnerable is its triple identity: biological, economic and logistical all three at the same time. On the farm side, production depends on volatile inputs like, soil, water, climate, labour, fertilizers, on the other side, distribution depends on cold chains, storage and open markets which ultimately means that building reliance isn't about securing food is fundamentally a sustainability issue as well.

5.2 Compounding Vulnerabilities in Agri-Food Networks: Climate Instability and Geopolitical Shocks

5.2.1 Biophysical Exposure and Climate Volatility

Climate instability with more frequent and more intense impact is one of the biggest long-term risks for agri-food supply chains. Droughts, floods and heatwaves can reduce crop yields, destroy infrastructure and disrupt transport systems, precipitating a simultaneous cascade of failures across the supply chain. Agriculture is directly dependent upon natural conditions and is more exposed than other industries that might benefit from controlled environments. Seasonal cycles are affected by climate variability, thus there is greater uncertainty in production. Introducing acute uncertainty for both primary producers and downstream commodity markets, adaptation needs crop diversification, better storage and improved forecasting systems but implementation remains severely constrained by capital scarcity (Davis et al., 2021; Zhao et al., 2020).

5.2.2 Geopolitical Concurrency and Transnational Chokepoints

Geopolitical crises add a parallel layer of vulnerability and even when production is stable, food supply chains can be disrupted due to disruption in transport routes and export flows, triggering localized conflicts and trade volatility. The war in Ukraine serves as a critical case study, demonstrating that localized shocks instantly destabilize global grain and fertilizer markets. Importing nations exhibit acute vulnerability to these dynamics; an operational bottleneck at a single global chokepoint triggers immediate inflationary pressures worldwide, impacting food security thousands of miles away. Consequently, modern agri-food supply chains are globally interlinked ecosystems wherein localized disruptions rapidly metastasize into transnational systemic crises (Jagtap et al., 2022; Zhang et al., 2023).

5.2.3 Non-Linear Risk Interactivity and Policy Insulation

Climate and geopolitical shocks interact in shaping food security, interacting non-linearly with biophysical risks. If trade routes are also blocked at the same time, the decline in production caused by drought may be worsened. A country can restrict exports to protect its own market, this can lead to worldwide shortages with ripple effects, resilience demands integrated planning, not separate strategies for a single risk. There is a challenge to address the need for food systems to be resilient to multiple shocks occurring at the same time (Béné, 2020; Katsaliaki et al., 2022).

5.2.4 Socio-Economic Dimensions: Access, Affordability, and Nutrition

The stability dimension of food security is another important but neglected aspect. Food must be accessible over the long term and not just during times of market stability. Food access in the long term must be guaranteed, not only in stability and supply disruptions are destabilizing and affect the most vulnerable populations. Households frequently adapt by switching to lower-cost, nutrient-poor dietary substitutes—a behavioural shift that degrades dietary quality even if price rises are only temporary. This suggests that resilience is not only about the quantity of supply, but also about access and affordability (Béné, 2020; Hobbs, 2021). In analyzing quantity, nutritional quality is sometimes ignored but also suffers from climate instability. Extreme weather can limit the availability of fruits and vegetables, while systemic turmoil alters consumption patterns away from diverse diets. Food security is not only calories, but also nutrition and food diversity. These supply chain strategies for staple production may disregard these dimensions and they may affect public health in the longer run (Davis et al., 2021; Thilmany et al., 2021).

5.2.5 Upstream Resilience and Producer Economic Viability

It is also important for the resilience of the overall system, as producers are impacted by geopolitical crises and climate instability too. Farmers are facing increasing input costs, unpredictable markets and crop losses, making it harder to stay in business. Small producers are especially vulnerable because they have fewer financial resources and fewer tools to manage risk. Access to credit, insurance and markets can build resilience for producers but such supports are not always available or adequate. The resilience of producers has a direct relationship with continuity of supply, without which food systems cannot be sustained in the long term (Zhao et al., 2020; Béné, 2020).

5.3 Dependencies on Fertilizers, Seeds, Energy and Transport

The real output of any agri-food supply chain depends solely on its foundation: the inputs supplied upstream like fertilizers, seeds, energy and transportation. Each of them plays a different role because seed provides crops' resilience while fertilizers bring total yield, energy keeps the machines moving and transportation connects farms and processors to the stores. These components are linked together in the food chain and a disruption of any one of them sends ripples of shock throughout the rest of the chain and is reflected at the shelf price eventually. The strangest thing is that such shocks never occur on the farms but come from outside sources such as the crash of the world energy market (Hormuz strain with oil and fertilizers) (Zhao et al., 2020; Jagtap et al., 2022) Fertilizer manufacturing relies on natural gas hence the crop yield is exposed to geopolitical sanctions and market volatility and that's why when fertilizer becomes expensive farmers use less fertilizer triggering a domino effect of reduced yield. With this we prove that building agri-food resilience requires managing deep external systems that support the farms rather than focusing only on the crop itself.

5.4 Trade Restrictions and Disruptions in International Food Flows

The movement of food across borders helps even out differences in land quality, water access, and weather conditions between countries. When one area has more food than needed, it sends some of it to places that have less, so people do not have to go without food because of droughts, bad harvests, or other issues. If there is a war or armed conflicts, or countries set very low limits on what they will let out of their area of influence, or if there are interruptions in food supply from other nations (Zhang et al., 2023; Jagtap et al., 2022), food trade can become expensive and unreliable. Even in peaceful times, trade ensures our food supply. Yet, the very interdependence which renders trade such an essential buffer can become a weapon or be weaponised in times of crisis. Resilience is built when food trade moves beyond the short-term crisis culture that favours restrictive policies toward diversification, local reserves and international rules and agreements to limit food trade restrictions.

5.5 Localization, diversification and resilient supply chains

Although reducing supply chain length is a fashionable prescription for food security, localisation is not a magic bullet. The move to regional food systems most assuredly comes with its own advantages; reducing transportation miles, building resilient, agile, secondary distribution networks, and enhancing grassroots-level resilience in the event of a breakdown in long-haul international supply chains. However, all these benefits cannot make local sourcing a global substitute. Regions' climates, soil capabilities, available varieties of products and inputs, and initial baseline availability differ too much over the regions of the globe for that to be the case. The real test of supply chain resilience is not that local networks are isolated from their needs. Rather, they are a strategic reserve to protect against local shocks and systemic interdependencies. Local farms and processing facilities are only as strong as the broader ecosystem supporting them. To survive a crisis, these regional nodes must be backed by a diversified global network, strategic storage buffers, regional processing hubs, secure upstream inputs, and climate-resilient logistics channels.

5.6 Sustainability, environmental risks and resilience of the agri-food system

Sustainability and resilience are two sides of the same coin in agri-food supply chains, agriculture depends on the quality of soil, the availability of water, and biodiversity, as well as stable climate. Environmental degradation does not always lead to an immediate collapse but reduces productivity steadily over time and makes supply chains more unpredictable. Soil erosion, water scarcity, biodiversity loss, pollution and climate change are therefore long-term supply risks, and not only environmental issues (Davis et al., 2021; Béné, 2020). Sustainable practices, like soil conservation, efficient irrigation, integrated pest management, reducing food loss, and climate-adaptive production, can increase resilience, but these also have material, knowledge, infrastructural and political prerequisites. Sustainability can only be made to work by putting in money and governance, not as a nice-to-have aspiration.

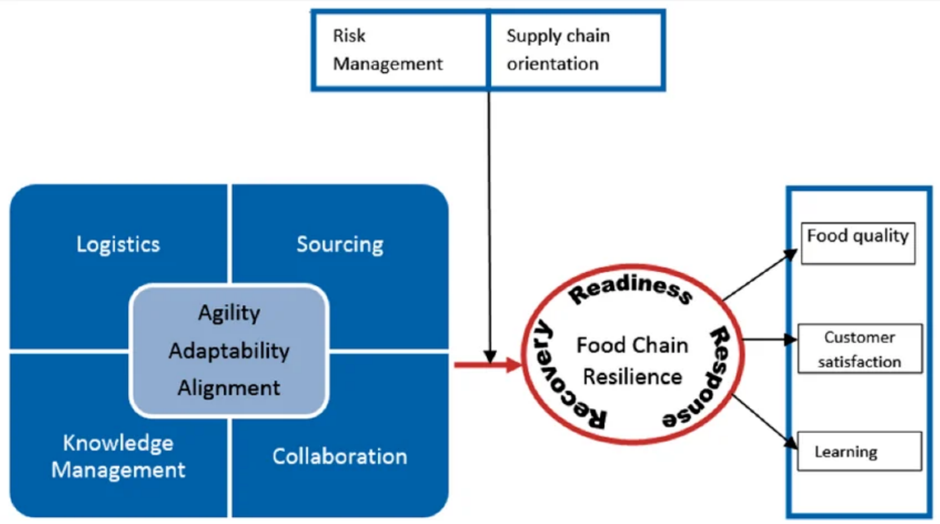

Figure 4. Conceptual framework of food chain resilience capabilities and outcomes. *Source: ResearchGate figure repository.*

Sector-specific structural constraint. In spite of these structural limits, the agri-food networks are also limited by their own perishable products and geographic distribution that cannot be stopped by the localized sourcing, since the perishability of products, seasonality, dependency on seeds, fertilizer and energy and fluid production schedules all tend toward a localized climate shock which is only going to get worse in a world of increasing extreme weather events. This is especially true in that the localisation is not the same as national self-sufficiency, but it is in fact the goal to design highly flexible and regional ecologies, which at the same time ensure the market access and affordability of consumers and the environment in the long run (Béné, 2020; Davis et al., 2021; Jagtap et al., 2022).

6 Findings and Comparative Assessment of Sectoral Strategies

When we place these sectors next to each other, the emperor's new clothes of generic supply chain advice completely fall apart. There's no way that a bunch of corporate checklists – stockpiling, supplier diversity or a switch to closed loops – will address any real systemic issue without regard for the structural constraints of an industry or unique structural boundaries. The real breakthrough of this research is that it shows you must build resilience at the point where a geopolitical shock becomes a systemic collapse. Crucially, the breaking point will vary based on what you are shifting. For example, semiconductors: the whole world market is hostage to extremely complex, tacit, and inflexible technology concentrated in a small number of minds and plants. In moving to energy and critical minerals you have a geographic choke hold on where it is extracted and processed chemically. The pharmaceutical business has a rigid regulatory qualification and safety compliance freeze on agility. Meanwhile agri-food systems are stuck fighting a volatile biophysical cycle and a ticking perishability clock. True resilience requires fixing the specific fuse that is bound to blow, not applying a blanket solution.

6.1 Comparative Mapping of Geopolitical Vulnerabilities

Four industries inhabit this geopolitical fault line, and yet they cannot be treated the same because their vulnerabilities are not the same. Semiconductors, for instance, are entirely bound by a technology trap—held hostage by cutting-edge fabrication tools and guarded intellectual property. Shift over to energy and critical minerals, and the risk profile is dictated entirely by physical geography, refining bottlenecks, and vulnerable shipping lanes. Pharmaceuticals? Regulated to the point of freezing, so that if one plant does not follow the rules, we all suffer shortages worldwide. Agri-food? They are stuck fighting an unstable biophysical cycle, where a single weather shift or a spike in fertilizer prices instantly warps shelf costs.

Such is the nature of the variance: the lazy generic advice of 'diversify your suppliers' doesn't even come close, until an executive says precisely what needs diversifying, the effort is a wasted strategy that fails. To diversify semiconductors, you need to reshape fabrication, specialized equipment tooling, and packaging networks, and you need to invest in the future. If we dig another hole in the ground for critical minerals, it doesn't help unless we also invest in alternative chemical processing plants to refine and upgrade them. To achieve resilience in the pharmaceutical industry, we require the creation of additional approved, validated API labs and stockpiles of active pharmaceutical ingredients. In the agri-food world, on the other hand, resilience requires that a manager balance a completely different set of factors. That is, shifting production areas, securing access to input vendors, and ensuring the existence of regional cold-storage facilities.

Table 6.1 Strategic trade-offs across resilience instruments

Resilience instrument	**Efficiency effect**	**Security effect**	**Sustainability implication**	**Main sectoral constraint**
Supplier diversification	May increase procurement and coordination costs	Reduces exposure to single points of failure	Can reduce pressure on risky locations but may increase transport complexity	Limited by real substitutability and technical qualification
Strategic stockpiling	Ties up capital and may increase storage costs	Provides short-term buffer during shocks	Risk of waste for perishable or obsolete goods; useful when rotation is feasible	Strongest for selected medical supplies; weaker for perishable food and fast-changing chips
Regionalization / relocation	Reduce scale economies and requires investment	Improves trusted access and political control	May lower transport exposure but can duplicate resource-intensive capacity	Slowest in semiconductors and minerals; constrained by skills, infrastructure and permits
Friend-shoring	Narrows supplier pool and may raise costs	Reduces adversarial political exposure	Sustainability depends on standards among partner countries	Useful only when partners hold relevant capacity
Circularity / recycling	Requires technology, collection systems and capital	Reduces dependence on primary inputs over time	Directly supports environmental objectives when properly governed	Most relevant to critical minerals; limited in short-term emergency supply

6.2 Common Risk Mitigation Strategies

However, notwithstanding the fact that these four sectors have common playbook of tools of mitigation, treating any of them as interchangeable would be a big mistake. Supplier diversification, stockpiling, regionalization, friend-shoring and public-private coordination are all tools to address some exposures. Their true strategic utility resides exclusively in their ability to identify exactly where that chokepoint lies in the respective ecosystem.

Let us consider for example supplier diversification, which is the most popular panacea prescribed today. True diversification isn't just a ticked spreadsheet; true diversification is about true and immediate substitutability. A second source is only helpful if you can swap it out for one that has the same technical, regulatory, chemical, or climatological capacity. Strategic stockpiling is a fast-moving buffer against moving factories, but stockpiling doesn't replace capacity, workers, plants, or farms. Regionalization or friend-shoring will certainly secure national security but only by sacrificing operational costs and agility from global specialization.

Circular economy practices are also on a different timeline altogether. In contrast to treating the short-term supply symptoms, circularity actively works on starving the long-term reliance on concentrated primary inputs. Circular economy in critical minerals region is an aggressive leverage opportunity to steadily break the long-term chokehold of foreign extraction and refining nodes. In the electronics industry, though, that circular relationship is much less direct; here, the sustainable production of semiconductor chips is heavily dependent on reliable energy grids, massive water treatment infrastructure, and strict management of toxic chemicals. The pharmaceutical sector faces a different equation, where circularity pivots around waste reduction, equitable drug access, and absolute quality systems. Meanwhile, the agri-food networks must apply circular logic to a basic problem: restore and protect top-soil health, increase water-use efficiencies, enhance crop varieties that are resistant to climate change, and dramatically reduce food waste.

6.3 Differences among the Four Sectors

The most defining divide between these four industries, therefore, is not even in their exposure to geopolitical risk—it is the nature of their binding constraints themselves. Let us look at semiconductors as an example. It is not a lack of raw materials we see as the limiting factor in this industry, there is no shortage of them. Advanced fabrication, specialized tooling, proprietary design ecosystems, and highly concentrated, tacit process know-how, cannot be swapped overnight; in this sector, short-term flexibility is basically non-existent. Compare that to energy and critical minerals, which are physically bound by their geographies of resource extraction, permanently locked in, permanently locked into permanent geography, chemical refinement centers being concentrated in just a handful of countries. And pharmaceuticals have an entirely different institutional barrier. The manufacturing of medicines, however, is a much different beast. Unless it is produced on an open factory floor (which has its own issues), any attempt at phased manufacturing is doomed to face intense gauntlets of regulatory approvals and strict adherence to product quality. And agri-food networks? Their boundaries are strictly ecological and temporal, forever dictated by seasonal cycles, high perishability, and chaotic climate shifts.

Once you draw these distinctions, it is not surprising that one tool delivers such a lopsided result when dropped in any given place. Moving production by hand would be a great idea on paper for semiconductors, but it is an incredibly slow, capital-intensive, and resource-consuming nightmare. Diversification of critical minerals is a half-baked and futile attempt when restricted to mining and not extending to the ownership of refining capacity. Hoarding stockpiles works beautifully for basic medical supplies, but they fall apart completely when applied to perishable food or rapidly evolving tech-specific chips. Localizing agricultural output makes sense and is excellent, insofar as it creates self-sufficiency of a particular community, but it has no protection against a country experiencing climate shock or a critical disruption in its reliance on foreign synthetic fertilizers. True resilience requires matching the operational tool to the specific sectoral constraint—not forcing a one-size-fits-all corporate template onto completely different worlds.

Finally, when we compare self-sufficiency with geopolitical supply chain resilience, there is only one logical conclusion to draw. Complete national self-sufficiency is uneconomic, structurally bulky, and often environmentally suicidal. A far more credible approach is selective autonomy—an economic strategy that relies deeply on trusted alliances, targeted industrial redundancies, and a long-term pivot toward designing for sustainability.

6.4 Effectiveness of Diversification, Stockpiling and Relocation

Supplier diversification is only effective if there exist technically capable, politically reliable, logistically available, and institutionally usable alternatives. This plan's Achilles' heel is that there is often no alternative supply, at least not in real life, when there is one on paper. For instance, diversifying semiconductors is heavily gated by staggering entry barriers and deep ecosystem dependencies. It's very hard to diversify critical mineral sources: we have a fixed underlying geology, limited concentration of global refining nodes, and multi-year environmental permitting. Pharmaceutical diversification is just as hard: intense regulatory approval processes coupled with rigorous quality assurance validation. Even in agri-food systems, switching suppliers means dealing with volatile climate exposures, fixed seasonal timelines, high perishability, and a heavy reliance on upstream inputs like fertilizer.

Stockpiling, however, must be considered a stopgap measure only, never a long-term solution, although hoarding some products gives a period to react to an interruption, it does not reduce the dependency issue. Similarly, strategic food reserves can temporarily stabilize baseline market supply, but they do absolutely nothing to solve an underlying fertilizer shortage or a systemic, climate-driven crop failure. In the high-tech space, semiconductor stockpiling is fiercely constrained by extreme product specificity and rapid technological obsolescence. Even keeping large inventories of critical raw minerals, while useful, ties up massive amounts of corporate capital without ever substituting for a lack of domestic refining capabilities.

Lastly, relocation and regionalization are very strategic, but they are inherently slow-moving and capital-capacity into trusted or near jurisdiction, it is undeniably enhancing the national security, but at a cost, of course, of economies of scale and a duplication of extremely costly infrastructure. Given these trade-offs, the strategic value of regionalization is greatest when it focuses narrowly on specific points of bottleneck, rather than seeking full-scale supply chain duplication. For example, in semiconductors it would involve funding select nodes in fabrication, specialized packaging, and advanced equipment, tooling and materials capacity; for critical minerals it should be concentrated on downstream chemical processing and refining infrastructure; for pharmaceuticals on the expansion of approved API facilities and local finished dose; and for agri-food resilience on expanding regional processing, secure cold-chain and resilient input supply.

6.5 Balancing Efficiency, Security and Sustainability

This finding highlights the constant conflict between efficiency, security and sustainability. Supply chains designed for efficiency only tend to be fragile because they rely on minimizing redundancy, inventories and overlaps in the suppliers. Supply chains designed exclusively for security may become costly, rigid and protectionist. Supply chains designed without sustainability can create environmental and social liabilities that later become supply risks themselves. Achieving strategic resilience therefore requires striking a balance between these three objectives and not focusing on only one of them.

Efficiency remains a strict requirement because resilience measures must be economically viable; firms simply do not have the luxury of disregarding cost, scale, and productivity. Nonetheless, recent disruptions demonstrate that low costs frequently mask unpriced exposures. A supplier may seem highly efficient on paper simply because geopolitical, environmental, or concentration risks are left out of the procurement equation. Similarly, a lean inventory strategy looks ideal until a sudden market shock hits. The real task for a firm is learning to differentiate between productive efficiency and mere fragile efficiency.

Security needs redundancy. It also needs trusted access and coordination between the public and the private sectors in those industries critical to national wellbeing and strategic self-sufficiency. These are expenses which are easier to justify in the case of essential goods and services, but even then, should not be considered as a solution to redundancy. Redundancy wherever possible is not sustainable and not affordable. Redundancy should be limited to places where it makes sense (e.g. targeted redundancy at systemic bottlenecks is more defensible than broad duplication of whole supply chains).

Sustainability, then, isn’t just something that exists outside of the idea of resilience: shocks related to climate already impact food systems and the capacity for water, transport and energy. The manufacturing of semiconductors generates water, energy and chemical burdens, while the extraction of critical minerals generates environmental and social concerns. The waste generated by the pharmaceutical industry as well as the disposal of medical supplies also raises sustainability issues. Thus, focusing only on one aspect of resilience while completely ignoring pressures related to sustainability could create one set of vulnerabilities and eliminate another. True risk mitigation means reducing exposure in ways that remain consistent with environmental responsibility and long-term social stability (Sovacool et al., 2020; Béné, 2020; Wieland & Durach, 2021).

6.6 Conclusions and Strategic Policy Recommendations

In comparison, the lesson that is ultimately learned is that geopolitical resilience needs to be built sector by sector. While general rules are useful as a starting point, applying them means considering the specific blueprint of every single supply chain, this dissertation reframes resilience as an active, strategic design capability. What we’re trying to do is not to go against globalization, but rather to pinpoint our critical dependencies, to reduce our exposure to the systemic bottlenecks, to make the networks flexible, so that we can survive in the face of geopolitical stress.

This is why it is a top priority for executives to map the interdependence far beyond the immediate suppliers, most critical weaknesses are much farther upstream concealed in raw materials processing, in custom machinery, in logistical choke points, in permitting, or even in essential utilities infrastructure. Organisations must identify precisely which inputs have no substitute, which suppliers they are locked into, and what combination of shocks would stop them in their tracks. This mapping must also be an ongoing discipline, not a crisis management exercise limited to times of crisis.

Second, companies should engage in selective diversification. Growing your list of suppliers shouldn't be a reflex to fill out a balance sheet or to meet a regulatory requirement – it should serve a purpose. In the semiconductor industry, that means going deeper into actual technology inputs. Critical minerals depend on refining and chemical processing capacity. Pharmaceuticals require approved APIs and domestic manufacturing capacity. In the agri-food sector, growing regions are expanding, input supply sources are being diversified, and so are the logistics routes.

On the policy side, governments must do a better job of aligning industrial policy with trade, sustainability, and emergency preparedness goals. Public funding and intervention make sense in areas where a sudden shortage directly threatens national tech capabilities, the energy transition, public health, or food security. But Washington and other capitals should not succumb to protectionism. Instead, a more sensible course would be targeted public-private coordination, regulatory coordination with trusted partners, and investments in bottlenecks and monitoring of strategic materials.

Lastly, any plan for resilience must be considered in three dimensions at the same time: efficiency, security and sustainability. An approach that prioritizes security at the cost of economic viability will never be sustainable in the long run. However, the pursuit of efficiency without regard for concentration risk leads to a house of cards, and an attempt at mitigation of geopolitical risk by causing environmental devastation is merely a stopgap solution.

Finally, attempting to mitigate geopolitical risk by causing environmental devastation is a self-defeating stopgap. For instance, aggressively moving a supply chain to avoid a geopolitical rival is pointless if the new location is highly vulnerable to systemic climate disruptions or lacks the underlying labour ecosystem to remain viable. Building a truly resilient supply chain relies entirely on carefully calibrating these difficult trade-offs on a sector-by-sector basis.

Question is not if a disruption will come again but when and what we can do to prepare.

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