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The Dual Nature of Innovation Ecosystem Factors in Semiconductor Hub Development Evidence from Penang Malaysia

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Abstract

Innovative ecosystems in the semiconductor industry can be viewed as networks of interdependent players, such as companies, government institutions, research organizations, and infrastructural providers, whose overall interactions influence the speed and direction of technological progress. In the context of developing countries aspiring to rise in the semiconductor value chain, an appreciation of particular factors which can either expedite or hinder the process of ecosystem upgrade is crucial for proper policy-making and industrial strategy formulation. This paper aims at formulating the theoretical model of analysis of innovation ecosystem development drivers and obstacles in the developing economy semiconductor cluster. The research is carried out as a qualitative multiple case study of five purposefully chosen organizations, namely multinationals, technology champions, integrated circuit design start-up, and industry governing body, of the Penang semiconductor ecosystem in Malaysia. The data collection was achieved through the use of focus group discussions, semi-structured interviews, and document reviews between April and July 2025. The results show that there are four drivers within Penang's ecosystem that distinguish this ecosystem from others namely, the existence of mature back-end manufacturing, deep and diversified supply chain network, the rise of local technology champions, and the presence of a geopolitically neutral investment climate that facilitates investment in supply chain diversification. The six structural barriers that have been identified include the lack of a domestic demand base for locally designed chips, continued talent deficits worsened by brain drain, infrastructure limitations, import dependent supply chains, insufficient funding for deep technology initiatives, and inadequate policy coordination. What is significant about the study is that there are five core ecosystem drivers namely, multinational corporations anchor, geopolitics, sustainability requirements, quality of the talent pool, and the intensity

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of the government policy that can function at the same time as both drivers and barriers depending on the context and strategy of each ecosystem actor.

Keywords: Innovation Ecosystem, Semiconductor Industry, Value Chain Upgrading, Qualitative Case Study, National Semiconductor Strategy.

Introduction

The semiconductor sector has emerged as an important cornerstone of technological advancements in the modern world and is now essential to innovative fields like artificial intelligence, electric vehicles, communications, healthcare, and manufacturing. The strategic significance of semiconductors has risen immensely owing to disruptions in the supply chain, competition in geopolitics, and requirements for technological sovereignty by nations. Current studies have emphasized that the competitiveness of semiconductors is not only dependent on manufacturing capacity but also depends on innovation ecosystem made up of companies, governments, research organizations, infrastructure organizations, and related industries (Hong et al., 2026; Jia et al., 2025). Resilience of semiconductor supply chains has become an important strategic concern since disruptions in materials, equipment, and manufacturing can have a significant effect on technological development (Zuo, 2025; Xiong et al., 2025). Economies in development encounter many difficulties in progressing beyond the stage of conventional semiconductor production activities towards more sophisticated activities like the design of integrated circuits, advanced packaging, and semiconductor research and development. Progress in semiconductor processing technology entails a constant process of innovation, sustainable manufacturing processes, human resource capacity, and effective industrial coordination (Chien et al., 2025; Al-hassan et al., 2026). Nations that want semiconductor competitiveness must thus have an ecosystem approach that incorporates industrial capacity building, policies, knowledge creation, and value chain upgrading (Huang & Malkin, 2026). The capacity of an area to progress through the semiconductor value chain is a function of how well the ecosystem players work together to create innovation from industrial capacities. Innovation ecosystems serve as an essential approach to studying technological industry evolution based on connectedness within firms, organizations, knowledge and policy networks. Ecosystem development focused on sustainability is becoming especially critical since the process of semiconductor manufacturing implies the use of high levels of energy and raises various environmental issues along with rising demands of international customers for ethical manufacturing (Abeysekera, 2022). In addition, the semiconductor industries have a great dependence on geopolitical transformations due to the impact of technology competition between leading economies (Sampaolo et al., 2026). Malaysia is considered to be a significant emerging semiconductor center due to the extensive experience of Malaysia in semiconductor assembly, testing, and manufacturing processes. Penang, which is known to be one of the main centers of Southeast Asia semiconductors, has gained a solid base of industrial development due to the cooperation between multinational companies, suppliers, engineering, and government industrial programs. Nonetheless, changing the focus from manufacturing processes to innovation-based semiconductor development becomes a difficult task. Existing structures of the ecosystems could be beneficial or problematic for different stakeholders. Competitiveness of semiconductors has been analyzed by previous researchers from a range of different perspectives, such as national policies, resiliency of the supply chain, sustainability, and technology (Vaduganathan, 2024; Xiong et al., 2025; Al-hassan et al., 2026). Nevertheless, not many empirical studies have analyzed the same ecosystem components acting both as drivers and obstacles for developing economy semiconductor clusters. This knowledge is especially vital for such regions as Penang, which already have their advantages in manufacturing but face problems associated with innovation capacity, home market demand, talent development, and value chain upgrading. This is because the study seeks to establish a theoretical framework for understanding the two-sided nature of innovation ecosystem determinants in the formation of semiconductor hub, using Penang, Malaysia as the empirical environment. This research is important since it will identify ecosystem determinants that either facilitate or inhibit semiconductor development and also explain how contextual determinants determine whether certain ecosystem elements are beneficial or harmful.

The study addresses the following research objective and research questions:

Research Objective

In order to create a theoretical framework to study the factors that drive and hinder innovation ecosystem development in a semiconductor hub located in a developing economy, using Penang, Malaysia as an empirical setting.

RQ1: What are the key drivers and barriers affecting innovation ecosystem development in the semiconductor industry of Penang?

RQ2: How do the same ecosystem factors work as drivers and barriers at the same time?

The main contribution of this study is the development of an innovation ecosystem that comprises both nature characteristics. Unlike other theories, this research shows that the variables that exist in the semiconductor ecosystem cannot be viewed as entirely positive or negative; rather, their effects are influenced by several aspects.

The rest of this paper is organized as follows. The next section, section 2, deals with the theoretical background and literature review in relation to innovation ecosystems, semiconductor innovation, resilience in the supply chain, sustainability, and value chain improvement. Section 3 discusses the research methodology used. Empirical results are found in section 4. Section 5 discusses the conceptual model and theoretical implications. Section 6 concludes this study.

Theoretical Background

Innovation Ecosystem Development in Semiconductor Industries

Innovation ecosystems can be understood to be networked ecosystems comprising firms, institutions, technologies, and other stakeholders, whose actions together determine technological innovation and industrial competitiveness. In the case of semiconductors, the coordination of the activities of multinationals, local firms, research organizations, government agencies, and infrastructures is key to ecosystem effectiveness. The competitiveness of semiconductors has evolved from the individual firm capability to the ecosystem level of coordination, whereby knowledge exchange, industrial collaboration, and policymaking determine the long-term creation of value (Bailey, 2023; de Vasconcelos Gomes et al., 2018; Huang & Malkin, 2026). Contemporary studies on semiconductors have shown that national policies are very important for the enhancement of innovation systems and global competitiveness of the industry. Benchmarking semiconductors in terms of strategies in various countries shows that coordination of policies, investments, research, and industrial upgradations are key to success (Hong et al., 2026). Sustainable construction practices emphasize the utilization of recycled waste materials to reduce environmental impact, conserve natural resources, and promote greener building approaches through improved material efficiency (Vaduganathan, 2024).

Semiconductor Supply Chain Resilience and Value Chain Upgrading

The vulnerability of global supply chains of semiconductors has been exacerbated by the effects of geopolitics, technology competition, and dependence on specialty suppliers. Hence, the resilience of the supply chain has been an important issue for semiconductor manufacturing countries. Literature indicates that semiconductor ecosystems need strategies for diversification, domestic capability, and coordination among supply chain members in order to avoid disruption threats (Xiong et al., 2025; Mody, 2023). The process of global reorganization in the semiconductor industry has facilitated the pursuit of emerging economies to engage in value-added operations other than assembling and testing. Countries trying to move up the value chain need to build their capabilities in the areas of designing, researching, inventing, and manufacturing technologies (Mii, 2024).

Geopolitics, Sustainability, and Semiconductor Ecosystem Transformation

Geopolitical competition has affected greatly the decisions and strategies in the field of semiconductor investments. Geopolitical environment and global technology competition have prompted nations and corporations to seek other alternatives for semiconductor locations and improve their technological capabilities (S Sayankina, 2024). This is illustrated by the transformation of semiconductor industries in some key Asian economies, which are influenced by geopolitical environment and supply chain relocation, industrial policy, and ecosystem transformation (Huang, 2025). Additionally, sustainability has been identified as a vital component of competitiveness in semiconductors. The manufacturing of semiconductors consumes high amounts of energy, water, and materials; therefore, there has been an increasing need for sustainable production processes (Li et al., 2022; Yang et al., 2025).

Industrial Policy, Innovation Capability, and Semiconductor Competitiveness

Intervention by the government is another key aspect related to semiconductor ecosystem development. Policies related to industry, digital infrastructure, and innovation play an essential role in the upgrading and development of the economy (Chong et al., 2026). But for these policies to have an effect, there should be coordination between government bodies, firms, and institutes of research. Leading semiconductor regions have shown that innovation capability is a result of ecosystem development over a long period of time instead of just investments. The success of Taiwan in semiconductors shows the significance of industry coordination, building technological capability, and integration into the global semiconductor networks (Chiang, 2023). In addition, competition in semiconductors among different countries proves that technological supremacy has become increasingly reliant on innovation ecosystems instead of only company performance. Therefore, the emerging semiconductor ecosystems need to strike a balance between external investment and capability development. Multinational companies from abroad will speed up ecosystem development through technology transfer, employment creation, and supplier development, but too much dependence will limit the capability for innovation.

Research Methodology

Research Design

The current research will follow a qualitative multiple case study design that allows for an exploration of a complex phenomenon within its real-world environment, especially when the phenomenon under investigation is directly linked to the environment within which it exists and the aim of research is the development of the theory rather than testing a hypothesis. The reason behind selecting the qualitative methodology lies in the nature of the variables that drive or hinder innovation ecosystems development in Penang. These variables are interpreted, experienced and constructed by the human beings that operate within certain organizational, institutional and interpersonal contexts.

Multiple case studies were chosen as opposed to single case studies for the purpose of making comparisons between various organizations in terms of their type, position on the value chain and capability. Making such comparisons not only improves the comprehension of what is happening at the level of the entire ecosystem but also allows the identification of differences that might be experienced by various actors in the process of driver-barrier interactions. Five cases were chosen through maximum variation sampling in order to have representatives from different categories of stakeholders in the Penang semiconductor ecosystem. Fig.1 below provides the methodology used in the identification of the ecosystem drivers, barriers and dual nature factors.

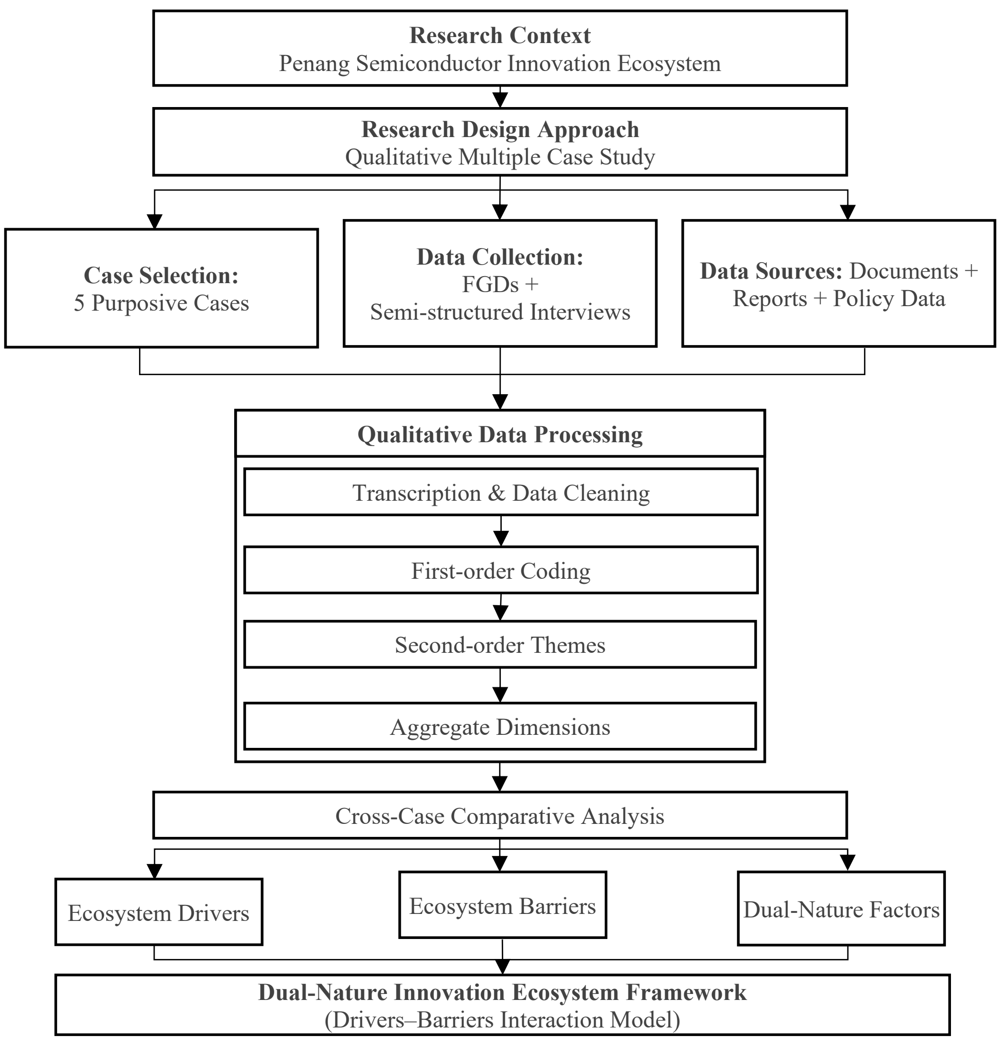

Fig. 1: Research Methodology Framework for Semiconductor Ecosystem Analysis

Case Description and Selection

Research Context: The Penang semiconductor ecosystem in Malaysia consists of more than 350 multinational corporations, more than 6,500 small and medium enterprises, and a cluster of growing local technology champions and integrated circuit design firms. Five different cases have been selected for the study that would reflect different organizational types and value chain positions in this ecosystem. Case A: Large multinational corporation focusing on OSAT and advanced packaging. Case B: International firm with operations related to IC design in Penang. Case C: Local technology champion with globally competitive capabilities in semiconductor equipment and automation. Case D: Local integrated circuit design firm functioning in a new design incubation programme of Penang. Case E: Industry body responsible for coordinating across the ecosystem. The details of cases are presented in table 1.

The inclusion of five cases was defended using the maximum variation approach as a sampling strategy, which allowed for the inclusion of various actors within the ecosystem such as multinational corporations, local technology champions, integrated circuit design firms, and governance organizations.

Data saturation was determined during data collection and analysis through the observation of repetitive themes that were emerging in the interviews, focus groups, and documentary data. Collection of data was considered adequate when the additional data being collected did not yield further information on the drivers, barriers, or dual nature of factors within the ecosystem.

The sampling frame was drawn from organizations operating within the Penang semiconductor ecosystem and includes multinational semiconductor corporations, local semiconductor technology firms, integrated circuit design organizations, and semiconductor industry governance organizations. The preliminary list of possible case organizations was gathered from industry associations, semiconductor clusters, government semiconductor initiatives, and organizational publicly available data. Based on this, five organizations were purposively chosen based on different roles in the ecosystem and positions in the value chain. These organizations include one multinational organization related to outsourced semiconductor assembly and testing (OSAT) and advanced packaging, one multinational organization related to integrated circuit design, one local semiconductor technology leader, one new integrated circuit design organization, and one industry governance organization managing ecosystem coordination.

Table 1: Case Overview

Case	Organisation Type	Value Chain Position	Size / Reach	Ecosystem Role
Case A	Multinational Corporation (MNC)	OSAT / Advanced Packaging	Global; Large (>5,000 Employees in MY)	Anchor Tenant; Technology Standard-Setter
Case B	MNC – IC Design	Upstream Design & Engineering	Global; Medium (500–1,000 in MY)	IC Design Hub; Talent Developer
Case C	Local Technology Champion	Equipment/Automation	Regional; Medium (200–500)	Equipment Ecosystem Builder; IP Creator
Case D	Local SME / Emerging IC Design Firm	Upstream IC Design (Nascent)	Local; Small (<50)	Incubatee; IP Development; Domestic Demand Test Case
Case E	Industry Association / Governance Body	Cross-Ecosystem Coordination	State-Level; Institutional	Policy Facilitator; Investor Interface; Talent Pipeline Steward

Note: Case identities are anonymised to protect commercially sensitive information. Organisation type and role descriptions are drawn from fieldwork data and triangulated with documentary sources.

Data Collection

Data were gathered between April and July 2025 through three different methods to ensure methodological triangulation. The first stage was documentary analysis that entailed analyzing the Malaysia National Semiconductor Strategy, the New Industrial Master Plan 2030, the semiconductor policy at state level, reports from industry, research on other semiconductor clusters in Taiwan, South Korea and Japan and the corporate reports of entities working in the semiconductor value chain. The documentary analysis helped provide a background of the semiconductor industry and develop interview guidelines for future data gathering stages.

Phase two involved three FGDs. FGD1 comprised participants from semiconductor trade associations, government organizations, and research universities (n = 8). FGD2 and FGD3 involved top and middle managers as well as non-executive directors from semiconductor companies covering multinational corporations, local firms, and SMEs (n = 9 combined). FGDs were designed according to four themes: overview of Penang semiconductor ecosystem and its competitive positioning compared to other regions; challenges and opportunities in the semiconductor ecosystem;

alignment strategies with the NSS; and ways to improve the situation. Phase three consisted of in-depth semi-structured interviews involving participants from government organizations, multinational corporations, and local/foreign listed companies (n = 5). Table 2 provides an overview of data sources used.

Table 2: Data Sources and Collection Overview

Data Source	Participants / Documents	Key Themes Covered	Period
FGD Group 1	Trade Associations, Government Agencies, Research Universities (n = 8)	Industry Overview; Policy Effectiveness; Ecosystem Maturity; Strategy Alignment	Apr–Jul 2025
FGD Groups 2 & 3	Top/Middle Management and Non-Executive Directors, Semiconductor Companies (n = 9)	Operational Challenges; Supply Chain; Innovation; NSS Alignment; Recommendations	Apr–Jul 2025
Semi-structured interviews	Government Agencies, MNCs, Listed Local/Foreign Companies (n = 5)	Ecosystem Experiences; Success Factors; Strategic Decisions; Opportunities	Apr–Jul 2025
Documentary review	NSS, NIMP 2030, Industry Reports, Academic Analyses, Annual Reports (n = 40+)	Policy Frameworks; Industry Statistics; Global Hub Comparisons; Trends	2020–2025

FGD = Focus Group Discussion. n values refer to individual participants within each data collection mode.

Table 3: Participant Demographic Profile

Participant Group	Organization Type	Participant Role/Position	Number of Participants	Relevant Experience/Representation
FGD Group 1	Trade Associations, Government Agencies, Research Universities	Industry Representatives, Policy Stakeholders, and Academic Experts	8	Represent Ecosystem Governance, Semiconductor Policy Development, Research Collaboration, and Industry Coordination
FGD Groups 2 & 3	Multinational Semiconductor Companies, Local Semiconductor Firms, and SMEs	Top Management, Middle Management, and Non-Executive Directors	9	Represent Semiconductor Operations, Supply-Chain Management, Innovation Activities, and Organizational Strategy
Semi-structured Interviews	Government Agencies, Multinational Corporations, Listed Local and Foreign Companies	Senior Representatives and Decision-Makers	5	Provide Insights into Ecosystem Development, Strategic Decisions, Investment Opportunities, And Value-Chain Upgrading
Total Participants	Semiconductor Ecosystem Stakeholders	Industry, Government, Academic, And Organizational Representatives	22	Covers Diverse Perspectives Across Semiconductor Ecosystem Actors

Table 3 presents the demographic profile of the participants involved in the study. It summarises the stakeholder categories, organization types, participant roles, and representation across the semiconductor ecosystem.

Participant Selection Criteria and Interview Procedures

The participants chosen for the study were those who met the following three conditions: (a) being part of the ecosystem of semiconductors in Penang, (b) having prior professional experience associated with semiconductors, and (c) having the capacity to give insights into the issues and problems associated with the development of the ecosystem. The participants belonged to various stakeholder organizations such as multinational semiconductor companies, local technology firms, IC designers, etc.

Both the focus group discussions and the semi-structured interviews included senior representatives, managers, professionals, and ecosystem players with appropriate knowledge about semiconductor development. The focus group discussion was conducted in 90-120 minutes on average, while the duration of each semi-structured interview was 45-60 minutes on average. All focus group discussions and semi-structured interviews took place during April-July 2025.

The code validation stage included several steps aimed at enhancing analytical accuracy. The initial codes were scrutinized separately through constant comparison with the raw data. The obtained codes were discussed within the research team in order to ensure uniformity in their interpretation in relation to the research aims. The second-level codes and dimensions were also subjected to validation through cross-case comparison and comparison with documentation in order to ensure that the obtained conceptual framework reflected the viewpoints of various ecosystem actors.

Data Analysis

Audio recordings of all focus group discussions and interviews were done with the consent of participants, and all transcriptions resulted in about 280,000 words of primary qualitative data. The data analysis process took an iterative thematic analysis form. During the first-level coding process, key terms, concepts, and statements related to the conditions of the ecosystems were systematically extracted and coded for all transcripts. During the second-level coding process, initial codes were classified under broad thematic categories related to drivers, barriers, and dual nature aspects of the ecosystem. These thematic categories became the fundamental constructs in the analysis of the research process. During the third-level analysis process, these themes were compared across cases and linked with the theoretical framework to come up with the conceptual framework in Section 5. Document data analysis was done to provide contextual support to findings.

A selection of sample codes used in the coding process is given in table 4. The first order codes were obtained from the participants' statements, which were further classified into second order themes and other aggregate dimensions.

Table 4: Qualitative Coding Structure and Thematic Dimensions

First-order Codes (Representative Examples)	Second-order Themes	Aggregate Dimensions
Long-Term Semiconductor Manufacturing Experience; Established Supplier Relationships; Operational Expertise	Industrial Heritage and Ecosystem Maturity	Ecosystem Drivers
Lack of Domestic Chip Customers; Difficulty Obtaining Design Validation; Limited Market Adoption	Domestic demand deficit	Ecosystem Barriers
Technology Transfer from MNCS; Dependence on Foreign Decision-Making; Limited Local Ownership	MNC anchoring effects	Dual-Nature Factors
Engineer shortages; skills mismatch; talent migration	Talent capability constraints	Ecosystem Barriers
Sustainability compliance requirements; environmental infrastructure challenges	Sustainability pressures	Dual-Nature Factors

Findings

Ecosystem Drivers

Mature Industrial Heritage and Back-End Manufacturing Depth

One factor that has been cited most persistently and strongly across all five cases is the accumulated industrial experience of Penang in assembly, testing, and packaging. Both foreign and local companies pointed out that the more than five decades' experience of manufacturing semiconductors in Penang can be considered a unique and hard-to-duplicate competitive advantage. It is due to the process control expertise, yield, and reliability of the ecosystem that make it an attractive destination for complex and large-scale back-end manufacturing operations. As the representative of Case E (industry governance organization) said at the FGD:

The greatest strength of Penang is something that cannot be replicated in ten years. That is the process expertise, the connections with suppliers, the institutional know-how of what businesses require, which has taken fifty years to achieve. In speaking to investors who are looking to diversify from China and Taiwan, that history is what seals the deal.

This result applies uniformly to all the examples regardless of the organisation, although there may be variations depending on the nature of the organisation. In Case A and B (multinational corporation), heritage becomes a form of efficiency and availability of skilled workforce. In Case C (local champion of technology), heritage is a technological base from which the organisation develops its competitiveness through equipment and automation. In Case D (emerging company designing ICs), heritage becomes an ability to have access to a pool of engineering skills and a logistical base.

Deep and Diversified Supplier Ecosystem

Another key driver common to all the examples is the sophistication of the Penang supplier ecosystem. The fact that many services related to semiconductor production, such as engineering, provision of materials, automation solutions, calibration services, and specialized logistics are available in close geographical proximity ensures shorter lead times, lower costs of transactions, and increased operational flexibility. The fact that there are many interconnected companies in the supplier ecosystem allows for increased efficiency by means of quick solving of issues, exchange of knowledge, and provision of necessary resources to semiconductor firms. It can be seen from the findings that the supplier ecosystem acts as an important facilitator for semiconductor companies by minimizing reliance on suppliers who are geographically far away and increasing their ability to respond to operational needs. The intimate connection between the semiconductor manufacturing companies and the nearby companies enables them to resolve technical problems effectively, giving them flexibility as compared to dispersed production chains. It shows that the depth of supplier ecosystems not only provides an operational benefit but is also the basis for innovation ecosystem development.

Suspicious activity detected

Emergence of Local Technology Champions

The third factor observed in Cases C, D, and E is the existence of local technology champions with internationally competitive capabilities related to semiconductor equipment, automation, and integrated circuit design. It can be said that the appearance of such companies shows that Malaysian engineering capabilities have the potential to not only assist manufacturing processes but also create intellectual property and innovative products, participate in international markets provided that proper ecosystem conditions are in place. The appearance of local technology champions positively impacts the development of the ecosystem through the creation of new paths for innovations, enhancement of domestic capabilities, and serving as an example for the next generation of semiconductor experts and entrepreneurs. The results have shown that local champions create broader ecosystem effects through building up the confidence of new firms, recruitment of skilled labor, and increased involvement in advanced semiconductor operations. The success of these companies has shown that there is a possibility for developing nations to develop their technological capabilities without having to solely depend on multinationals. This driver becomes even stronger due to the presence of semiconductor development and capability-building programs that are designed to boost local innovation capabilities. Programs for semiconductor design development, industry collaborations, and advanced engineering training play a vital role in increasing Malaysia's capacity to participate in advanced semiconductor activities.

Geopolitical Neutrality and Supply Chain Diversification Opportunity

Fourthly, Malaysia's geopolitical neutrality in the semiconductor industry worldwide also plays a role. With growing geopolitical rivalry and rethinking of the structure of semiconductor supply chains, firms started diversifying their manufacturing facilities to lessen their reliance on particular geographic regions for production processes. Being politically stable and maintaining good relations with both Western and Asian countries, while not taking part in any of the major technological disputes, Malaysia gained advantages as a new location for semiconductor investments. Thus, according to the results, it could be said that Penang is a beneficiary of this diversification process. The capacity of the region to absorb investments from various geopolitical factions indicates the strategic importance of the region within global semiconductor networks. The recent trend of investments made by multinational semiconductor companies also reflects the rising importance of Penang as an attractive destination for diversifying the supply chain. However, the neutrality from the perspective of geopolitics is not only helpful in attracting investment but also improves the resilience of the ecosystem. With the presence of multinational semiconductor corporations along with existing manufacturing capabilities and suppliers, Penang can benefit from global semiconductor restructuring.

Ecosystem Barriers

The Domestic Demand Deficit

The unique structural barrier identified in this study is the lack of a robust domestic demand base for the locally designed integrated circuits. While in more advanced ecosystems, domestic systems manufacturers generate demand and thus give a chance for the validation of the locally designed chip technology, Malaysia lacks any such product-based companies that will utilize and commercialize locally designed semiconductor technologies. This represents a very serious structural problem for emerging IC design firms looking to develop their innovation through learning how to respond to market demands. The lack of domestic systems manufacturers results in demand side constraints that affect the growth path of local semiconductor design competencies. While local firms might have the necessary technical competence to design chips that can compete internationally, they lack chances to commercialize locally their technology and get reference designs and investments. This problem results in a vicious cycle where companies need market validation to get their customers, while the customers would not be able to use the locally designed solutions before getting market validation. This problem is evident from the results of Case D and similar problems have been observed in the other case groupings. The weak domestic demand infrastructure makes it difficult for the local IC design houses to create linkages with the downstream industries and limits the creation of local semiconductor industry capabilities. Thus, the problem of domestic demand becomes an important problem that distinguishes the semiconductor ecosystem of Penang from other innovation-led semiconductor ecosystems.

Talent Shortages, Skills Mismatches, and Brain Drain

Talent shortage was found to be one of the key barriers to the development of semiconductor ecosystems in all the five cases studied. There has been difficulty in retaining the semiconductor workforce in Malaysia due to a considerable number of skilled personnel shifting to higher paying jobs in Singapore, Taiwan, China, and Vietnam. Talent shortage is not only linked to the issue of lack of skilled workforce but is also linked to a qualitative mismatch between the needs of the semiconductor industry and what engineers available possess, especially with respect to IC design, process engineering, materials science, and advanced packaging. Moreover, the discussions that took place in the focus group discussions revealed that the universities tend to graduate students who have sound theoretical knowledge but lack practical preparedness for the needs of the semiconductor industry. It was highlighted by the participants that the demands from the industry now expect graduates to be experienced in using advanced design tools. This creates a barrier for the growth of the ecosystem towards higher semiconductor operations.

Infrastructure Constraints and Operational Risks

Infrastructure restrictions, including power grid reliability, water supply, hazardous waste disposal, land, and transport, were among those that featured in all three cases as critical inhibitors of ecosystem development. Modern semiconductor factories demand constant access to reliable electricity, and any interruptions will automatically mean shutting down fabrication equipment and costly losses for the firm. According to interviewees in Case A and Case B, the Penang electricity grid is not always up to the mark when it comes to reliability needed by such advanced semiconductor companies. The water supply chain faces increasing pressure from growing industry demands; Penang's existing water supply infrastructure is capable of accommodating very little slack in the process of running the industries continuously. The lack of a licensed plant for hazardous waste disposal means that these wastes have to be moved to other states, causing additional burden for the companies. Scarcity of land on Penang Island is forcing investments out of the state or even the country, endangering the geographical concentration of the ecosystem.

Supply Chain Import Dependency

The ecosystem of semiconductor industry in Malaysia is still very much reliant on the supply of various inputs such as high purity gases, chemicals, machines and equipment that come primarily from Japan, Taiwan, China and United States. Such reliance exposes the industry to various threats such as those caused by geopolitical tensions, logistical issues, as well as changing supply situation around the world. Growing technological rivalry among the big economies of the world has had impact on the availability and pricing situation of the materials in use by semiconductor firms in Malaysia. Although Malaysia has been able to build up strong capacities for the assembly, testing, and production processes of semiconductors, relying on external providers of vital materials increases vulnerability to supply disruptions and international policy developments. The supply chain participant in Case A noted that the main vulnerability factor is not linked to the manufacturing process but to the supply of materials. Any disruption to the specialised materials suppliers would cause serious disturbances because of the lack of readily available alternative sources within the country.

Funding Constraints and Capital Market Gaps

In the case of locally emerging semiconductor ventures, especially those specializing in IC design and deep technology areas, access to funds becomes very challenging. Private and venture capital firms prefer industries that give faster returns, while banks offer traditional models of collateral-based financing that do not fit the technology-based firms that have long research periods. The informant in the Case D states that the situation is 'the valley of death without any bridge,' meaning there are enough government grants to initiate the product development process, but the absence of funds to keep the business going throughout the long period from the start of the research up to the point when revenues start. In addition, multinational companies usually record revenues in other regions, which limits economic spillovers within the country, and do not prefer listing on local stock markets.

Dual-Nature Factors: Operating Simultaneously as Drivers and Barriers

An essential theoretical result from this research is that there are five ecosystem factors that concurrently play the role of both driving and hindering forces, where their general impact depends on the strategy, capabilities, and ambitions of the particular actors of the ecosystems being studied. This two-fold impact has been demonstrated for all five case studies and all sources of data used. In particular, the findings show that these ecosystem factors neither provide unchangeable positive or negative results, but their impact varies based on organizational characteristics and ecosystem positioning. Table 5 shows the drivers and barriers found in the research, while table 6 includes the two-fold factors and their activation conditions.

Table 5: Ecosystem Drivers and Barriers in Penang's Semiconductor Innovation Ecosystem

Category	Drivers	Barriers
Industrial Heritage & Ecosystem Depth	50+ years OSAT Experience; Established Supplier Base; World-Class Industrial Parks; Deep MNC Network	Concentration in Back-End; Limited Front-End Capabilities; MNC Dependency Reducing Local IP Ownership
Talent & Human Capital	Multilingual, Trainable Workforce; STEM Blueprint; ARM deal (10,000 Engineers); IC Design Academy Launch	Annual 15% Brain Drain; Skills Mismatch; Declining STEM Enrolment; Shortage of IC Design/Process Engineers
Policy & Governance	NSS (2024): RM500bn Target; Tax Incentives (Pioneer Status, ITA); FIZ duty Exemptions; NIMP 2030 Mandate	Fragmented Inter-Agency Coordination; Low Technical Depth in Policymakers; Political Cycle Risk to Long-Horizon Plans
Geopolitics & FDI	Geopolitical Neutrality; US–China Tech War Driving Supply Chain Diversification; FDI inflows from Chinese, European, US firms	Export Restrictions on Advanced Tools; Import Dependency on Critical Materials; Geopolitical Risk to Supply Continuity
Innovation & Domestic Demand	Penang Silicon Design @5km+; GBS TechSpace Incubator; ARM IP deal; local Champions (ViTrox, SkyeChip)	Absence of Domestic System Makers; Circular Demand Deficit for Local Chips; Inadequate Funding for Deep-Tech Ventures
Infrastructure & Sustainability	World-class industrial parks; RE target (40% by 2035); TPA from Sept 2024; Global Customer ESG Alignment	Grid Instability; Water Stress; No Hazardous Waste Facility in Northern Region; Land Scarcity; High Energy Intensity

Source: Developed from primary fieldwork data and supported by previous studies on semiconductor ecosystems, supply-chain resilience, and innovation development (Abeysekera, 2022; Vaduganathan, 2024; Xiong et al., 2025; Huang & Malkin, 2026).

Table 6: Dual-Nature Ecosystem Factors: Conditions for Driver vs Barrier Activation

Factor	As a Driver, When...	As a Barrier, when...
MNC Ecosystem Anchoring	MNCs Transfer Technology, Build Supplier Capability, And Develop Local Engineering Talent Through Sustained Operations	MNCs Treat Malaysia as a Cost-Execution Centre, Limiting Local IP Ownership, R&D Investment, and Technology Decisions
Geopolitical Tensions	Supply Chain Diversification Pressure Drives New FDI to Malaysia as a Neutral, Reliable Alternative to China and Taiwan	Export Controls Restrict Access to Advanced Equipment and Critical Materials; Limits Technology Transfer for Frontier Activities
Sustainability Requirements	Alignment with Customer ESG Expectations Differentiates Malaysia; Renewable Energy Transition Creates Investment Incentive	Operational Compliance Burden (Energy, Water, Waste) Raises Costs; Inadequate Infrastructure Limits Advanced Fab Readiness
Talent Pool Quality	Multilingual, Technically Capable Workforce Enables Complex Manufacturing and is a Primary FDI Attraction Factor	Persistent Brain Drain and Skills Mismatch Constrain the Pipeline for IC Design, Process Engineering, and R&D Roles
Government Policy Intensity	NSS, FIZ Incentives, Pioneer Status, and Co-Funding Frameworks Attract Investors and Support Ecosystem Upgrading	Fragmented Implementation, Ministerial Duplication, And Short Political Cycles Undermine Long-Horizon Investment Confidence

Source: Developed by the authors from cross-case analysis of primary fieldwork data. Illustrative quotes available from the corresponding author on request.

Cross-Case Patterns and Divergences

Through cross-case analysis, there are three systematic aspects with regards to how driver and barrier dynamics vary by type of organisation. First, multinational firms (Cases A and B) view the industrial heritage and supplier environment as highly activating drivers, while they view talent constraints and infrastructure challenges as the strongest barriers towards developing more advanced operations in Penang. Second, the local technology star (Case C) sees the presence of MNCs as both an enabling and a limiting factor. They have benefited from the increased demand among the MNCs for locally-made equipment, however, the fact that the MNCs tend to source globally rather than locally is a challenge in attaining sufficient scale. Finally, the emerging IC design firm (Case D) views the domestic demand shortage as the most binding barrier, while viewing the engineering talent pool within the ecosystem as an actual driver.

The critical point of cross-case divergence lies in the sustainability aspect. For multinational corporations (Cases A and B), the sustainability criteria become both an inducement for investments and a barrier, as customers put direct pressure on the company to prove its success in implementing sustainability measures. Local companies (Cases C and D) have limited exposure to the customers' sustainability criteria but are faced with problems associated with insufficient infrastructure, unreliable energy grid, and water scarcity that hinder their sustainability efforts. Such organizational-specific differences between the drivers and barriers of sustainability have not yet been described in the literature on the semiconductor industry ecosystem.

Discussion

A Conceptual Framework of Dual-Nature Ecosystem Factors

Given the evidence found through the empirical research process, a conceptual framework is developed to explain innovation ecosystem development in developing economies' semiconductor clusters. The conceptual framework includes three analytical dimensions. The first analytical dimension highlights the ecosystem assets - industrial heritage, supply chain depth, emerging champions, and geopolitical positioning – that make up the ecosystem's main structural drivers of competitiveness. Such ecosystem assets are largely path-dependent and result from past investments and decisions. The second analytical dimension involves the structural barriers to ecosystem improvement: domestic demand deficiency, talent shortfall, infrastructure challenges, import dependence, financing gap, and policy disarray. These barriers are not autonomous but are systematically interconnected with each other: the domestic demand deficiency is aggravated by talent shortage (as IC designers seek markets with a higher level of domestic demand); the financing gap makes the domestic demand deficiency worse (underfinanced firms do not have enough maturity to appeal to customers); and policy disarray impairs coordination efforts to overcome infrastructure challenges.

The third and most theoretically important part of the framework consists of the dual-nature variable: the five aspects of the ecosystem, the anchor of the MNCs, geopolitical conflicts, sustainability needs, quality of the talent pool, and intensity of government policies serve both as drivers and as barriers. The direction of impact of each dual-nature element is not predetermined; rather, it depends on four context variables: (1) the strategic focus of the particular actor from the ecosystem (production orientation vs innovation orientation); (2) the capability level of this actor (established vs nascent); (3) the ambition level of this actor regarding value chain upgrading; and (4) the policy environment in which this actor operates.

Theoretical Implications

The current models for innovation ecosystems provide explanation regarding the way in which actors, resources, and institutional relationships lead to innovation emergence. Nevertheless, the current models treat ecosystem variables in terms of enabling conditions. This research contributes to current knowledge about innovation by providing a model for analysis of semiconductor innovation ecosystems based on a concept of dual nature of variables. That is, the effects of MNC anchoring, intensity of policies, sustainability demands, geopolitics, and talent capacities depend on the nature of actors, strategic focus, and institutional environment.

The research also helps in gaining insight into the impact of agglomeration by providing evidence that despite being beneficial and significant, back-end manufacturing capability does not automatically lead to the creation of knowledge spillovers necessary for creating front-end semiconductor capability. This implies that the process of upgrading an ecosystem involves more than merely scaling up the current manufacturing activities, but rather involves establishing a demand structure through which local chip designers can meet domestic product firms that will use these semiconductor technologies.

Practical Implications for Policy and Industry

For Malaysian decision-makers, the model brings out three key areas where more efforts need to be made in relation to the current strategy of developing semiconductor industry in Malaysia. These areas include fostering local demand for Malaysian-designed semiconductor solutions which will involve procurement programs, reference laboratories and building up system makers domestically in strategic sectors like automotive electronics and industrial automation. Demand-side measures will help overcome some of the challenges that the local integrated circuit design companies are currently facing.

Limitations

This study also recognizes possible limitations regarding researcher subjectivity and case selection. Even though systematic coding, triangulation, and decision tracking were used, qualitative research may include researcher bias in interpreting the data. Moreover, the purposive selection of five cases might create case selection bias since the selected cases are the ones that fit a particular role in the ecosystem and not all semiconductor ecosystem stakeholders. In addition, the results of the research are based on the subjective opinions of the ecosystem participants. Future research should take into account larger sample size, longitudinal research, and quantitative verification.

Conclusions

This research provided an approach for the analysis of the motivations, constraints and dual motivations related to the innovation ecosystem development process in a developing country semiconductor cluster, based on the case of Penang semiconductor ecosystem in Malaysia. Based on the qualitative multiple case study design with a sample of five purposively selected firms, supplemented with the results of focus groups, semi-structured interviews and documentation analysis, four key drivers of the ecosystem have been discovered: the presence of an established industry tradition; the well-developed supplier base; the emergence of technology leaders in the local environment; and the geopolitical position, which makes the region attractive in terms of supply chain diversification. Six key barriers were determined as well. Among the contributions of this study is the recognition of the existence of five ecosystem characteristics that are able to play both the role of driver and barrier at the same time, depending on organizational and institutional capacities. Ecosystem development in the present research setting is thus shown not to depend only on attracting investments but also on increasing innovation capabilities, creating domestic demand, building talents, and implementing policies effectively. Practical implications of this study include the suggestion that targeted actions should be implemented in order to turn current weaknesses of the ecosystem into strengths. Future research may be focused on the development of this idea, with the use of comparisons among emerging semiconductor clusters, longitudinal research of ecosystem transformations, and quantitative confirmation of the suggested dual nature of these factors.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Interview transcripts and focus group discussion recordings are not publicly available to protect participant confidentiality. All documentary sources used in analysis are fully cited in the reference list and publicly accessible.

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