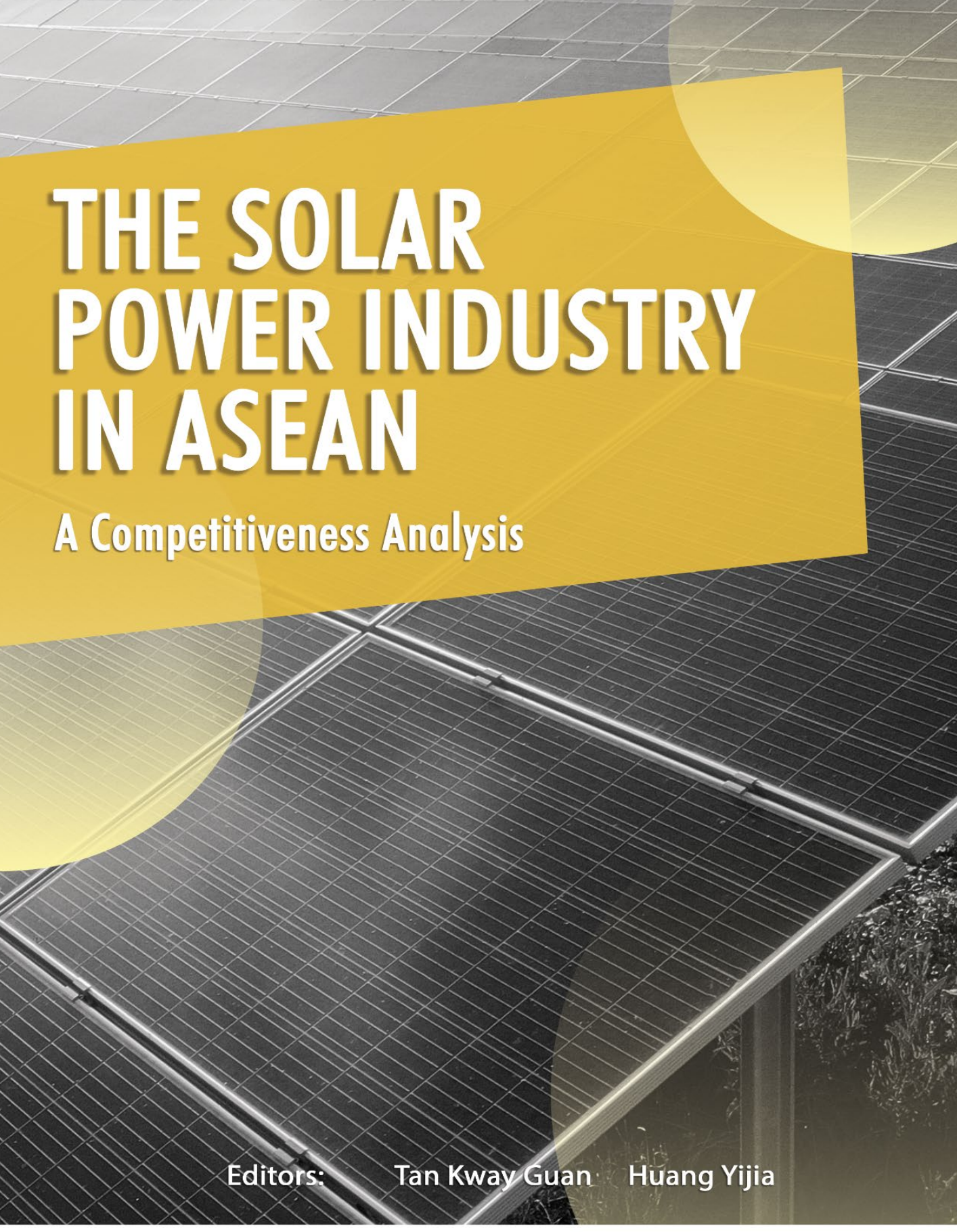

THE SOLAR POWER INDUSTRY IN ASEAN

A Competitiveness Analysis

Editors: Tan Kway Guan Huang Yijia

Lee Kuan Yew School of Public Policy
Asia Competitiveness Institute

NUS National University of Singapore

The Solar Power Industry In ASEAN: A Competitiveness Analysis

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About ACI

The Asia Competitiveness Institute (ACI) was established in August 2006 as a research centre at the Lee Kuan Yew School of Public Policy (LKYSPP), National University of Singapore (NUS). It aims to build intellectual leadership and network for understanding and developing competitiveness and sustainable growth in Asia. ACI seeks to contribute to the enhancement of inclusive growth, living standards, and institutional governance through competitiveness research on sub-national economies in Asia. It identifies mitigating issues and challenges for potential public policy interventions through close collaboration with regional governments, business corporations, policy think tanks, and academics. ACI's three key research pillars include (i) sub-national economies level competitiveness analysis, (ii) emerging sustainable development landscape in 16 Asia economies, and (iii) Asia's long-term growth strategies and public policy analysis.

ACI's value propositions may be encapsulated in its acronym:
Analytical inputs to initiate policies for policy-makers and business leaders in Asia
Capacity building to enable others through improvement in productivity and efficiency
Intellectual leadership to create pragmatic models of competitiveness and inclusive growth

Vision and Mission

- ACI's over-arching vision is to build up its research credibility with policy impact, contributing as a professional, world-class think-tank.
- ACI's mission is to establish our niche as a leading policy think-tank by identifying development trends, opportunities, and challenges among Asian economies and business corporations.
- ACI endeavours to articulate sound recommendations, promote discussion, and shape research agenda in the arena of public policy amongst Asian governments.
- ACI undertakes evidence-based analysis of public policy issues and decisions, in order to provide assessment of their effectiveness as well as economic and societal impact

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Preface

As strategic competition intensifies globally, countries and firms are increasingly de-risking and reshoring their supply chains, driving a global reconfiguration that prioritises diversification and resilience. ASEAN has become a key destination for supply chain relocation, particularly in strategic manufacturing. At the same time, climate change and related natural disasters have posed significant challenges to ASEAN and member states' long-term growth. Yet, climate mitigation efforts, such as the rising adoption of renewable energy, also present opportunities for the green economy, like the solar photovoltaic (PV) manufacturing industry, for example. Meanwhile, emerging technologies such as artificial intelligence have reshaped society, from economic development to people's livelihoods.

The Asia Competitiveness Institute (ACI), Lee Kuan Yew School of Public Policy (LKYSPP), and the National University of Singapore (NUS) seek to expand their understanding of the developmental issues facing ASEAN. Through the publication of ACI's long-running series of annual studies on the competitiveness of the ASEAN Member States (AMS), ACI hopes to contribute meaningful research, highlighting key policy interest areas.

The Solar Power Industry in ASEAN – A Competitiveness Analysis builds on the long-standing ACI ASEAN Annual Competitiveness Analysis and the more recent ASEAN+ Digital Competitiveness Analysis. It offers a comprehensive perspective on the developmental policies, strengths, and challenges of ASEAN+ economies, providing valuable insights for addressing the digital divide.

The research in this volume centres on ASEAN's two core policy issues -- the green and the digital economy. For the green economy, this volume focuses on solar PV, a critical green technology to global energy transition and climate mitigation plans. We examine ASEAN's role in the global solar PV supply chain, from research and development to the export of solar PV cells and modules, providing critical insights into the green economy potential of ASEAN in concrete terms.

The digital transition in ASEAN continues to be challenged by a persistent digital divide, as reflected in the ASEAN+ Digital Competitiveness Index indicators. As the region seeks to seize opportunities in the digital economy, including the development of artificial intelligence and digital service trade, and further integration through initiatives like the Digital Economy Partnership Framework, member states must accelerate efforts to fully harness the digital economy's potential. Key priorities include improving digital connectivity, advancing emerging digital technologies, attracting greater investment in the Information and Communication Technology (ICT) sector, and fostering a strong digital talent pipeline.

This volume aims to provide readers with a vigorous understanding of the evolving dynamics of the ASEAN region amid global disruptions. Moving forward, ACI will continue to strengthen and expand its research on ASEAN's development.

Professor Paul Cheung
Director, Asia Competitiveness Institute
Lee Kuan Yew School of Public Policy
National University of Singapore

Executive Summary

The intensification of strategic competition among global economies presents significant challenges. ASEAN is not an exception. ASEAN member states (AMS) recognise that this geopolitical rivalry has the potential to heighten policy uncertainty, reshape international supply chains, and contribute to economic fragmentation. These developments could undermine market confidence and impede the region's long-term economic growth. Meanwhile, climate change substantially threatens ASEAN's economic stability, given the region's heightened vulnerability to its impacts, including an increased frequency of natural disasters. At the same time, frontier technologies such as artificial intelligence (AI) have reshaped economic development and people's livelihoods.

Yet, there are also opportunities arising from the above challenges. We observed supply chain relocation into the ASEAN region, particularly for strategic manufacturing sectors, such as batteries and electronic components, thanks to its established supply chain in these industries and lower production costs. As a part of the climate change mitigation efforts, the world saw a rising adoption of renewable energy. Solar photovoltaic (PV) power has been one of the most popular options. This provides business opportunities for ASEAN's solar PV manufacturing industry. Another growth opportunity for ASEAN lies in the digital economy, notably the new wave of generative AI proliferation, which is estimated to push up ASEAN's GDP by 10% by 2030.

The Solar Power Industry in ASEAN – A Competitiveness Analysis builds upon this foundation by presenting the latest findings from the ACI ASEAN Annual Competitiveness Analysis and the newly developed ASEAN+ Digital Competitiveness Analysis. This study offers a comprehensive evaluation of the region's developmental trajectory through rigorous quantitative assessments and an examination of key policies proposed and implemented by ASEAN and individual member states. By critically analysing the strengths and weaknesses identified in the Competitiveness Indicators (Chapters 2 and 3), the analysis provides valuable insights on how ASEAN and AMS could ride on the trending opportunities in supply chain reconfiguration, the green economy and the digital economy.

Chapter 1 features ASEAN's role in the global solar PV supply chain, from its research and development (R&D) capacity to the exports of finished solar PVs. The findings indicate that ASEAN's contribution to global solar PV R&D remains marginal, with Malaysia and Singapore emerging as the primary regional contributors. In terms of trade, ASEAN has solidified its position as the world's second-largest exporter of solar PV cells and modules—led by Vietnam, Malaysia and Singapore in 2022. Meanwhile, ASEAN was also the world's largest importer of wafers and the second-largest importer of polysilicon, underscoring its reliance on external sources for critical intermediates. As for trade partners, ASEAN has a strong reliance on the US as its largest export market for finished goods, and on China for key inputs, which poses risks should there be higher US tariffs on products linked to Chinese supply chains. This highlights the importance of AMS diversifying its export markets and import sources by further regional integration, for instance.

Chapter 2 presents the 2024 edition of the ACI's Annual ASEAN Competitiveness Index. Among the ten AMS, Singapore remained the most competitive country and excelled in all environments: Macroeconomic Stability ; Government and Institutional Setting ; Financial,

Business and Manpower Conditions; and Quality of Life and Infrastructure Development. Indonesia and Vietnam demonstrated significant progress, highlighting their resilience amid global uncertainties and disruptions. Compared to the 2023 edition, Indonesia's ranking in Macroeconomic Stability jumped from the sixth position to the third. Vietnam showed a more comprehensive improvement, scoring above the regional average across three environments: Macroeconomic Stability; Financial, Business and Manpower Conditions; and Quality of Life and Infrastructure Development, for the first time. Comparing across environments, except for the Financial, Business and Manpower Conditions environment, the other three environments saw a widening gap between the regional leader, Singapore, and those that rank at the bottom. This underscores the importance of strengthening efforts to enhance competitiveness in order to seize opportunities from the green and the digital economy, and from supply chain reconfiguration.

Chapter 3 examines the latest developments in digital transformation across the ASEAN+ economies, presenting findings from the 2024 edition of the ASEAN+ Digital Competitiveness Analysis. Compared to the 2023 edition, Singapore maintains its leadership in Overall Digital Competitiveness. The Republic of Korea climbed up from fourth to second place, while China and Hong Kong SAR lost ground. There is a persistent digital divide within the region. A widening gap was seen in Institutional Capacity, Digital Infrastructure and Core Inputs, from 2023 to 2024. Frontrunners like Singapore and China pulled further ahead while countries such as the Philippines, Indonesia and Vietnam lagged further behind. As ASEAN progresses towards a more integrated digital economy through initiatives like the Digital Economy Framework Agreement, bridging these divides is essential to fully unlock the region's digital potential. Encouragingly, the AMS are actively implementing strategies to achieve this goal. These efforts include investments in technological infrastructure, research and development of frontier technologies, encouraging private sector participation in the digital economy, cultivating digital talents, and enhancing the efficiency of digital governance.

Acknowledgements

The Solar Power Industry in ASEAN: A Competitiveness Analysis is supervised and led by Tan Kway Guan and Huang Yijia and contributed to by Yan Bowen, Wong Kai Ying Christy, and Brendan Lee.

This book presents the most recent update of the Annual ASEAN Competitiveness and Digital Competitiveness studies, incorporating the latest available data. Our comprehensive frameworks monitor and assess the factors influencing regional economies' economic and digital competitiveness and inform what they should do to strengthen their competitiveness to seize and commercialize the trending opportunities from global supply chain reconfiguration and the green and digital economy. Our analysis aims to provide readers with a nuanced understanding of multi-faceted topics, which debunks conventional assumptions and opens new avenues for further examination and development.

This book would not have been realized without the invaluable support of our research and administrative colleagues. We would like to express our sincere gratitude to the dedicated administrative team at ACI, including Cai Jiao Tracy, Dewi Jelina Ayu Binte Johari, Lyne Po Lai Yin, and Nur Atiqah Binte Rahmat.

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List of Abbreviations

ACFTA	ASEAN-China Free Trade Area
ACI	Asia Competitiveness Institute
ADM	ASEAN Digital Masterplan
AEC	ASEAN Economic Community
AI	Artificial Intelligence
AML	Anti-Money Laundering
AMS	ASEAN member states
APAC	Asia-Pacific
APAEC	ASEAN Plan of Action for Energy Cooperation
AR	Augmented Reality
ASEAN	Association of Southeast Asian Nations
Bernama	Berita Nasional Malaysia (Malaysia National News)
BFI	Brunei Fertiliser Industries
BOS	Balance of System
BRI	Belt and Road Initiative
BSP	Bangko Sentral ng Pilipinas (Central Bank of the Republic of the Philippines)
BTSs	Base Transceiver Stations
CIA	Currency Interchangeability Agreement
CMGP	Conditional Matching Grant to Provinces
CO2e	Carbon dioxide equivalent
COMPASS	Complementarity Assessment Framework
CPC	Cooperative Patent Classification
CPTPP	Comprehensive and Progressive Agreement for Trans-Pacific Partnership
c-Si	Crystalline Silicon
CyCord	Cyber Coordination Centre
DBN	Digital Bharat Nidhi (Digital India Fund)
DDS	Digitally-deliverable services
DEFA	ASEAN Digital Economy Framework Agreement
DEPA	Digital Economy Partnership Agreement
DPDPA	Digital Personal Data Protection Act
E-commerce	Electronic commerce
EIU	Economist Intelligence Unit
EP	Employment Pass
ESSDP	Education and Sports Sector Development Plan

F&B	Food and Beverage
FATF	Financial Action Task Force
FBMC	Financial, Business and Manpower Conditions
FiT	Feed-in Tariffs
FTA	Free trade agreements
FTZs	Free trade zones
FY	Financial Year
Gbps	Gigabits per second
GCI	Global Competitiveness Index
GCR	Global Competition Review
GDP	Gross Domestic Product
GMV	Gross Merchandise Value
GST	Goods and Services Tax
GVA	Gross Value Added
GW	Gigawatts
HS	Harmonised System
ICT	Information Communication and Technology
IDI	ICT Development Index
IGE	Intergovernmental Group of Experts
IMD	International Institute for Management Development
IMDA	Infocomm Media Development Authority
IMF	Internationla Monetary Fund
IOH	Indosat Ooredoo Hutchison
IP	Intellectual property
IPC	International Patent Classification
IRENA	International Renewable Energy Agency
ITU	International Telecommunication Union
IUs	in-vehicle units
JRL	Jurong Region Line
KeTTHA	Kementerian Tenaga, Teknologi Hijau dan Air (Ministry of Energy, Green Technology and Water, Malaysia)
KPK	Komisi Pemberantasan Korupsi (Corruption Eradication Commission, Indonesia)
LKYSPP	Lee Kuan Yew School of Public Policy
LRT	Light Rail Transit
LTA	Land Transport Authority
LTIF	Long Term Investment Fund
MAS	Monetary Authority of Singapore
MCC	Model Contractual Clauses

M-commerce	Mobile commerce
MGS	Metallurgical-grade silicon
MNEs	Multinational Enterprises
MPEC	Manpower Planning and Employment Council
M-SEP	Manpower for Strategic Economic Priorities
MSME	Micro, Small and Medium Enterprises
Mt	Million tons
MtCO2e	Million tons of carbon dioxide equivalent
MW	Mega watt
MOU	Memorandum of Understanding
NDC	Nationally Determined Contribution
NISC	National Centre of Incident Readiness and Strategy
NSEDP	National Socio-Economic Development Plan
NUS	National University of Singapore
OBUs	On-board units
OECD	Organisation for Economic Co-operation and Development
PCGF	Private Credit Growth Fund
PdPR	Pengajaran dan Pembelajaran di Rumah (Teaching and Learning at home)
PIPA	Personal Information Protection Act
PLI	Production Linked Incentive
PMGDISHA	Pradhan Mantri Gramin Digital Saksharta Abhiyaan (Prime Minister's Rural Digital Literacy Program)
PPP	Public-Private Partnerships
PV	Photovoltaic
PWM	Progressive Wage Model
R&D	Research and development
RCEP	Regional Comprehensive Economic Partnership
RM	Ringgit Malaysia
SCC	Standard Contractual Clauses
SDG	Sustainable Development Goals
SEDA	Sustainable Energy Development Authority, Malaysia
SINGA	Significant Infrastructure Government Loan Act
SMEs	Small and Medium Enterprises
SSO	Single-Sign-On
TEL	Thomson-East Coast Line
THB	Thai Baht
TVET	Technical and Vocational Education and Training
UNCTAD	UN Trade and Development
UNDP	United Nations Development Programme

UNFCCC	United Nations Framework Convention on Climate Change
UPU	Universal Postal Union
US	United States
USD	US Dollar
VAT	Value Added Tax
VND	Vietnamese Dong
VR	Virtual Reality
WCY	World Competitiveness Yearbook
WIPO	World Intellectual Property Organization
WSS	Workfare Skills Support
WTO	World Trade Organization

Chapter 1

ASEAN in the Solar PV Supply Chain

Tan Kway Guan, Huang Yijia, Wong Ka Ying, Yan Bowen

1.1 Introduction

The timing of this volume is highly crucial as member states of the Association of Southeast Asian Nations (ASEAN) are exposed to global disruption. The global economy has become more fragmented; the International Monetary Fund (IMF) projects that this could cost the world between 0.2% to 7% of gross domestic product (GDP).[1] Global trade and supply chains are being disrupted and are responding by undergoing reconfiguration. For example, multinational companies (MNCs) that traditionally relied strongly on Chinese suppliers have pursued a China + N strategy to diversify their supply chain to enhance resilience.[2] The drivers behind this global supply chain reconfiguration include geopolitical tensions, such as the US-China strategic rivalry and the trade war that has emerged from it; rising production costs in China; and the relatively lower production costs in countries and regions with established supply chains, such as Southeast Asia. The vulnerability of over-reliance on a single supplier, further highlighted by the COVID-19 pandemic, has also encouraged MNCs to diversify their supply chain.

Climate change has also brought challenges for ASEAN, from natural disasters to economic loss, and ASEAN is particularly exposed to and vulnerable to the negative impact of climate change.[3] In the most severe scenario, ASEAN is projected to lose about 37% of its GDP by 2048, due to climate change. Notably, the economic powerhouses in the region - Indonesia, Malaysia, the Philippines, Singapore and Thailand could lose more than seven times of their 2019 GDP, by 2050.[4]

Meanwhile, frontier technologies have transformed society, affecting economic development and people's livelihoods. The most recent example is the rise of artificial intelligence (AI). IMF found that in developed economies, around 60% of employment is impacted by AI, with half of them being negatively impacted. However, in emerging markets and low-income economies, 40% and 26% of employment is exposed to AI respectively, indicating less immediate AI-related disruptions in the labour market compared to developed economies.[5] This could be due to the lack of readiness in using AI, which could also result in a greater income disparity between the developed and developing economies.

[1] See Aiyar et al (2023).
[2] See Doarest and Wihardja (2024) and Aiyar et al (2023).
[3] See University of Notre Dame (n.d.a) and University of Notre Dame (n.d.b).
[4] See Gray and Varbanov (2021).
[5] See Cazzaniga et al. (2024).

Yet, these challenges also bring opportunities for ASEAN. Amid the global supply chain reconfiguration, we observed supply chain relocation into the ASEAN region, particularly for strategic manufacturing sectors.[6] For example, right after the US imposed tariffs on Chinese-manufactured products in 2018,[7] China's foreign direct investment (FDI) in ASEAN's manufacturing sector surged by 106% from 2018 to 2019.[8] After the outbreak of the COVID-19 pandemic, China's FDI in ASEAN's manufacturing sector also grew by 43.8% from 2020 to 2021, and by 47.8% from 2021 to 2022.[9] After a declining trend from 2013 to 2017, the US's FDI in ASEAN's manufacturing sector displayed a strong growth of 4717% from 2017 to 2022, except for a decline in 2020 during the COVID-19 pandemic. The growth was exceptionally significant from 2017 to 2018 -- 2761%, from -463 million USD to 12.3 billion USD.[10]

In terms of the green economy, ASEAN countries stayed committed. This can be seen in their commitments to preventing loss and damage from climate change impacts, enhancing climate mitigation and adaptation, and promoting sustainable development, highlighted in the ASEAN Summit in 2024.[11] It can also be seen in the China-ASEAN Free Trade Agreement (FTA) Upgrade 3.0, which concluded in October 2024. The upgraded FTA introduces a dedicated chapter on the green economy, including provisions on environmental goods and services to foster a green and climate-resilient economy and support regional energy transition. It also intends to promote deeper cooperation in green investment and technology.[12]

One of the key avenues to mitigate the negative impacts of climate change would be to expand the consumption of renewable energy. ASEAN aims to have 23% of renewable energy in its total primary energy supply by 2025, prioritising solar photovoltaic (PV).[13] This will also benefit the green economy development by inducing a rising demand for solar PV-related products. ASEAN, as the world's second-largest solar PV cell or module exporter in 2022, will be able to take advantage of the opportunities.

Another growth opportunity for ASEAN lies in the digital economy, and in particular, the new wave of AI proliferation. The proliferation of generative AI is estimated to drive a 7% increase in global GDP, equivalent to approximately 7 trillion USD. It will also lift annual productivity growth by 1.5 percentage points over a 10-year period.[14] Zooming in on the ASEAN region, research estimates that AI could increase ASEAN's GDP by 10% to 18% (approximately 1 trillion USD) by 2030.[15]

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[6] Strategic sectors mainly lie in the manufacturing industry, such as the manufacturing batteries and accumulators, domestic appliances, electronic components and boards and general-purpose machinery. The definition of strategic sector can be found in the International Monetary Fund (2023) and UNCTAD (2024b). For more discussions on the supply chain reconfiguration and their relocation to the ASEAN region, see Aiyar et al (2023), Doarest and Wihardja (2024) and Chu et al. (2024).

[7] See Bown and Kolb (2025).

[8] See ASEANStats. (n.d.).

[9] Ibid.

[10] Ibid.

[11] See ASEAN Secretariat (2024).

[12] See Ministry of Trade and Industry, Singapore (2024).

[13] See IRENA, COP28, COP29, Global Renewables Alliance, Ministry of Energy of the Republic of Azerbaijan and Government of Brazil (2024) and ASEAN Centre for Energy (2024).

[14] See Goldman Sachs (2023).

[15] See ASEAN Main Portal (2024).

These developments have made understanding the competitiveness of ASEAN members in supply chain reconfiguration, the green, and the digital economy , essential to good policy making. To contribute comprehensively to the discussion, this volume features three chapters covering the following: the remainder of Chapter 1 presents key figures on ASEAN to provide necessary context for the book, followed by an in-depth study mapping ASEAN's role in the global solar PV supply chain. Solar PVs are a critical part of green technology, essential to energy transition and climate mitigation plans worldwide. The chapter comprehensively charts the role of ASEAN economies from R&D to the export of finished solar PVs. This will provide critical insights into the green economy potential of ASEAN in concrete terms.

Chapter 2 provides an in-depth Competitiveness analysis of the ten ASEAN Member States (AMS) and identifies strengths and weaknesses from four perspectives: Macroeconomic Stability; Government and Institutional Settings; Financial, Business and Manpower Conditions; and Quality of Life and Infrastructure Development. Such analysis will inform ASEAN and its individual member states what they could do to further enhance their competitiveness. It is pressing and essential for ASEAN and AMS to capture the opportunities in supply chain reconfiguration, the green, and the digital economy, in pursuit of their ambitions to forge an inclusive, sustainable, dynamic, and resilient ASEAN.[16]

Chapter 3 presents the 2024 ASEAN+ Digital Competitiveness Index, including strengths and weaknesses in 11 ASEAN+ economies from five perspectives: Digital Outputs, Institutional Capacity, Digital Infrastructure, Core Inputs and Digital Utilisation. This will allow the regional countries to have a better understanding on how they could ride on the latest digital economy, including AI and digital service trade, given their strengths and weaknesses in digital transformation.

1.2 ASEAN in Numbers

Drawing on data from relevant government sources and international organisations, we present Table 1.1, which outlines key macroeconomic and social indicators that define ASEAN. These indicators highlight the diverse characteristics of ASEAN Member States (AMS) across various dimensions and provide insights into their unique dynamics. As the rest of the book delves deeper into the impact of policies and legislation, this table serves as a foundation for analysing each member state's competitiveness.

ASEAN comprises diverse nations with substantial geographic, demographic, and human development variations. With a total population of 676.6 million, the region ranks among the most populous economic blocs globally, accounting for approximately 8.4% of the world's population. Economic development in the AMS varies greatly. Table 1.1 shows the GDP per capita (constant 2015) of the 10 AMS. High-income countries such as Singapore and Brunei recorded GDP per capita (constant 2015) figures of 65.4 thousand USD and 28.7 thousand USD, respectively, in 2023.[17] Malaysia, Thailand and Indonesia, the upper-middle-income countries, had GDP per capita (constant 2015) of 11.4 thousand USD, 6.4 thousand USD and 4.2 thousand USD, respectively, in the same year. Meanwhile, Vietnam, the Philippines, Cambodia and Lao

[16] See ASEAN Secretariat (2024).
[17] For more information on countries by income groups, see World Bank (n.d.).

PDR (Laos) are classified as lower-middle-income economies, with GDP per capita ranging from 2.1 thousand USD to 3.8 thousand USD. Myanmar remains the only ASEAN country classified as a low-income economy, with a GDP per capita of 1.2 thousand USD, reflecting significant developmental challenges.

Table 1.1: ASEAN Key Indicators 2023

Country	Land Area (`000km^2)	Population (million)	Human Development Index	GDP (current prices in US$ billion)
Brunei	5.8	0.5	0.823	15.1
Cambodia	181.0	17.1	0.6	42.0
Indonesia	1892.4	278.7	0.713	1,371.1
Lao PDR	236.8	7.5	0.62	14.2
Malaysia	330.4	33.4	0.807	396.3
Myanmar	676.6	56.2	0.608	64.4
Philippines	300.0	111.9	0.71	437.2
Singapore	0.7	5.9	0.949	501.3
Thailand	497.4	65.1	0.803	514.9
Vietnam	331.3	100.3	0.726	429.5
ASEAN	4452.4	676.6	N/A	3786
Country	**GDP per capita (const. 2015 US$)**	**Trade (% of GDP)**	**FDI Inflows**	
			Million US$	**% of GDP**
Brunei	28,725.1	137	-56.9	-0.3
Cambodia	2,083.6	134	3,958.8	9.4
Indonesia	4,192.6	41	22040.1	1.6
Lao PDR	2,648.9	108	1,781.2	11.2
Malaysia	11,429.6	132	8,781.5	2.0
Myanmar	1,177.8	55[18]	2,204.1	3.4[19]
Philippines	3,745.7	67	9116.3	2.1
Singapore	65,422.5	311	159,630.1	34.9
Thailand	6,393.9	129	8053.4	1.3
Vietnam	3,760.4	166	18,500.0	4.3
ASEAN	N/A	121	234,008.4	6.17

Source: Collectively aggregated from ASEANStats, The World Bank Group World Development Indicators, UNCTAD and UNDP (accessed 3 March 2025)

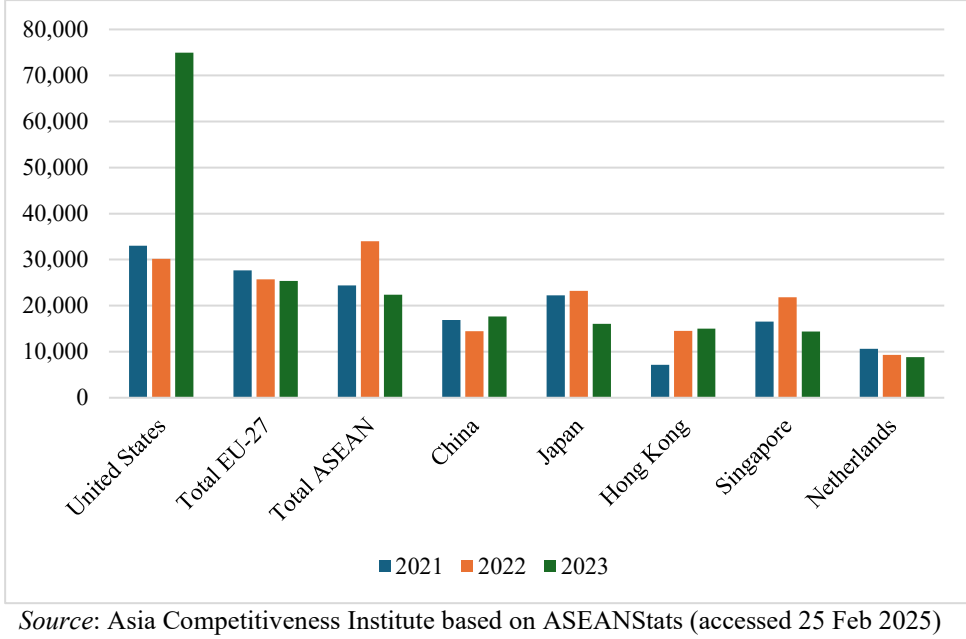
Trade remains a key driver of ASEAN economies, though member states exhibit significant disparities in trade dependency. Singapore (311%) maintained the highest trade-to-GDP ratio in the region in 2023, underscoring its position as a global trade hub. Vietnam (166%), Brunei (137%), Cambodia (134%), Malaysia (132%) and Thailand (129%) also demonstrated high trade integration, showing that they are export-oriented economies. In contrast, the Philippines (67%),

[18] Data for Myanmar is not available from WDI. This number is calculated based on the international trade data and GDP (current US$) from ASEANStats.
[19] Data for Myanmar is not available from WDI. This number is calculated based on the FDI data and GDP (current US$) from ASEANStats.

and Indonesia (41%) reported lower trade-to-GDP ratios in 2023, indicating a greater reliance on domestic markets and less exposure to international trade.

ASEAN has been a popular Foreign Direct Investment (FDI) destination, with inflows growing by 12.5% from 2021 to 2023.[20] In 2023, ASEAN attracted approximately 234.0 billion USD in FDI, reaffirming its significance as a strategic investment hub. Singapore (160 billion USD) remained the top recipient in 2023, reflecting its position as the regional financial and investment centre. Other key beneficiaries included Indonesia (22.0 billion USD) and Vietnam (US$18.5 billion).

Figure 1.1: FDI Inflows to ASEAN by Top Sources in Million USD, 2021-2023



Source: Asia Competitiveness Institute based on ASEANStats (accessed 25 Feb 2025)

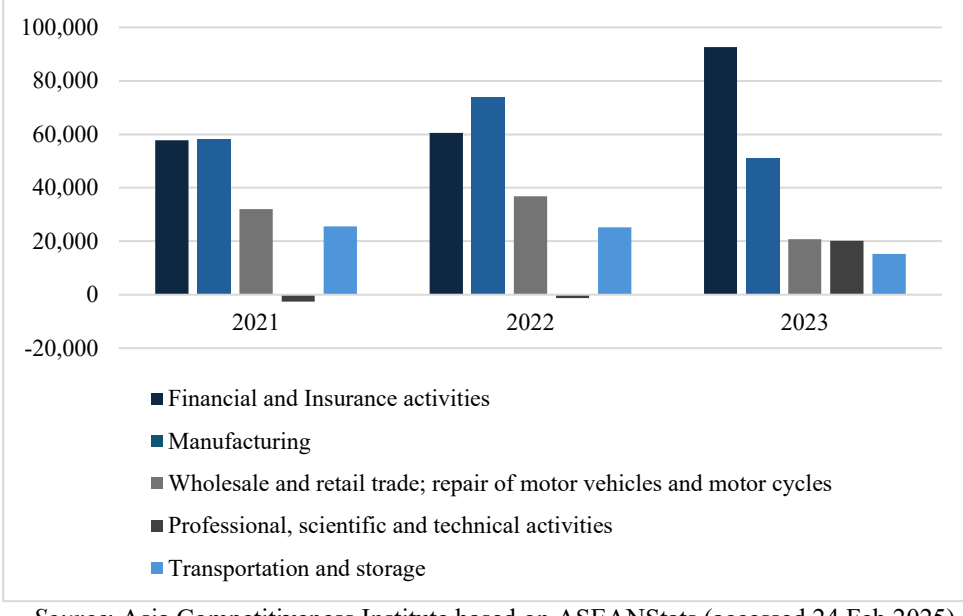
The data presented in Figure 1.1 illustrates the FDI inflows into ASEAN from key source countries between 2021 and 2023. The United States (US), the European Union (EU-27, mainly Netherlands), intra-ASEAN (mainly Singapore), China, Japan, and Hong Kong SAR, were among the primary FDI sources for ASEAN. Notably, FDI inflows from the US saw an extraordinary increase of 148% from 30.2 billion USD in 2022 to USD 75.0 billion in 2023. The growth was mainly driven by the US's FDI to financial and insurance activities, which experienced a 790% growth from 2022 to 2023.[21] Singapore was the most attractive destination for US capital.[22] Investment from China, including mainland China and Hong Kong, also increased but did not keep pace with the growth from the US. China's FDI inflow to the ASEAN region increased by 22.3% from 2022 to 2023 and reached 17.6 billion USD in 2023. Chinese investors have shown strong interest in the manufacturing industry, such as automotive,

[20] See ASEANStats (n.d.a).
[21] Ibid.
[22] See ASEANStats (n.d.b).

electronics, and renewables.[23] Among the 20 industries receiving FDI from China, the manufacturing industry has received the largest amount of FDI inflows from 2021 to 2023.[24]

In contrast, FDI from the EU-27 moderately decreased from 2022 to 2023, by 1.27%. As the EU's largest FDI investor to ASEAN, the Netherlands' FDI inflow decreased by 5.17% over the same period. Although ASEAN's FDI inflow to the region increased by 39.3% from 2021 to 2022, it decreased by 34.2% from 2022 to 2023. The decline between 2022 and 2023 was mainly driven by Singapore, whose FDI flows to ASEAN dropped by 34.0% over the same period.

Figure 1.2: FDI Inflows to ASEAN by Top 5 Industries in millions USD, 2021-2023



Source: Asia Competitiveness Institute based on ASEANStats (accessed 24 Feb 2025)

In terms of destination industries, FDI in the ASEAN region was led by the Financial and Insurance activities in 2023 (Figure 1.2), followed by Manufacturing; Wholesale and Retail Trade; Professional, Scientific and Technical activities; and Transportation and Storage. As shown in Figure 1.2, FDI inflows into Financial and Insurance activities grew steadily from 57.8 billion USD in 2021 to 60.5 billion USD in 2022 and surged significantly to 92.6 billion USD in 2023. The Manufacturing industry experienced some fluctuations in FDI inflow from 2021 to 2023. It saw an increase from 58.1 billion USD in 2021 to 73.7 billion USD in 2022 but experienced a decline to 51.0 billion USD in 2023. In contrast, FDI to Professional, Scientific, and Technical Activities increased from -1.23 billion USD in 2022 to 20.2 billion USD in 2023. This shows that multinational enterprises (MNEs) have rising interests in knowledge-based or high-value-added activities in ASEAN and support the industrial upgrading efforts of some AMS.[25] The growth of FDI in the Professional, Scientific and Technical activities was mainly driven by the US, whose FDI in this industry surged from -854 million USD in 2022 to 13.1

[23] See Association of Southeast Asian Nations (2024).
[24] See ASEANStats (n.d.a).
[25] Ibid.

billion USD in 2023. Most R&D and innovation-related investments were concentrated in Singapore.[26]

Table 1.2: ASEAN Digital Economic Indicators

Country	Internet Users 2023[27] (% Total Population)	Trade of digitally-deliverable service in 2023[28]		Online Retail Sales (billion US$) in 2024	ICT Goods Exports 2022[29] (% Total Goods Exports)	ICT Goods Imports 2022[30] (% Total Goods Imports)
		(Million US$)	% Total Trade in Services			
Brunei	99.0	656	33.1	N/A	0.0	1.5
Cambodia	56.7	861	12.2	N/A	2.5	1.0
Indonesia	69.2	45893	54.2	71.8	2.9	8.5
Laos	66.2	85	9.10	N/A	3.0	3.9
Malaysia	97.7	40718	42.9	10.3	32.2	27.0
Myanmar	44.0	2358	31.5	N/A	0.2	0.8
Philippines	75.2	35641	46.0	25.3	50.7	19.4
Singapore	94.3	349429	56.0	6.9	32.7	31.1
Thailand	89.5	40266	48.3	21.6	16.1	14.3
Vietnam	78.1	7935	19.4	23.2	38.0	29.4

Note: Figures in red are estimates by the EIU; N/A indicates data are not available.

Sources: Euromonitor, UNCTAD, EIU, ITU and The World Bank (accessed 24 March 2025)

A key focus for ASEAN's development remains the advancement of the digital economy. Table 1.2 provides a snapshot of ASEAN's development in the digital economy between 2022 and 2024. The data highlights a great regional digital divide in terms of access, inputs and outputs. In terms of access to the Internet, countries such as Brunei (99.0%), Malaysia (97.7%) and Singapore (94.3%) had most of their population connected to the Internet, while only 44.0% of the population of Myanmar were Internet users. In terms of digitally-deliverable services (DDS) trade, Singapore took the lead with 349 billion USD of DDS trade in 2023, largely ahead of the other AMS, such as Indonesia (45.9 billion USD) and Malaysia (40.7 billion USD), which ranked second and third in the region's DDS trade in 2023 (Table 1.2). Meanwhile, Laos ranked at the bottom of the DDS trade, with its DDS trade value being less than 1% of Singapore's. Similarly, as shown in Table 1.2, while ICT goods exports accounted for more than 30% of the goods exports in the Philippines, Vietnam, Singapore and Malaysia, the numbers were less than 5% in the other

[26] Ibid.
[27] Where available, figures and estimates for 2023 are shown. Where figures for 2023 are absent, figures from 2022 or 2021 are used instead.
[28] Where available, figures for 2023 are shown. Where figures for 2023 are absent, figures from 2018-2022 are used instead.
[29] Where available, figures and estimates for 2022 are shown. Where figures for 2022 are absent, figures from 2021 are used instead.
[30] Where available, figures and estimates for 2022 are shown. Where figures for 2022 are absent, figures from 2021 are used instead.

AMS except for Thailand. These disparities highlight the need for targeted policy interventions to enhance e-government capabilities, strengthen digital infrastructure, and promote greater digital inclusivity across the region. The ASEAN Digital Economy Framework Agreement (DEFA), which is estimated to conclude negotiations in 2025, could offer hope for more inclusive growth and development and allow AMS to ride on the 2 trillion-USD opportunities that emerged from the development of the digital economy by harmonising regulations, enhancing interoperability of standards, and removing barriers to drive digital transformation and economic growth.[31] More discussions on how to boost the digital transformation in AMS will be presented in Chapter 3.

Table 1.3: ASEAN E-Governance Indicators

	UN E-Government Survey 2024				ITU Global Cybersecurity Index 2024
Country	E-Government Index	Online Service Index	Human Capital Index	Telecommunication Infrastructure Index	
Brunei	0.7554	0.5802	0.6991	0.9868	70.38
Cambodia	0.5754	0.4503	0.5149	0.7609	37.02
Indonesia	0.7991	0.8035	0.7293	0.8645	100
Laos	0.4404	0.3265	0.4608	0.5338	33.74
Malaysia	0.8111	0.7280	0.7192	0.9862	98.82
Myanmar	0.5001	0.3259	0.5081	0.6662	73.72
Philippines	0.7621	0.8054	0.7256	0.7554	93.49
Singapore	0.9691	0.9831	0.9362	0.9881	99.86
Thailand	0.8351	0.7611	0.8032	0.9410	99.22
Vietnam	0.7709	0.7081	0.7267	0.8780	99.74

Source: United Nations E-Government Development Database and ITU (accessed 24 Feb 2025)

On top of the disparities in the digital economy, AMS also demonstrated heterogeneity in e-governance, as shown in Table 1.3. While providing better e-government services is one of the key desired outcomes of the ASEAN Digital Masterplan (ADM) 2025,[32] AMS still exhibited a large disparity in e-government services provision in 2024. Regional leaders such as Singapore scored above 90% for all indicators in the table, while those lagging behind, such as Cambodia, Laos, and Myanmar, presented limited achievements in indicators across the board. This poses challenges for enhancing regulatory coherence in digital governance, which is called for in the ASEAN Economic Community (AEC) 2025 agenda[33] and is further highlighted in the ASEAN Digital Masterplan (ADM) 2025.

Table 1.4 presents a snapshot of the prevalence of key types of digital legislation in the region, compiled by UN Trade and Development (2021).[34] It demonstrates a strong recognition of the need for robust regulatory protections to govern the digital economy. These regulations and legislation play a critical role in establishing wider trust in the digital economy to encourage uptake. However, the AMS currently lack a clear consensus on digital governance (Table 1.4),

[31] See Rahardja et al. (2024).
[32] See ASEAN Secretariat. (2021).
[33] Association of Southeast Asian Nations (2025).
[34] See UN Trade and Development (UNCTAD) (2021).

despite the emphasis on oneness in the ASEAN mechanism, and the emphasis of the ASEAN Digital Master Plan on harmonising regulations and standards across ASEAN.[35] This underscores the fact that governing philosophies around specific issues differ widely within ASEAN. It also poses a key challenge to the ASEAN integration agenda, both within the bloc and with external partners.

Table 1.4: State of Digital Legislation in ASEAN

Country	E-Transactions Laws	Consumer Protection Laws	Data Protection & Privacy Laws	Cybercrime Laws
Brunei				
Cambodia				
Indonesia				
Laos				
Malaysia				
Myanmar				
Philippines				
Singapore				
Thailand				
Vietnam				

Legend

Has Legislation

Legislation Drafted

No Legislation

Source: Asia Competitiveness Institute based on UNCTAD (2021) (accessed on 24 March 2025)

[35] Ibid.

1.3 Mapping ASEAN's Position in the Global Solar PV Supply Chain

1.3.1 Introduction

Global commitments to sustainable development and climate change mitigation, such as the UN Sustainable Development Goals (SDG) and the Paris Agreement, have driven nations worldwide to reduce carbon emissions. ASEAN is not an exception. The ten ASEAN member states (AMS) have committed to the Nationally Determined Contributions (NDC), including greenhouse gas reduction targets. The most recent update in the region is that Singapore submitted its second NDC to the United Nations Framework Convention on Climate Change (UNFCCC). It committed to reducing carbon emissions from 58.59 million tons (Mt) of carbon dioxide equivalent (CO2e) in 2022[36] to between 45 and 50 Mt in 2035.[37]

Expanding the adoption of renewable energy is one of the avenues to reduce carbon emissions, address climate change, and achieve sustainability, as stated in the ASEAN Plan of Action for Energy Cooperation (APAEC) 2021-2025.[38] In the plan, ASEAN aims to have 23% renewable energy in its total primary energy supply. The AMS also have specific goals for renewable energy adoption and implementing supporting policy measures to encourage uptake.[39]

Solar photovoltaic (PV) power is and will continue to be one of the most widely adopted renewable energy sources, globally and in ASEAN. Globally, solar PV's share of installed capacity increased from 2.37% in 2013 to 15.7% in 2023.[40] The International Renewable Energy Agency (IRENA) estimated that globally, solar PV will have the largest average annual additional power capacity among all renewable energy from 2024 to 2030.[41] The trend also extends to ASEAN, with solar PV power generation estimated to grow tenfold from 2020 to 2050. The share of solar PV power in the region's total power generation will increase from 2% in 2020 to 24% in 2050 and to be the second largest renewable power source in ASEAN.[42]

The prevalence of solar PV power can also be seen in the AMS's domestic energy policy documents. For example, solar power is regarded as one of the most viable domestic renewable sources to reduce carbon emissions in Singapore. The country plans to accelerate the deployment of solar energy by further investing in research and development (R&D) to improve the efficiency and lower the price of solar technologies and associated systems.[43] In its latest NDC submission to the UNFCCC in 2025, Singapore highlighted that it would maximise its solar power deployment to meet its climate targets, projecting that solar energy will satisfy around 3% of national electricity demand by 2030.[44] Similarly, in February 2025, the Indonesian government announced that it will increase the share of renewable energy in the energy mix from 12% in 2024

[36] See Begum (2025).
[37] See The National Climate Change Secretariat, Singapore (2025).
[38] See APAEC Drafting Committee et al. (2020).
[39] See Huang and Tan (2024).
[40] See International Renewable Energy Agency (IRENA) (2025).
[41] See IRENA, COP28, COP29, GRA, MoEA and Government of Brazil (2024).
[42] See International Energy Agency (IEA) (2022a and 2022b).
[43] See National Environment Agency (2024).
[44] See The National Climate Change Secretariat, Singapore (2025).

to 35% by 2034. Solar power will be a priority among renewables. Indonesia plans to add 17 gigawatts (GW) of solar power capacity, compared to 16 GW of hydro power and 5 GW of geothermal power.[45]

Rising global demand for solar PV power is also reflected in the rising trade value of solar PV cells or modules.[46] Globally, the total trade value of solar PV cells or modules grew by 79.6% from 102 billion US dollar (USD) in 2013 to 182 billion USD in 2022. ASEAN's significance in the global solar PV industry has also grown. ASEAN's total trade value of solar PV cells or modules increased by 187% from 9.39 billion USD to 26.9 billion USD from 2013 to 2022, far outpacing the global growth rate (79.6%). In exports, the region has been the world's second-largest solar PV cell or module exporter after China since 2013, and its share in global exports grew from 12.7% in 2013 to 19.8% in 2022, reflecting its capability to meet the rising global demand for solar PV finished products. Concurrently, ASEAN's import share also increased from 5.82% to 9.27% from 2013 to 2022, highlighting the growing local demand in the region.

Leveraging on its emerging role as a global trading hub of solar PV cells or modules, ASEAN envisions increasing its manufacturing capacities in relevant key inputs along the supply chain. At the regional level, this is highlighted in ASEAN's Carbon Neutrality Strategy. Developing green industries is one of the four key outcomes of the strategy.[47] It was also mentioned in the AMS's renewable energy industrial development strategies. For example, Malaysia saw that the export of solar PV panels will be a major driver of the energy sector's GDP growth between 2013 and 2030[48] and regarded itself as a major international hub for PV components manufacturing.[49] Indonesia expects that with the rising demand for solar modules domestically, there will be a growing incentive for manufacturers of these products to establish production facilities within the country, and it can also grow the market for relevant material manufacturing.[50] The country also secured an 11.5 billion USD investment commitment from a Chinese glass company in 2023 to build an integrated wafer industry.[51]

To advance these regional and national ambitions, ASEAN and AMS need to map their positions within the global solar PV supply chain. Here, ASEAN's "position" refers to both its collective role and the contributions of its AMS to the global share of solar PV cells or modules, and key inputs. To facilitate this mapping, we will deconstruct the global solar PV supply chain, from R&D to the trade of key inputs and finished products. This process will allow us to see the strengths within the supply chain at both regional and national scales.

The study will proceed as follows; Subsection 1.3.2 provides a technical background of a solar PV system and introduces key components of the solar PV supply chain. Subsection 1.3.3 focuses on ASEAN and AMS' global position in solar PV R&D, including international co-invention

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[45] See Spence (2025) and Reuters (2025).
[46] "Solar PV cells or modules" refer to Harmonised System (HS) (2017 version) 6-digit product code "854140". This code covers "Electrical apparatus; photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light-emitting diodes (LED)." But in the 2022 version of HS codes, "854140" is divided into 4 new codes ("854141", "854142", "854143", "854149"). For those countries that have switched to HS 2022, we obtain their trade value of "854140" in 2022 by summing up the trade value of the 4 new codes.
[47] See ASEAN Secretariat (2023).
[48] See Ministry of Energy, Green Technology and Water (KeTTHA) (2017).
[49] See Ministry of Economy, Malaysia (2023).
[50] See Just Energy Transition Partnership Indonesia (JETP) (2023).
[51] See Karyza (2023).

partnerships. Subsection 1.3.4 explores the dynamics of ASEAN's and individual AMS' roles in the trade of solar PV cells or modules and their key inputs, including the raw materials, intermediates, and manufacturing machines. Furthermore, we provide a detailed mapping of ASEAN's major import sources and export destinations for each product. Subsection 1.3.5 synthesises the research findings and concludes that as an exporter, ASEAN's strength in the solar PV supply chain lies in finished products – solar PV cells or modules and one of the key intermediates – polysilicon. As an import market, ASEAN is an important market for wafers and wafer machines.

1.3.2 Technical Structure of a Solar PV System

To explore the global landscape of the solar PV supply chain, it is necessary to first understand a solar PV system's technical structure, including its key components and their functions. A solar PV system primarily consists of two main parts: solar PV cells and the balance of system (BOS) technologies (Figure 1.3). Solar PV cells generate electricity from solar radiation. In this study, we focus specifically on crystalline silicon (c-Si) solar cells, the most prevalent type of solar cells in the global solar PV cell market.[52] The BOS manages the efficient transfer of electricity generated by solar cells to end-users. It comprises of solar panels (also known as solar modules),[53] electronics, energy storage systems, testing and monitoring systems, and portable devices. Solar panels are manufactured by assembling PV cells through a coating, wiring, and encapsulation processes. Electronics protect the system and connect it to the grid. Energy storage stores generated solar power to ensure a stable power supply. Testing systems check the performance of PV products.[54]

The solar PV supply chain in this study spans both technological and trade dimensions. It starts with R&D to establish foundational knowledge, followed by the manufacturing phase for solar PV cells and BOS components. As presented in Figure 1.4, the manufacturing process of solar PV cells commences with acquiring the core raw material, silica sands and quartz sands (hereafter silica sands). Silica sands first undergo a series of purification and other chemical processes and become metallurgical-grade silicon (MGS) and polysilicon. Following this, polysilicon is melted to make ingots, which are then sliced into wafers with wafer manufacturing machines. Wafers are then turned into cells using relevant manufacturing machines.[55]

The production of BOS components also begins with sourcing raw materials, including silica sands, aluminium ores and copper ores. As shown in Figure 1.4, these raw materials first go through refinement processes to become aluminium structures, copper wires and glass. Then, these components are assembled with cells to produce modules. Glass is primarily used in the back sheets as a protective layer for solar modules. Aluminium frameworks provide structural support. Copper wires are essential components in electrical connections.[56]

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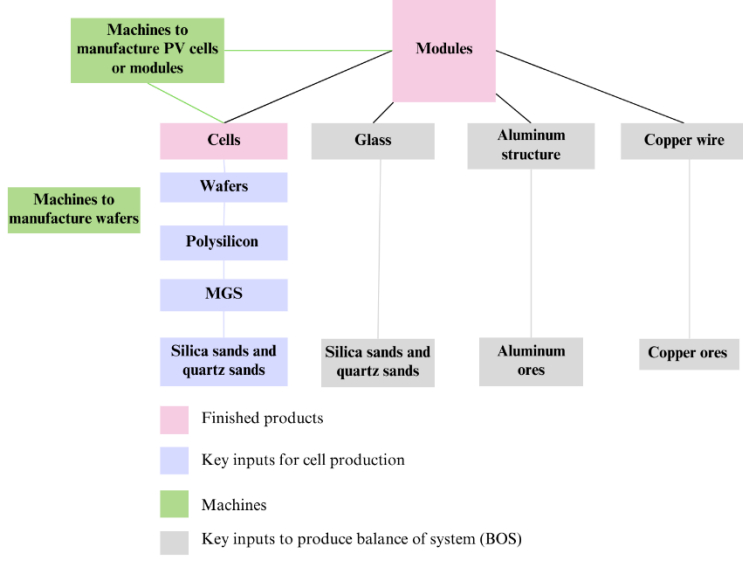
[52] See International Energy Agency (IEA) (2022c).
[53] Since in HS codes descriptions, solar panels are usually described as solar modules, we will use solar modules in the following sections.
[54] See Shubbak (2019).
[55] See Shubbak (2019); Osenius-Eite, Mirrlees-Black, and Scott (2023); International Energy Agency (IEA) (2022c and 2024); Carrara et al. (2020); InfoLink Consulting 2024a and 2024b)
[56] Ibid.

Figure 1.3: The Overview of a Solar PV Technical System

Source: ACI's recreation based on Shubbak (2019).

Figure 1.4: Key Inputs for Manufacturing Solar PV Cells and Modules



Source: ACI based on Osenius-Eite (2023), IEA (2022) and IEA (2024). [57]

In this study, we will only focus on the trade of three groups of products specific to cell production (Figure 1.4): (1) finished products, namely solar PV cells or modules (pink boxes in

[57] See Osenius-Eite, Mirrlees-Black, and Scott (2023) and International Energy Agency (IEA) (2022c and 2024).

the diagram); (2) wafers and key inputs to produce wafers (purple boxes), including raw materials (silica sands) and intermediates (polysilicon); (3) manufacturing machines used for producing cells or modules, and those for wafers (green boxes).

1.3.3 R&D

R&D capability is fundamental to solar PV manufacturing as it enhances system efficiency, reduces costs, and drives next-generation innovations to maintain market leadership.[58] ASEAN recognises these advantages, viewing renewable technologies as key to expanding clean energy access, and improving affordability—critical to its regional energy goals. Additionally, stronger R&D capacity can attract greater foreign investment in the sector. To advance these objectives, ASEAN aims to enhance its renewable energy R&D capabilities, as evidenced by two strategies of the Renewable Energy programme in the APAEC 2021-2025: enhancing the renewable energy R&D network and promoting renewable energy financing schemes and mechanisms for greater innovation and partnership.[59]

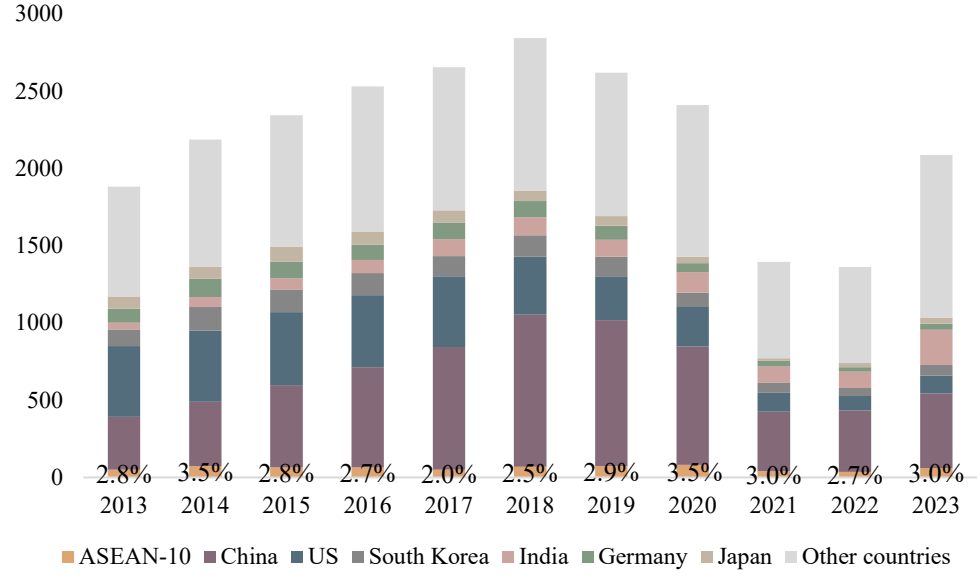
In this subsection, ASEAN's and AMS's performance in R&D is measured by two indicators. The first indicator is the ownership of high-quality research articles. This refers to articles with citation counts ranking in the top 10% of all papers published in the Web of Science Core Collection database for a given year.[60] This metric provides insight into emerging trends of frontier advancements in solar PV. The second indicator is based on patents, reflecting the capability to commercialise the knowledge in practice.

1.3.3.1 High-quality Papers

In 2013 and 2014, the United States (US) published the largest number of high-quality solar PV papers in the world (Figure 1.5), accounting for 25.0 % of the world's total in 2013 and 21.7% in 2014. Since 2015, China has surpassed the US to be the global leader in high-quality solar PV research papers, with its global share rising from 23.4% in 2015 to a peak of 37.1% in 2019 before dropping to 23.8% in 2023. The US further dropped to third place in 2022 and 2023, replaced by India (Figure 1.5). India caught up rapidly over the past decade. On average, the number of high-quality papers from India increased by 22.1% annually between 2013 and 2023, with a particularly notable jump from 107 to 228 between 2022 and 2023. As a result, India's share of global high-quality solar PV papers rose from 2% in 2013 to 11% in 2023.

[58] See Che, Zhou, and Chai (2022) and International Renewable Energy Agency (IRENA) (2019).
[59] See APAEC Drafting Committee et al. (2020).
[60] See Leung, Robin, and Cave (2024).

Figure 1.5: Annual Publications of High-Quality Solar PV Papers by Region, 2013-2023



Note: The data labels in the chart show ASEAN's share in the global total in the year.

Source: ACI based on Australian Strategic Policy Institute: *ASPI's Two-decade Critical Technology Tracker: The rewards of long-term research investment*

ASEAN has maintained a stable global share of the world's total high-quality papers on solar PV, around 2.85% from 2013 to 2023 (Figure 1.5). Its ranking stabilised between fifth and seventh in the world over the decade. However, the region's number of high-quality solar PV papers fluctuated over time, with a downward trend from 74.1 in 2014 to 50.6 in 2017 but bouncing back with 68.7 high-quality PV publications in 2018, and further up to 82.2 in 2020 (Figure 1.6). Yet, there was a sharp decline in 2021 and 2022, with the number of publications in both years dropping to just half of those in 2020.

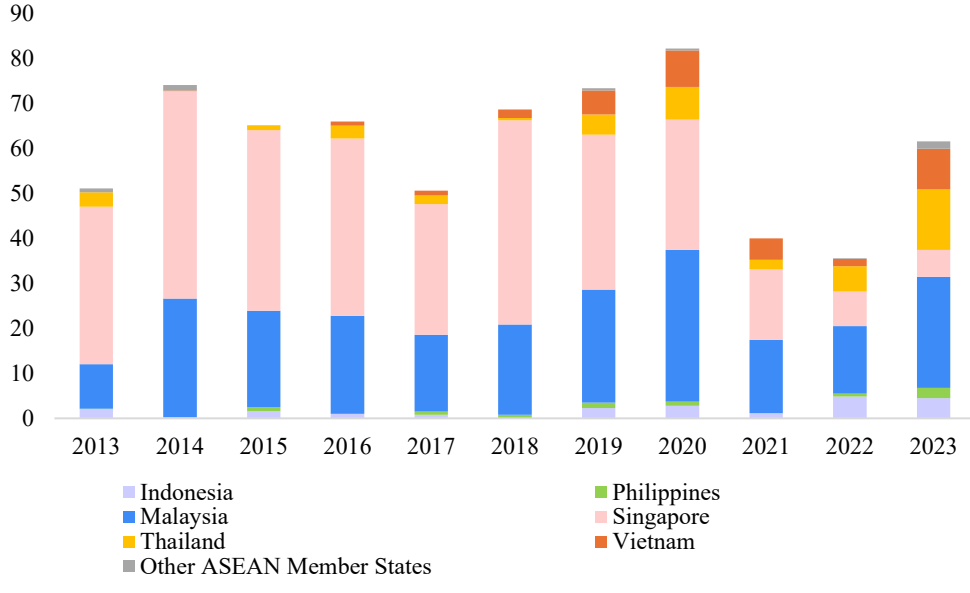
Figure 1.6 shows that the largest number of high-quality solar PV papers within ASEAN were contributed by Singapore and Malaysia, with Malaysia climbing up and surpassing Singapore from 2020. From 2020 to 2023, while Malaysia's global share stayed at approximately 1%, Singapore's share declined from 1.16% to 0.30%. Malaysia's strong performance can be attributed to long-standing government support for renewable technology development. The National Green Technology Policy in 2009 was its initial step to enhance the country's capability and capacity to develop green technology, facilitating its growth and enhancing its contribution to the national economy. To achieve these goals, the policy introduced financial and fiscal incentives for students majoring in green technology, along with funding for R&D and the commercialisation of green technologies in both the public and private sectors.[61] Building on this foundation, the Green Technology Masterplan 2017-2030 further strengthened cooperation

[61] See Ministry of Energy, Green Technology and Water (KeTTHA), Malaysia (2009).

between the Ministry of Energy, Green Technology and Water;[62] research institutes; and the private sector, to develop localised renewable technology, including solar PV. Improving the efficiency of solar PV modules is one of the prominent pillars in Malaysia's technological innovation strategy for decarbonisation, aligning with the goals of the Malaysia Renewable Energy Roadmap launched in 2021.[63]

Following Singapore and Malaysia, Thailand and Vietnam ranked third and fourth, respectively, in publishing high-quality PV papers (Figure 1.6). They were also the countries with the largest PV installed capacity in the region.[64] Interestingly, the Philippines, despite having the fourth-largest PV installed capacity in 2023, demonstrated weakness in publishing high-quality research papers, as shown in Figure 1.6.

Figure 1.6: Annual Publications of High-Quality Solar PV Papers by ASEAN Member State, 2013-2023



Source: ACI's calculations based on *ASPI's Two-decade Critical Technology Tracker: The rewards of long-term research investment*

1.3.3.2 Patents

The patent data used in this study is sourced from the PATSTAT database (2022 Autumn Version),[65] one of the most comprehensive databases of patent applications with bibliographical information. Notably, PATSTAT records the International Patent Classification (IPC) codes, which are commonly used by patent examiners to determine a patent's technical classes.

[62] The ministry was restructured and renamed as Ministry of Science, Technology and Innovation in 2020. See Official Portal, Ministry of science, technology and innovation, Malaysia. (n.d.)
[63] See Sustainable Energy Development Authority (SEDA) Malaysia (2021).
[64] See International Renewable Energy Agency (IRENA) (2024).
[65] See EPO (n.d.).

According to the literature, the choice of solar PV-related IPC codes varies depending on the definition of the supply chain.[66] But there are certain groups of technologies that are frequently mentioned, including photovoltaic energy generation (H02S), electric power distribution/storage systems (H02J), and semiconductor devices (H02L),[67] which we have incorporated in our selection (see Appendix 2). With these codes, we are able to obtain a collection of patents belonging to solar PV technologies. However, technologies for the refinement and purification processes from ores to compounds are not included.

To make patent indicators comparable across countries, patent families—rather than individual patents—are often used as measurement units for inventions to avoid double counting the R&D outputs. A patent family is a collection of all patent applications covering the same invention.[68]

Since patent protection is territorial, to seek international protection for the same invention, multiple patent applications are filed in different jurisdictions, likely at different times. To approximate the invention's completion date, we use the priority year, the year when the first patent application of each patent family, is filed.[69] In this study, we selected patent families with the earliest filing years from 2010 to 2020.[70]

To assess a country's invention performance, we count the number of patent families based on the inventor's country of residence.[71] Where inventor country information is missing, we impute data from other equivalent applications within the same patent family to construct a more complete picture of the geographical distribution of solar PV patent activities.[72]

1.3.3.2.1 Invention Activities

The stock of solar PV patent families invented by different regions in 2010 vs 2020 is plotted in Figure 1.7. The bar in 2010 is the number of patent families invented in the year, representing the initial invention capability of each region. Meanwhile, the 2020 bar is the cumulative number of patent families from 2010 to 2020. Comparing the two bars informs us of the region's progress over the years.

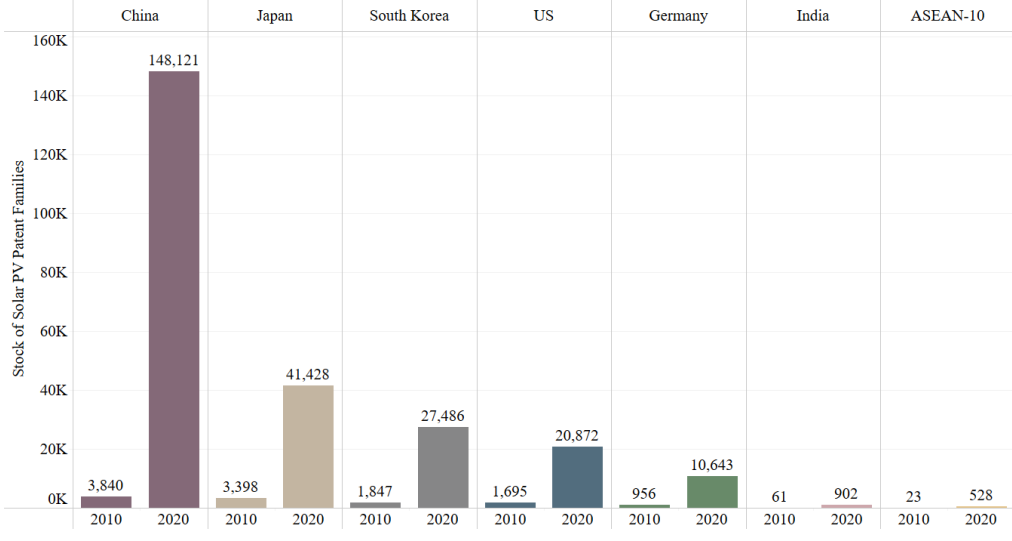
China has maintained its position as the undisputed global leader in solar PV patent invention, mirroring its exceptional performance in paper publication in the field. From 2010 to 2020, China experienced a 39-fold surge in solar PV patent families, contributing to 50.9% of the total number

[66] See Caravella et al. (2024).
[67] See Shubbak (2019), Trappey et al. (2019) and United States Patent and Trademark Office (n.d.b).
[68] See OECD (2009).
[69] While there are multiple types of patent families with varying scope and composition, in this study, we use DOCDB simple patent family. All members of a simple patent family will have exactly the same priorities.
[70] Patent applications are published between 18 and 30 months after they are filed. And PATSTAT only includes published patent applications. This makes statistics based on the date of the earliest filing have on average, a 3.5-year lag. Considering this delay, we set the end of the observation period as the year 2020 to ensure better data coverage.
[71] In the case when a patent family is invented by multiple inventors from the same country, each country will be counted once. When a patent family involves multiple inventors from different countries, to capture the internationalization of inventive activities regardless of each country's contribution, we apply whole counting so that each country is equally credited with one patent family. For example, a patent family invented by a resident in Singapore and a resident in Malaysia will be counted once for each country.
[72] See de Rassenfosse and Seliger (2021) and Ge, Xie, and Zhang (2022).

of patent families globally. Japan, another major innovator, saw a 12-fold growth during the period. Its residents contributed to 14.2% of the global stock of solar PV patent families. Other countries with a sizable stock of solar PV patent families in 2020 include South Korea, the US and Germany, although none secured a global share higher than 10%.

As for ASEAN, there were only a total of 23 patent families invented by the regional residents in 2010, representing 0.15% of the patent families globally. By the end of 2020, ASEAN had accumulated a stock of 528 patent families, which is a commendable 23-fold progress. However, this stock accounted for a mere 0.18% of all solar PV patent families with a priority year between 2010 and 2020.

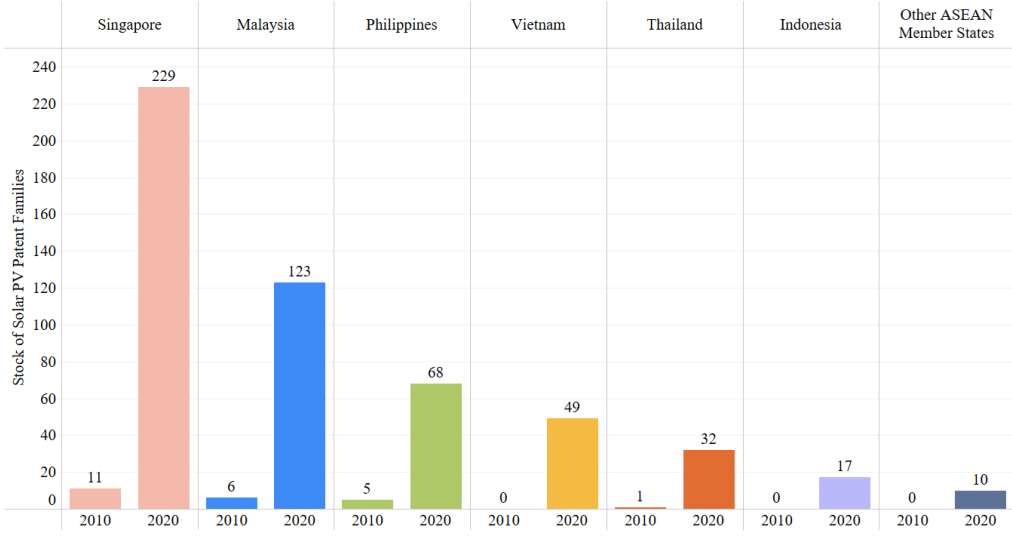
Figure 1.7: The Stock of Solar PV Patent Families by Inventor Country, 2010 vs 2020



Source: ACI's calculations based on PATSTAT 2022 Autumn Version

Delving into the AMS, Figure 1.8 shows that only residents in Singapore, Malaysia, the Philippines and Thailand filed patent applications in 2010. Among them, Singapore and Malaysia were the largest contributors, similar to the situations in publishing high-quality papers. The two countries collectively had 352 patent families and accounted for 66.7% of the ASEAN-invented patent families from 2010 to 2020. The Philippines followed with 68 patent families, contributing to 12.9% of ASEAN's solar PV patent families over the period. Inventors based in other AMS, especially Vietnam, had made noticeable improvements. Although none was attributable to Vietnam in 2010, by 2020, the country had accumulated 49 solar PV patent families, which represented 9.28% of the total number of patent families attributed to ASEAN between 2010 and 2020.

Figure 1.8: The Stock of Solar PV Patent Families Invented by ASEAN Residents, 2010 vs 2020



Note: Other ASEAN Member States include Brunei, Laos, and Cambodia. Myanmar had no patents during the 2010-2020 period.

Source: ACI's calculations based on PATSTAT 2022 Autumn Version

1.3.3.2.2 International Collaboration

Beyond invention activities, we gauged AMS' engagement in the global R&D network by examining patent families with international collaboration—defined as those with at least one inventor based in a foreign country. We refer to these as co-inventions. To quantify the intensity and geographic reach of ASEAN's international collaboration, we introduce two metrics, co-invention rate and co-invention diversity. Co-invention rate is the proportion of a country's total number of co-inventions relative to its entire stock of patent families from 2010 to 2020.[73] Co-invention diversity is obtained by counting the number of unique countries that a country collaborates with in co-inventions, regardless of the number of co-inventors from each country.

As Table 1.5 shows, Singapore owned 93 co-invented solar PV patent families, which was the largest number within the region. Notably, Singapore had the broadest collaboration network among all AMS, including collaborators from 21 other foreign countries. Germany, the US and China constituted 24.8%, 21.8%, and 10.9% of Singapore's co-invention portfolio, respectively. Following Singapore is Malaysia, with 53 co-inventions and a co-invention rate of 43.1%, similar to Singapore. But its collaborators only include 8 economies, primarily represented by the US (35.1%) and Chinese Taipei (33.3%). Vietnam had the third-largest number of co-inventions and the highest co-invention rate among the four leading ASEAN innovators listed in Table 1.5. South Korea, as Vietnam's most important partner in solar PV inventions, was engaged in over 77.1% of Vietnam's co-inventions. Lastly, although the Philippines had the third-largest stock of patent families between 2010 and 2020, it only had 10 co-inventions, with a co-invention rate of 14.7%, indicating a tendency for domestic collaboration rather than international partnerships.

[73] See Haščič, Silva, and Johnstone (2015).

Table 1.5: International Collaboration of Major ASEAN Innovators in Solar PV Technologies (2010-2020)

Country	Co-invention Count	Co-invention Rate	Co-invention Diversity
Singapore	93	40.6%	21
Malaysia	53	43.1%	8
Vietnam	42	85.7%	7
Philippines	10	14.7%	3

Source: ACI's calculations based on PATSTAT 2022 Autumn Version

1.3.3.3 Summary of ASEAN's Solar PV R&D Performance

ASEAN's performance in solar PV R&D has shown room for improvement. The region maintained a stable global share of high-quality solar PV papers from 2013 to 2023. Within ASEAN, Singapore and Malaysia have been the primary contributors to high-quality solar PV papers. However, Malaysia overtook Singapore in 2020. This shift can be attributed to its sustained support for renewable technology development, which aims to provide financial incentives for education and foster public-private sector collaboration. Thailand and Vietnam were the third and fourth-ranked AMS in this domain.

Regarding patenting activities, during the 2010-2020 period, the stock of solar PV patent families by ASEAN-based inventors only represented a modest global share. Nevertheless, ASEAN's progress had been remarkable, as evidenced by its 23 times expansion within the decade. Singapore and Malaysia again led the region. The Philippines, despite lagging behind Thailand and Vietnam in paper publication, secured the third-largest stock of solar PV patent families among the AMS.

The extent of international collaboration in solar PV technology development varied among the AMS. Singapore exhibited the largest co-invention counts and demonstrated the broadest collaboration network, engaging with 21 foreign countries. Although Malaysia showed a comparable co-invention rate to Singapore, its collaboration network was more limited in scope. Vietnam, among the leading ASEAN innovators, showed the highest co-invention rate, with South Korea emerging as its principal partner in these endeavours.

1.3.4 Trade in Solar PV Cells or Modules and Key Inputs

Building upon our analysis of R&D outputs, we now turn our attention to ASEAN's and AMS's trade performance across three key product categories in the solar PV industry. Existing studies have identified a wide range of goods and their corresponding 6-digit Harmonised System (HS) codes for analysing the global trade of solar PV-related products.[74] This study selects six products and uses the 2017 version of HS codes (hereafter as HS 2017). Among them, polysilicon (280461), wafers (381800), and solar PV cells or modules (854140) are primary components

[74] See World Trade Organization & IRENA (2021); Caravella, Crespi, Cucignatto, & Guarascio (2024); IEA (2024); UN Trade and Development (UNCTAD) (2024a).

frequently examined in the literature.[75] Further, since silica sands and quartz sands serve as the raw material for polysilicon, we search for their HS 2017 code (250510) in the classification documents from the World Customs Organization.[76] Lastly, to complete the supply chain mapping, we also include machines, namely, machines to manufacture solar PV cells or modules (848620), and machines to manufacture wafers (848610).[77] Using these 6-digit HS 2017 codes, we source bilateral trade data between 2013 and 2022 from the UN Comtrade database. A detailed list of HS codes and their descriptions is provided in Appendix 3.

There are two key limitations of using the 6-digit HS 2017 classification. First, there is a lack of granular data that allows for isolating trade values specifically related to the solar PV industry. This is because products classified under the HS 2017 code are often used across multiple industries, and the codes do not differentiate by end use. For example, while MGS can be processed into polysilicon for solar wafers, it can also be used in semiconductors, silicones, silanes, and aluminum alloys.[78] As a result, the reported trade values for solar PV-related products in this study are overestimated and should be interpreted with caution.

The second issue pertains to the identification of solar PV cells and modules. Despite being technically different, these two products share the same HS 2017 code, "854140", which covers "electrical apparatus; photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light-emitting diodes (LED)." However, as a result of the HS classification amendment in 2022, "854140" has been substituted with four new codes, including "854141" (Light-emitting diodes (LED)), "854142" (Photovoltaic cells not assembled in modules or made up into panels), "854143" (Photovoltaic cells assembled in modules or made up into panels), and "854149" (Other).[79] Since this study aims to monitor the changes in ASEAN's trade of solar PV products since 2013, we used "854140" to ensure consistency. For countries reported their trade value in 2022 under HS 2022, we computed their trade value of "854140" by summing up the trade value under the four new codes.

The remaining subsections are organised as follows. Subsection 1.3.4.1 focuses on the trade in finished goods, specifically solar PV cells or modules. 1.3.4.2 goes one step back to wafers and the key materials used in wafer production. Besides intermediates, machines are also indispensable inputs, as we shall discuss in 1.3.4.3. For each product, we will first outline the major global exporters and importers, highlighting ASEAN's collective position in the global market. Then, we will delve into the individual AMS to identify regional trade leaders as well as their primary trading partners. Finally, in 1.3.4.4, we will provide an overview of ASEAN's role in the global solar PV supply chain based on the key findings from trade.

1.3.4.1 Solar PV Cells or Modules

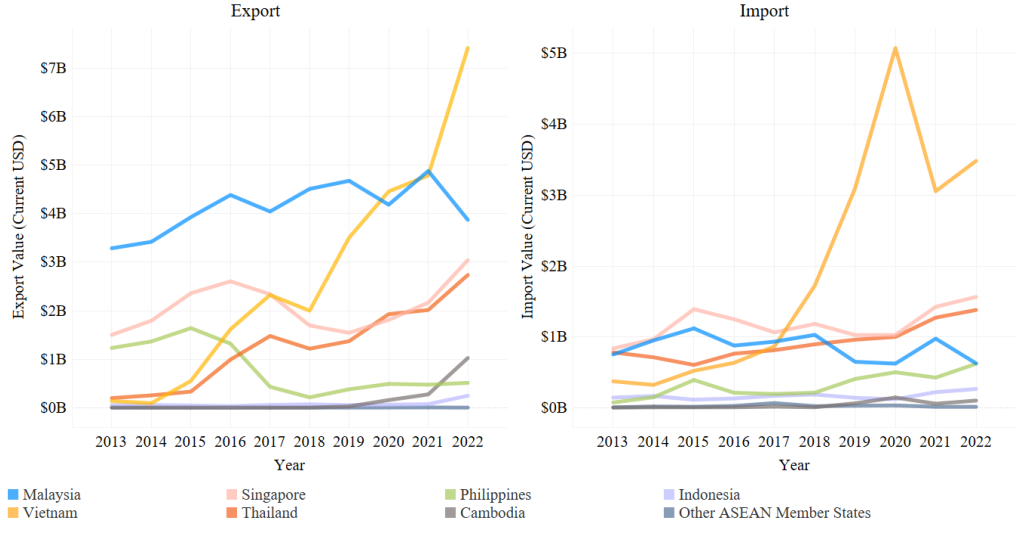
Throughout the period from 2013 to 2022, China maintained its dominance in solar PV cell and module exports globally. China's exports were valued at 15.8 billion USD in 2013, accounting for over 31.3% of global exports. By 2022, China had further enhanced its position as the top

[75] See Caravella, Crespi, Cucignatto, & Guarascio (2024); IEA (2024); UN Trade and Development (UNCTAD) (2024a)
[76] See World Customs Organization (n.d.a).
[77] See World Trade Organization & IRENA (2021); Caravella, Crespi, Cucignatto, & Guarascio (2024).
[78] See Basore & Feldman (2022).
[79] See Joint Research Centre (2023); World Customs Organization (n.d.b)

exporter globally. Its export values grew by 222% to 50.8 billion USD, and its market share expanded to 53.3%. ASEAN consistently held its position as the world's second-largest exporter during this period. Exports of solar PV cells or modules by all the AMS combined rose from 6.41 billion USD in 2013 to 18.9 billion USD in 2022, albeit at a lower growth rate (194%) compared to China. This corresponds to a modest increase in global share from 12.7% to 19.8%.

In terms of imports, China, once the top importer, experienced a negligible 1.64% growth rate from 2013 to 2022. In contrast, the US, another significant importer, saw more fluctuations in its import values. It replaced China to become the largest importer worldwide in 2016 with a total import value of 10.9 billion USD. After a brief decline to 5.60 billion USD in 2018, US imports rebounded to 13.2 billion USD by 2022, representing the highest share (15.1%) of global imports. Overall. ASEAN's collective imports demonstrated an upward trend. Its growth rate between 2013 and 2022 was 170%, which was higher than that of the US (127%). Regarding market share, however, imports by ASEAN only saw a modest increase from 5.82% in 2013 to 9.27% in 2022, still trailing behind the US (15.1%) and China (10.5%).

Figure 1.9: Trade Value of Solar PV Cells or Modules by ASEAN Member State, 2013-2022



Note: Other ASEAN Member States include Brunei, Laos and Myanmar. However, the trade data of Laos is only until 2021. This applies to all figures in subsection 1.3.4.

Source: ACI's calculations based on UN Comtrade

To further examine the evolution of the AMS' export performance, Figure 1.9 illustrates the changes across the 2013-2022 period. As the graph on the left in Figure 1.9 reveals, in earlier years, Malaysia, whose exports gradually climbed from 3.29 billion USD in 2013 to 4.68 billion USD in 2019, maintained its position as the largest ASEAN exporter. However, its exports contracted in 2020 and again in 2022, paving the way for Vietnam to take the lead. Vietnam, initially a minor player, saw a staggering growth rate of 5386% within less than a decade. Its exports surged from a mere 0.135 billion USD in 2013 to 7.42 billion USD in 2022. Its rapid expansion persisted almost every year, except for slight declines in 2014 and 2018.

By 2022, Vietnam and Malaysia had contributed 39.4% and 20.6%, respectively, to ASEAN's total exports of solar PV cells or modules, solidifying their roles as the region's key exporters. On a global scale, Vietnam and Malaysia became the second and third largest global exporters in 2022, with 7.78% and 4.06% of the market share, underscoring ASEAN's enhanced presence in the international market.

While Malaysia and Vietnam led in total export value, Singapore and Thailand also played key roles in ASEAN's solar PV trade. Singapore, the second-largest exporter among the AMS in 2013, reached its first peak in 2016 with exports of 2.61 billion USD, occupying 4.90% of the global share. Despite consecutive declines from 2016 to 2019, Singapore's exports rebounded to 3.04 billion USD in 2022, ranking third among the AMS. Thailand followed closely with an export value of 2.74 billion USD in 2022. Furthermore, although Thailand started at a low level in 2013, similar to Vietnam, its exports grew by 1290% by 2022. Globally, Singapore and Thailand ranked seventh and ninth, respectively, in solar PV cells or modules' export value.

In contrast to the expanding exports of the aforementioned AMS, the Philippines's exports experienced a prolonged decline, shrinking from a peak of 1.64 billion USD in 2015 to merely 0.212 billion USD in 2018. Since then, the country's exports stabilised at around 0.463 billion USD until it was surpassed by Cambodia (1.02 billion USD) in 2022.

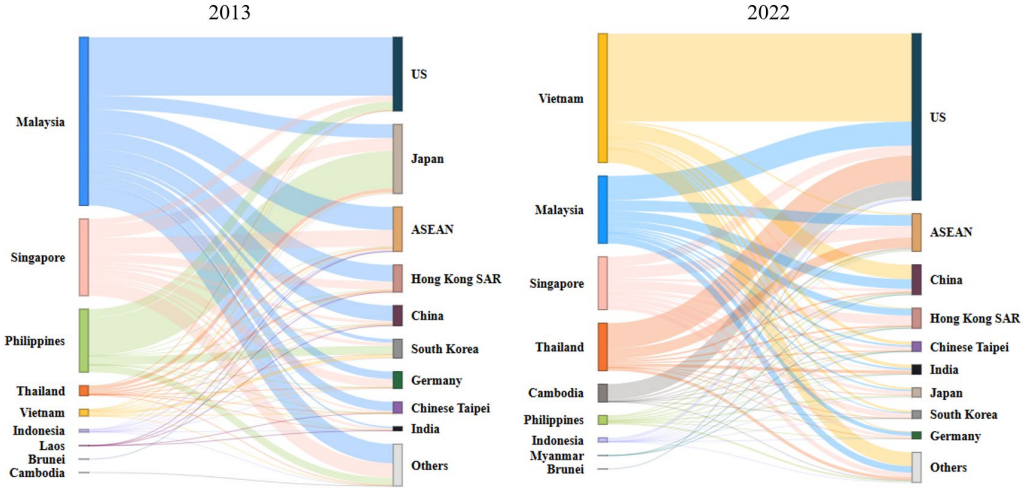
While several AMS rank among the global top 10 exporters, Vietnam was the only country with a significant import share of solar PV cells or modules worldwide. As shown in the graph on the right in Figure 1.9, Vietnam's imports grew exponentially from 2014 to 2020. Its import value skyrocketed from 0.324 billion USD to 5.07 billion USD, marking an average annual growth rate of 60.3%. In 2020, the country became the third largest importer globally (8.65%), following the US (17.9%) and China (12.4%). Although its import value plummeted to 3.05 billion USD in 2021, Vietnam still ranked 9th among all importers in the world. In 2022, it reversed the decline and grew imports back to 3.48 billion USD, which represented 4.00% of the global share.

The growth of Vietnam's imports of solar PV cells or modules reflects its heightened domestic demand for solar PV installation, driven by two generous feed-in tariffs (FiT) schemes. The first FiT framework took off in 2017, followed by the second round in 2019, under which solar PV electricity generation projects that entered commercial operation by 31 December 2020 were eligible for purchasing energy at an above-market rate fixed for over the next 20 years.[80] Despite domestic installation slowing down as the FiT incentive was phased out in 2021, Vietnam remained ASEAN's top and the world's eighth-largest importer, potentially indicating ongoing development and market demand in the solar PV industry.

To further examine the bilateral trade of solar PV cells or modules between each AMS and its trading partners, Sankey charts are employed to illustrate the composition of export markets and import destinations. Each chart consists of two panels, depicting trade flows in 2013 and 2022, with exporters displayed on the left and importers on the right. For instance, in Figure 1.10, when visualising the export flows from the AMS to the rest of the world, AMS exporters are located on the left-hand side, while their corresponding export destinations are placed on the right-hand side.

[80] See Do et al. (2021).

Figure 1.10: ASEAN Member States' Exports of Solar PV Cells or Modules, Share by Exporter and Destination, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

In 2013, the US and Japan were the two largest export markets of ASEAN's solar PV cells or modules, accounting for 22.5% and 21.1% of ASEAN's total exports. The US absorbed 34.7% of Malaysia's exports, while Japan received 59.6% of the Philippines' exports. Despite being the world's top importer of solar PV cells or modules at that time, China only represented 6.15% of ASEAN's total exports. Notably, intra-ASEAN trade represented 13.6% of the region's total exports this year. Among these regional flows, Malaysia's and Singapore's exports to other AMS amounted to 88.6% of the total value. Within the region, Malaysia's largest export destination was Singapore. For Singapore, Thailand was the top AMS export market in 2013.

By 2022, the trade landscape had changed significantly. Japan's presence in the ASEAN market diminished, leading to a noticeable contraction in the Philippines' exports. The share of intra-ASEAN trade also slightly decreased to 11.5%. Conversely, ASEAN's exports to the US grew by 565%, resulting in an increase of 28.3 percentage points in the US's share. At the AMS level, the US remained the largest export market for Malaysia since 2013. Furthermore, in 2022, the US also became the top buyer for other leading AMS exporters, like Vietnam, Singapore and Thailand.

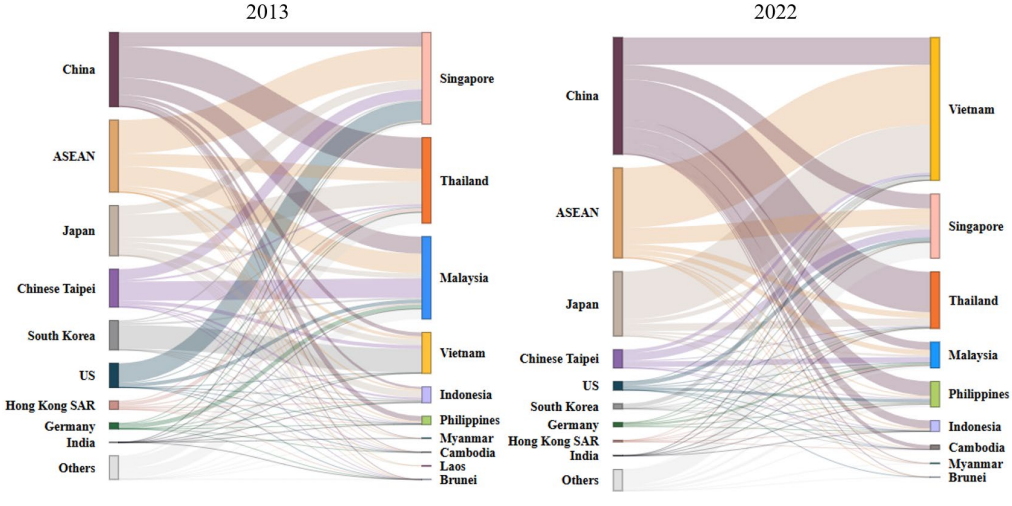
Vietnam's export growth to the US was particularly remarkable. From 2013 to 2022, Vietnam's exports to the US skyrocketed by almost 4 thousand times, while its exports to all other countries combined only had a 16.7-fold increase. This surge in Vietnam's exports predominantly contributed to its enhanced position in the global trade of solar PV cells or modules.

Regarding imports, as Figure 1.11 shows, ASEAN's top three import sources in both 2013 and 2022 were China, intra-ASEAN trade, and Japan, with each of them increasing their share relative to ASEAN's total imports. The most noticeable expansion came from China, whose proportion rose from 22.7% in 2013 to 35.3% in 2022, while intra-ASEAN and Japanese imports each increased by approximately 5 percentage points. By 2022, these three regions collectively supplied 82% of the solar PV cells or modules imported by this region.

Despite this overall trend, the AMS relied on imports of solar PV cells or modules from China to varying degrees. Among the top four ASEAN importers, Thailand exhibited the highest dependence throughout the period, with China's share in Thailand's imports nearly doubling from 36.4% in 2013 to 71.6% in 2022.

Meanwhile, Vietnam used to source mostly from South Korea. In 2013, solar PV cells or modules from South Korea dominated Vietnam's imports with a 57.6% share, while China captured only 9.48%. However, an interesting pattern emerged between 2017 and 2020, when Vietnam's FiT policies spurred a massive expansion of solar PV installations. Our study reveals that it was China's supplies that fuelled Vietnam's drastic import surge. When Vietnam's total imports of solar PV cells or modules peaked in 2020, 66.6% of these products were sourced from China. After 2020, when Vietnam's import growth slowed down, China's share decreased. In 2022, China accounted for 19.1% of Vietnam's imports. Intra-ASEAN trade (41.8%) and Japan (33.5%) had emerged as Vietnam's top two import sources. Furthermore, we found that Vietnam's rising imports from AMS suppliers, particularly Thailand, Malaysia and Cambodia, were key contributors to the growth of intra-ASEAN trade in solar PV cells or modules.

Figure 1.11: ASEAN Member States' Imports of Solar PV Cells or Modules, Share by Importer and Source, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

1.3.4.2 Wafers and Key Inputs

In 1.3.4.1, we highlighted that ASEAN is the world's second largest exporter of solar PV cells or modules and that Malaysia, Vietnam, Thailand and Singapore have emerged as ASEAN's major exporters and importers of solar PV cells or modules in recent years. As shown in Figure 1.4, wafers are a critical input in the cells' upstream production processes. Building on this, in 1.3.4.2, we "trace back" the trade analysis by examining the global position of ASEAN and AMS within the wafers segment, including the essential materials for manufacturing wafers. Specifically, 1.3.4.2.1 focuses on wafers; 1.3.4.2.2 explores the intermediate stage—polysilicon; and 1.3.4.2.3 addresses the raw materials, silica sands and quartz sands.

1.3.4.2.1 Wafers

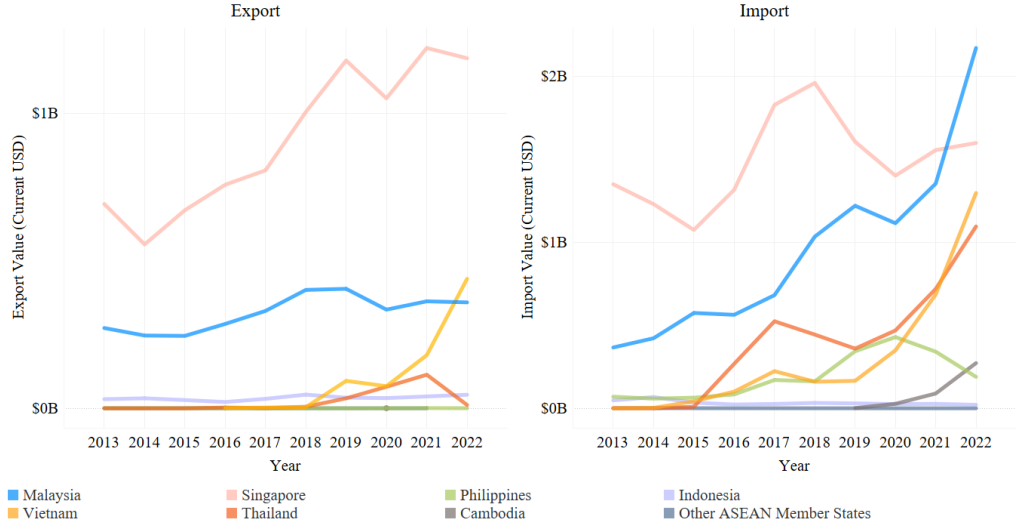
The major global wafer exporters from 2013 to 2016 were China, Japan and Chinese Taipei, collectively occupying around half of global wafer exports over the period. Since 2017, ASEAN has emerged as a significant competitor, replacing Chinese Taipei to rank third from 2017 to 2022. ASEAN collectively exported 2.04 billion USD worth of wafers in 2022, reflecting a 105% growth from 2013—comparable to the global growth rate (102%). This allowed its global share to stabilise at around 10.0%.

On the import side, Chinese Taipei was the world's largest wafer importer from 2013 to 2016, but it was overtaken by ASEAN in 2017. Since then, Chinese Taipei has ranked second globally, whose global share dropped from 24.9% in 2013 to 16.3% in 2022. In contrast, China's share in global wafer imports rose from 10.4% in 2013 to a stable level of around14.1% in 2020, making it the third largest importer. ASEAN's wafer import value grew by 262% from 2013 to 2022 and reached 6.64 billion USD in 2022. This growth was far ahead of the global rate, which was 102%. As a result, ASEAN's share in global wafer imports grew from 16.4% in 2013 to 29.4% in 2022, positioning the region as the world's largest wafer importer in 2022.

The breakdown of exports within ASEAN, as shown in the graph on the left in Figure 1.12, shows that Singapore, Vietnam and Malaysia were the major regional exporters, accounting for 5.82%, 2.15% and 1.76% of the global exports, respectively, in 2022. Among them, Vietnam demonstrated the most remarkable growth, with its global share rising from 0% in 2013 to 2.15% (valued at 400 million USD) in 2022. In comparison, throughout that period, Singapore and Malaysia's global share stabilised at around 6.67% and 2.41%, respectively.

In Figure 1.12, the graph on the right charts the import values of the AMS. Singapore was the largest importer from 2013 to 2021, but it was replaced by Malaysia in 2022. Singapore's global share in wafer imports declined from 12.1% to 7.06%, dropping from global third to sixth. In comparison, Malaysia grew from the global eighth to fourth, with its share rising from 3.27% to 9.59% from 2013 to 2022. Vietnam recorded the largest growth among all regional importers, surging from 46,831 in 2013 to 1.30 billion USD in 2022. This remarkable improvement propelled Vietnam to become the region's third-largest importer in 2022. Its global share increased from 0% to 5.73% over the same period.

Figure 1.12: Trade Value of Wafers by ASEAN Member State, 2013-2022



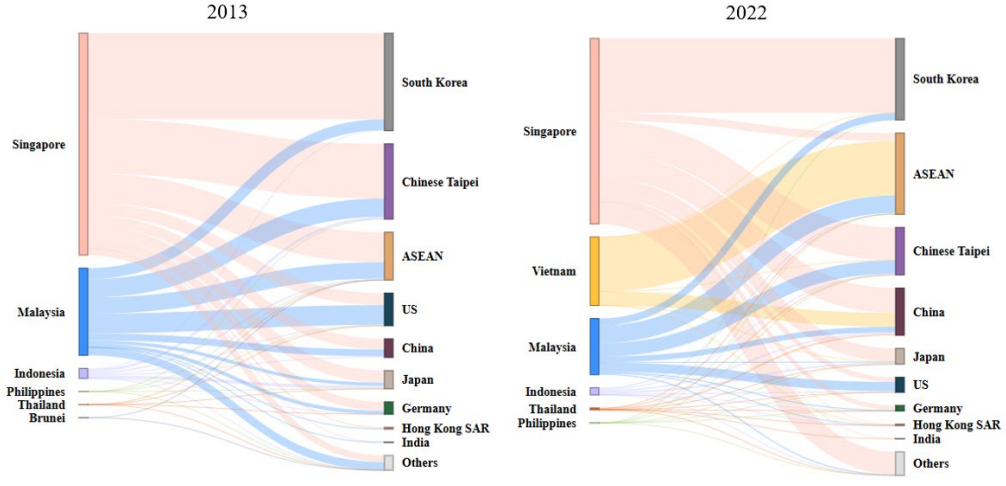
Source: ACI's calculations based on UN Comtrade

ASEAN's wafer trade dynamics among member states closely mirror the patterns observed in solar cell or module exports. Notably, the region's top three exporters and importers of solar PV cells or modules were also the leading importers and exporters of wafers.

In terms of trading partners, as shown in Figure 1.13, South Korea was ASEAN's largest wafer export destination in most years from 2013 to 2022, except for 2017, 2019 and 2020, when ASEAN's largest destination was Chinese Taipei. Despite this prominence, South Korea's share in ASEAN's exports slightly declined from 30.6% in 2013 to 25.5% in 2022 (Figure 1.13). Exports to South Korea were mainly contributed by Singapore, the region's largest exporter in 2022, with 40.1% of Singapore's wafer exports destined for South Korea.

Concurrently, intra-ASEAN exports' share rose from 14.9% to 25.5% over the period, making ASEAN itself the second-largest wafer export destination in 2022 (Figure 1.13). Vietnam, the region's second-largest exporter, played a crucial role in this trend, with 79.7% of its exports directed to Malaysia (68.3%) and Thailand (11.4%) in 2022. Additionally, Chinese Taipei and China were the third and fourth-largest destinations respectively, accounting for 14.9% and 14.8% of ASEAN's wafer exports in 2022.

Figure 1.13: ASEAN Member States' Exports of Wafers, Share by Exporter and Destination, 2013 vs 2022



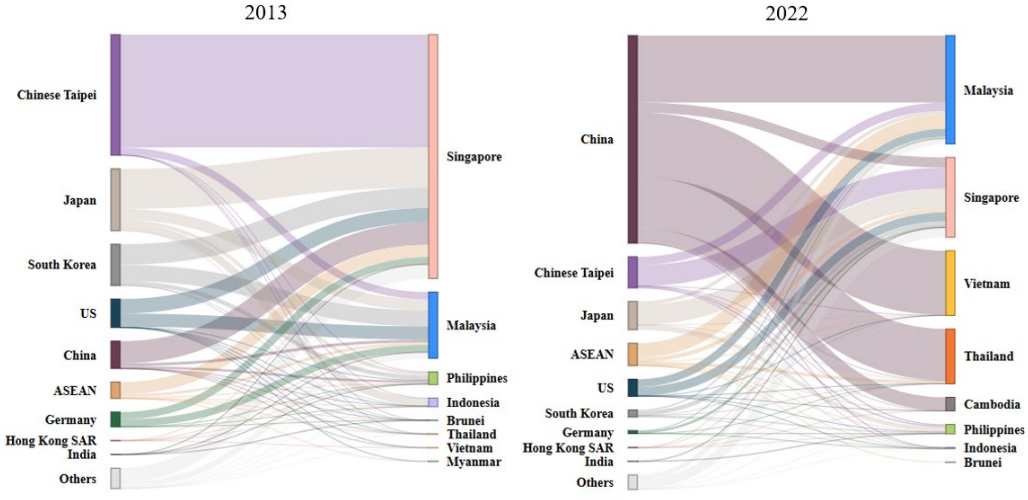
Source: ACI's calculations based on UN Comtrade

The trade flow between AMS and their import suppliers is presented in Figure 1.14. In 2013, the top three suppliers were Chinese Taipei, Japan and South Korea (Figure 1.14, left). But in 2022, China ascended to become ASEAN's largest wafer supplier, replacing Chinese Taipei (Figure 1.14, right). China's share in ASEAN's wafer imports surged dramatically from 8.24% in 2013 to 62.7% in 2022, a figure nearly equivalent to the combined share of the top three suppliers back in 2013. Amid intensified competition from China, Chinese Taipei and Japan's share dropped to approximately 9% of the regional imports (Chinese Taipei: 9.35%, Japan: 8.52%), while South Korea's share shrank to 2.12% in 2022. Intra-ASEAN imports of wafers, while limited, showed moderate growth from 4.95% in 2013 to 6.75% in 2022.

Within ASEAN, Malaysia emerged as the largest importer of Chinese wafers in 2022, with imports valued at 1.34 billion USD. This accounted for 61.8% of its total wafer imports in the year, a substantial increase from 4.27% in 2013. Other AMS exhibited even stronger dependence. China's share reached 100.0% in Cambodia, 99.7% in Vietnam and 94.1% in Thailand in 2022.

In contrast to these trends, Singapore had a more diversified wafer import source network in 2022, with 26.1% coming from Chinese Taipei, 25.1% from Japan, and similar shares from China (12.7%) and the US (11.0%). Intra-AESAN imports accounted for a stable share in Singapore's wafer imports, approximately 5.02% in both years.

Figure 1.14: ASEAN Member States' Imports of Wafers, Share by Importer and Source, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

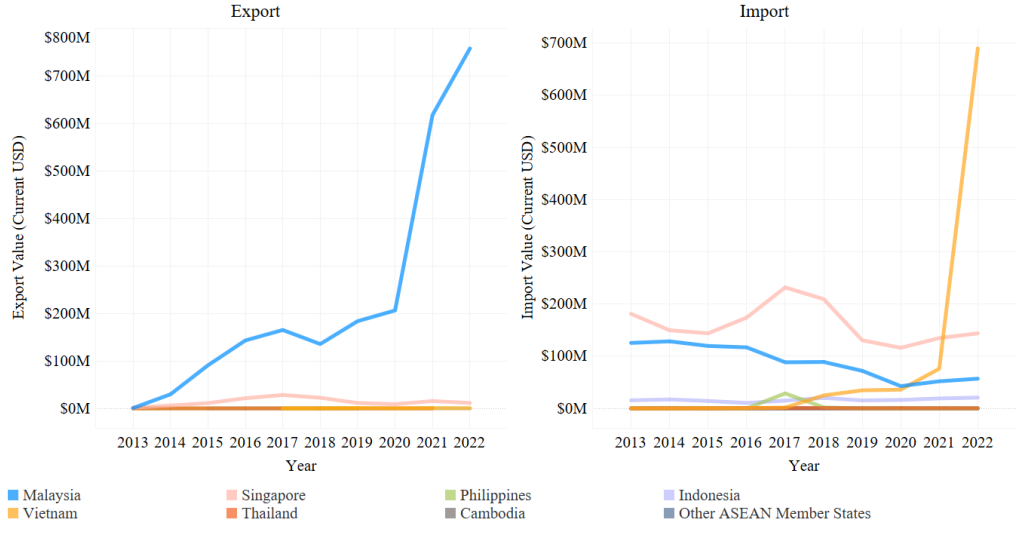
1.3.4.2.2 Polysilicon

Polysilicon serves as the critical upstream material for wafer production. Globally, Germany and the US have been leaders in polysilicon exports since 2013. On average, the two countries collectively accounted for 54.0% of the global polysilicon exports, from 2013 to 2022. While Germany occupied a rising share of global polysilicon exports, from 28.3% in 2013 to 36.7% in 2022, the US's share had been stable at around 27.1%. As for imports, China was the largest polysilicon importer from 2013 to 2022, with a rising share from 31.7% to nearly 47.4%. Besides China, Japan and Chinese Taipei were among the top 3 largest importers by 2021. But in 2022, their shares dropped to 12.8% and 8.61%, respectively. Meanwhile, ASEAN rose to become the world's second- largest importer of polysilicon, with a share of 15.7%.

ASEAN's polysilicon exports surged from 2.09 million USD in 2013 to nearly 770 million USD in 2022, increasing its global share from 0.0423% to 13.3%. During this period, the growth trend showed substantial volatility. While its exports grew exponentially between 2013 and 2014 (1,619%), growth rates later slowed, averaging 18.4% annually from 2016 to 2020. However, ASEAN's exports rebounded with a 194% surge from 2020 to 2021. The region surpassed South Korea and Japan in 2021 to become the world's third-largest exporter.

ASEAN's growth in polysilicon exports was predominantly contributed by Malaysia (Figure 1.15, left). It was the top regional polysilicon exporter from 2014 to 2022. Malaysia's share in regional exports soared from 27.3% to 98.5%, and its global share surged from around 0.0141% in 2013 to 13.1% in 2022.

Figure 1.15: Trade Value of Polysilicon by ASEAN Member State, 2013-2022

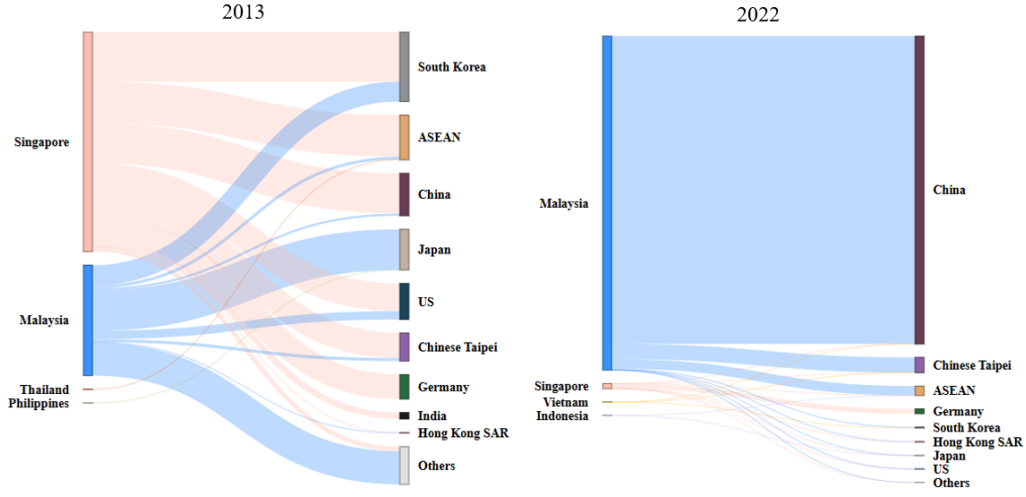


Source: ACI's calculations based on UN Comtrade

ASEAN's polysilicon imports increased by 183% to 900 million USD from 2013 to 2022, with an average annual growth rate of 24.8% over the period, far ahead of the global average (5.17%). This allowed ASEAN's global share to increase by ten percentage points from 6.44% in 2013 to 15.7% in 2022, and it climbed up the ranking from fifth position to second. Vietnam was the primary driver of this growth (Figure 1.15, right). Its polysilicon imports rose from 217 thousand USD to 689 million USD from 2013 to 2022, making its global share jump from 0.00434% to 11.9%. This growth took off in 2018 and further accelerated in 2022, when it surpassed the traditional regional leader, Singapore, to be ASEAN's largest and the world's third-largest polysilicon importer. In contrast, Singapore's share in global polysilicon imports dropped from 3.62% in 2013 to 2.48% in 2022, with its ranking dropping from sixth to ninth position.

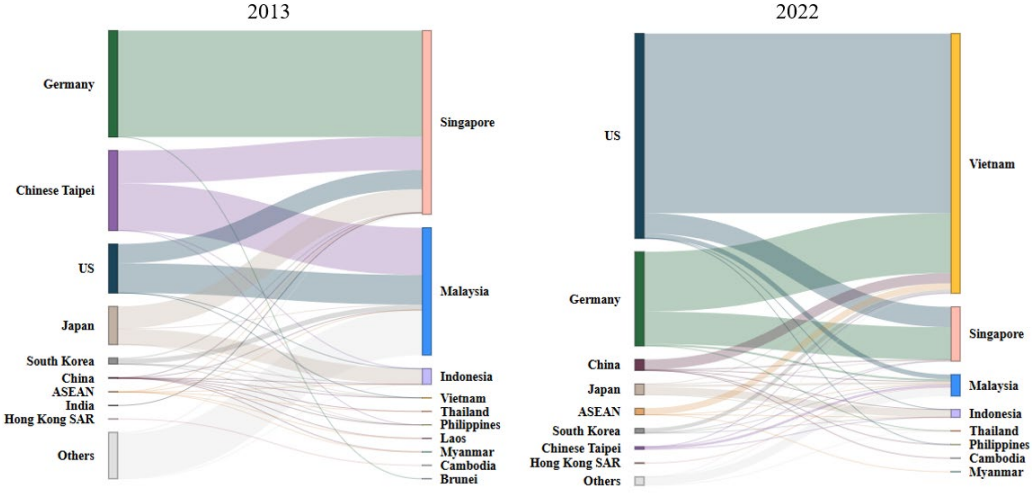
ASEAN's polysilicon export markets shifted significantly between 2013 and 2022, as shown in Figure 1.16. In 2013, ASEAN's polysilicon exports were distributed to diverse destinations, covering South Korea (21.0%), ASEAN (13.5%), China (12.9%), Japan (12.0%) and the US (10.1%). However, by 2022, the exports were overwhelmingly concentrated in China, which occupied 90.8% of the region's total polysilicon exports. This primarily reflected Malaysia's export patterns as the chief exporter in ASEAN. In 2022, 92.1% of polysilicon exports by Malaysia were directed to China, followed by 4.54% to Chinese Taipei and 2.84% to the other AMS.

Figure 1.16: ASEAN Member States' Exports of Polysilicon, Share by Exporter and Destination, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

Figure 1.17: ASEAN Member States' Imports of Polysilicon, Share by Importer and Source, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

Changes in ASEAN's polysilicon suppliers are illustrated in Figure 1.17. In 2013, ASEAN's major polysilicon suppliers were Germany (32.5%), Chinese Taipei (24.5%) and the US (15.0%). Singapore and Malaysia, two leading importers within the region in 2013, showed different supplier compositions. For Singapore, 57.9% of its polysilicon imports in 2013 were from Germany, 17.8% from Chinese Taipei and 12.1% from Japan. For Malaysia, Chinese Taipei (37.0%), Italy (35.3%, under the category of "Others" in Figure 1.17, left) and the US (23.3%) were its top three import sources. In 2022, ASEAN's three largest import sources shifted to the US (59.6%), Germany (27.4%) and China (3.16%). This change was predominantly driven by the

rise of Vietnam as the top importer in the region. The country imported 69.1% of its polysilicon from the US, 23.0% from Germany and 3.86% from China in 2022.

1.3.4.2.3 Silica Sands and Quartz Sands

Globally, the US and Belgium were the two largest silica sand and quartz sand exporters from 2013 to 2022. On average, the US itself accounted for 41.2% of silica sand exports, while Belgium occupied around 9.53% over the same period. Germany ranked third in 2013 (7.32%) but was replaced by ASEAN in 2020 and 2022.

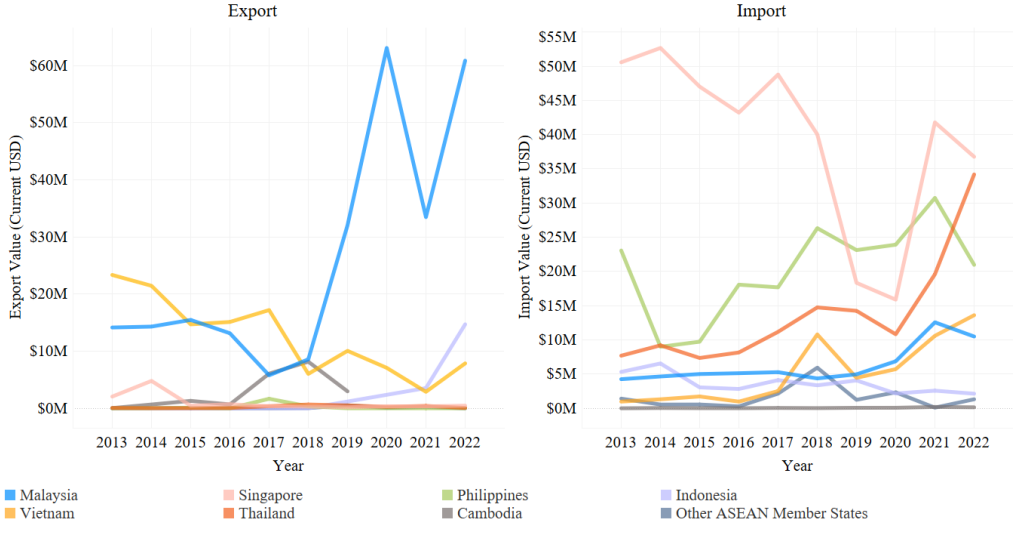
In terms of global imports, Canada has been the world's largest silica sand importer from 2013 to 2022, accounting for 15.7% of global imports on average. China and ASEAN have climbed up to be the second and third-largest importers by 2022, with China's share increasing from 4.50% in 2013 to 12.4% in 2022, and ASEAN's share stabilised at around 6.66%.

ASEAN collectively accounted for 6.96% of the global silica sand exports in 2022, slightly up from 4.61% in 2013. This growth in market share was accompanied by a growth of 112% in export value, outpacing the global growth rate of 40.2% during the same period. Malaysia emerged as the primary contributor to this regional expansion (Figure 1.18, left). Malaysia's silica sand exports increased by 330% from 2013 to 2022. This was particularly apparent between 2017 and 2020, during which Malaysia's silica sand exports surged by 993%. This growth allowed its regional share to rise significantly from 35.7% in 2013 to 72.5% in 2022; the global share also grew from 1.64% to 5.04%.

Indonesia was the second-largest silica sand exporter in the bloc in 2022. Its export surge happened only after 2020 (Figure 1.18, left), from 0 USD in 2020 to 3.53 million USD in 2021 and 14.7 million USD in 2022, accounting for 18% of regional exports and 1.2% of global exports, in 2022. Vietnam used to be the region's largest exporter from 2013 to 2017 but has since dropped to the third position in the region. Its global share also dropped from 2.71% to 0.651% between 2013 and 2022.

ASEAN's silica sand imports reached 120 million USD in 2022, 22% up from 2013. The region's collective share of global silica sand imports slightly decreased from 7.57% in 2013 to 7.13% in 2022. This can be attributed to the major importers in the region. Singapore, although remaining the region's largest silica sand importer in most years between 2013 and 2022 (except for 2019 and 2020), saw its import value decline by 27.3% in 2022 (Figure 1.18, right), reducing its global share from 4.11% to 2.19%. The Philippines was the region's largest or second-largest silica sand importer between 2013 and 2021. However, its silica sand imports also dropped slightly by 9.06% over the period, resulting in its global share decreasing slightly from 1.87% to 1.25%. This also made it lose out to Thailand, falling to the third position as ASEAN's silica sand importer, in 2022.

Figure 1.18: Trade Value of Silica Sands and Quartz Sands by ASEAN Member State, 2013-2022



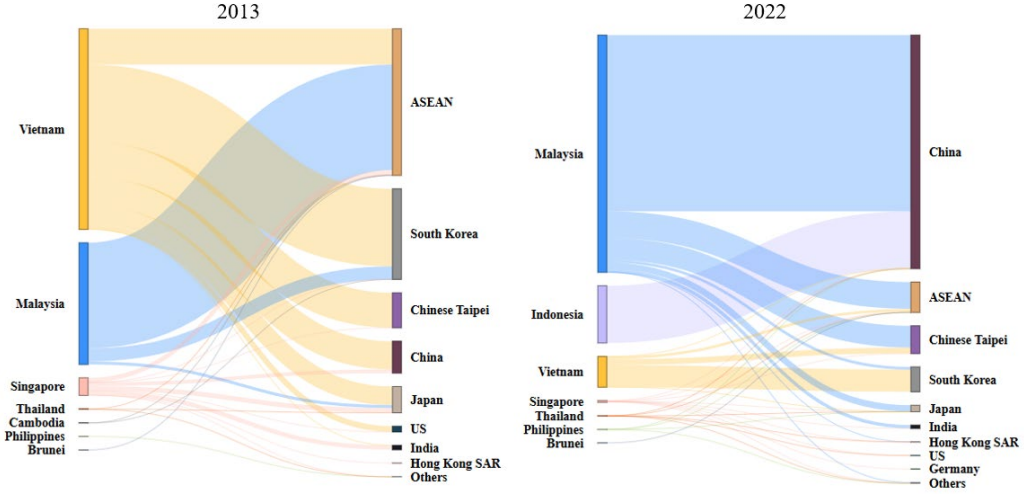
Source: ACI's calculations based on UN Comtrade

As for trade partners, ASEAN's silica sand export destinations were more diverse in 2013 compared to 2022, as can be seen in Figure 1.19. ASEAN, South Korea and Chinese Taipei each accounted for 43.1%, 26.6% and 10.3% of ASEAN's silica sand exports in 2013. Yet, the export markets became concentrated in China in 2022, when China's share in ASEAN's silica sand exports increased from 9.35% in 2013 to 71.4% in 2022. Meanwhile, the share of silica sand exports to other AMS declined from 43.1% in 2013 to 9.28% in 2022, but it still accounted for the second highest amount of exports among all export markets of this region. Chinese Taipei and South Korea accounted for a similar share of ASEAN's silica sand exports (8.44% and 7.59%, respectively) in 2022, positioning them in third and fourth place.

The dependence on China's market becomes more apparent when we look at the AMS. In 2022, China was the top export destination for Malaysia and Indonesia, the bloc's largest exporters, accounting for 74.3% and 100% of their silica sand exports, respectively (Figure 1.19, right). China's share in Malaysia's exports saw its most significant rise between 2018 and 2022, surging from 7.69% to 74.3%.

On the other hand, China accounted for a declining share in Vietnam's silica sands exports between 2013 to 2022 (Figure 1.19), with its share dropping from 14.02% to 0.0776% over the period. In 2022, Vietnam's silica sand exports were directed mainly to South Korea instead, with its share increasing from 38.6% to 72.2% over the same period, while the share of intra-ASEAN trade, and trade with China and Japan, all decreased. It is worth noting that ASEAN did not export silica sands to Canada the world's largest silica sand importer in both 2013 and 2022.

Figure 1.19: ASEAN Member States' Exports of Silica Sands and Quartz Sands, Share by Exporter and Destination, 2013 vs 2022

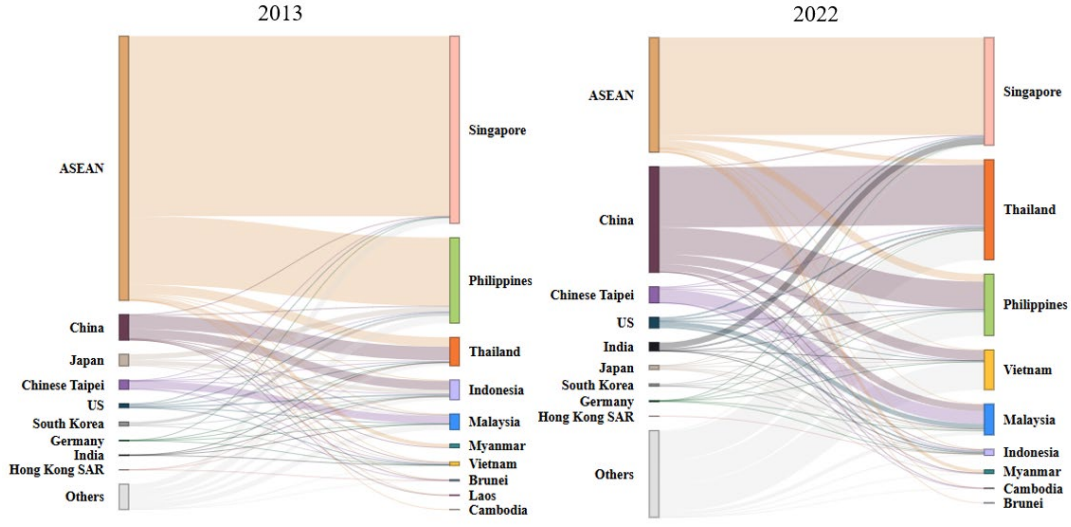


Source: ACI's calculations based on UN Comtrade

In terms of import partners, ASEAN and China were major suppliers of ASEAN's silica sand imports in 2013 and 2022 (Figure 1.20). Although within-ASEAN imports remained the largest silica source for regional countries, its share in ASEAN's total silica sand import shrank from 76.5% in 2013 to 32.7% in 2022 (Figure 1.20). This could be attributed to the sharp decline (-82.3%) in intra-ASEAN import value in silica sands throughout the period. Intra-ASEAN imports shrank for all of the bloc's top three importers (Singapore, Thailand and the Philippines) from 2013 to 2022.

Singapore, the region's largest importer, was the only major importer that still sourced most of its silica sands from within ASEAN—predominantly from Malaysia—though intra-ASEAN's share also declined slightly from 96.1% in 2013 and 90.5% in 2022 (Figure 1.20). The region's second and third largest importers, Thailand and the Philippines, presented rising reliance on China's silica sands from 2013 to 2022. China's share in Thailand's silica sand import increased from 47.8% in 2013 to 60.0% in 2022, and the share in the Philippines surged from 0.636% to 43.6%. Collectively, ASEAN's silica sand import value from China grew by 428% from 2013 to 2022, pushing up China's share from 7.33% to 30.2% over the same period. It is noteworthy that, although the US was the world's largest silica sand exporter, ASEAN's imports from it were quite limited at 2.26% on average.

Figure 1.20: ASEAN Member States' Imports of Silica Sands and Quartz Sands, Share by Importer and Source, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

1.3.4.3 Machines for Manufacturing

ASEAN's growing role as the world's top importer of wafers and the second largest exporter of solar PV cells or modules underscores its reliance on external manufacturing inputs. Hence, to comprehensively assess ASEAN's capacity to vertically integrate the solar PV supply chain, it is essential to understand the trade of production machinery for both wafers and solar PV cells or modules. Specifically, the imports of machines signal the region's efforts to localise upstream production (e.g., wafer fabrication), while the exports reflect ASEAN's potential as a high-end manufacturing technology provider.

1.3.4.3.1 Machines to Manufacture Solar PV Cells or Modules

Globally, the export of machines to manufacture solar PV cells or modules increased steadily by 266% from 21.6 billion USD in 2013 to 78.9 billion USD in 2022. The top three global exporters of these machines were Japan, the US and the Netherlands. In 2022, they accounted for 23.9%, 22.3% and 22.1% of global exports, respectively.

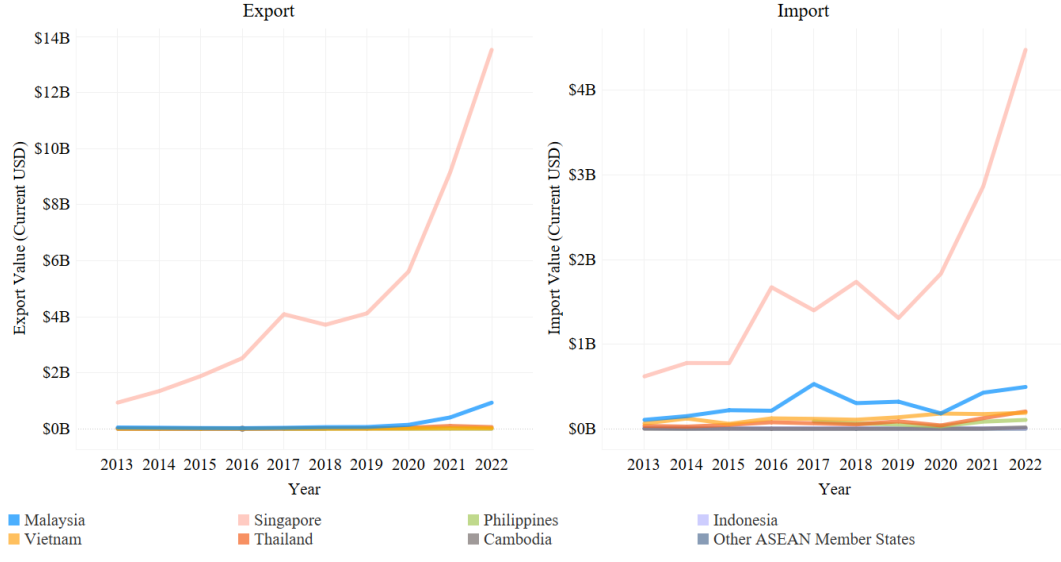
In 2013, the top three global importers were Chinese Taipei (40.0%), South Korea (17.5%) and the US (13.8%). In 2022, Chinese Taipei maintained its leading position, though its global share moderated to 33.5%. China rose to the second position, with its share increasing from 12.0% in 2013 to 22.8% in 2022. South Korea became the third-largest importer, with a global import share of 16.4%.

ASEAN's share in the world's total exports slightly increased from 4.57% in 2013 to 18.4% in 2022, although its global ranking remained at fourth position. Within the region, Singapore consistently performed better than other AMS, and it has been the key contributor to ASEAN's total exports (Figure 1.21, Left). Its global share increased sharply from 4.33% in 2013 to 17.1% in 2022. Malaysia ranked second in the region throughout the period. Its absolute trade value

grew by almost 2,000%, from 45.6 million USD in 2013 to 930 million USD in 2022, but its global share only increased moderately from 0.21% to 1.18%, way below that of Singapore.

ASEAN's collective share in global imports increased from 3.82% in 2013 to 6.71% in 2022, with its ranking climbing up slightly from sixth to fifth position. Singapore and Malaysia remained major regional importers. Globally, Singapore's share increased from 2.84% to 5.47% during that period, and Malaysia's share, from 0.482% to 0.603% (Figure 1.21, Right).

Figure 1.21: Trade Value of Machines to Manufacture Solar PV Cells or Modules by ASEAN Member State, 2013-2022

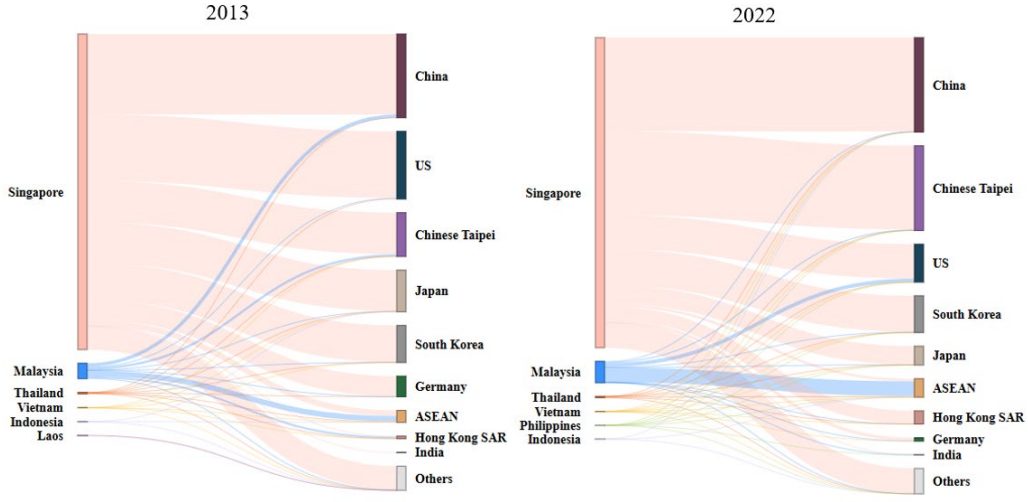


Source: ACI's calculations based on UN Comtrade

Taking a closer examination of ASEAN's export and import partners, we will only focus on Singapore and Malaysia since they are the predominant regional players. As shown in Figure 1.22, Singapore's exports in 2013 demonstrated a well-diversified market profile, with China (25.5%), the US (21.1%) and Chinese Taipei (13.1%) being the top three export destinations. Yet, by 2022, Singapore's export patterns had shifted slightly toward greater reliance on East Asia, with China's share rising to 30.2%, followed by Chinese Taipei (27.0%) and South Korea (11.6%). Meanwhile, the US's share halved to 11.1%.

In 2013, Malaysia's exports of machines to manufacture PV cells or modules were primarily intra-regional, with trade with other AMS accounting for 35.1% of total exports. This was followed by exports to China (21.5%) and Chinese Taipei (14.8%). By 2022, Malaysia had reinforced its involvement in the regional solar PV supply chain, with its share of intra-ASEAN trade increasing to 68.8%. In particular, Singapore became Malaysia's top export destination. Concurrently, the US emerged as Malaysia's second-largest export destination, covering 17.0% of its exports, which was a substantial growth from 4.83% in 2013. China's share declined to just 3.11%, indicating reduced export dependence on China's market.

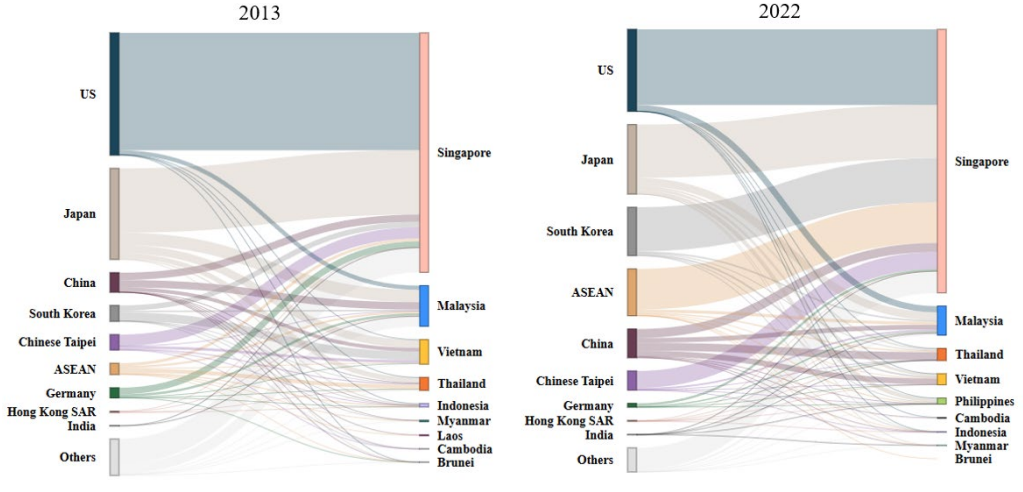
Figure 1.22: ASEAN Member States' Exports of Machines to Manufacture Solar PV Cells or Modules, Share by Exporter and Destination, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

The shifting dynamics of ASEAN's imports of machines to manufacture PV cells or modules can be observed in Figure 1.23. In Singapore, the region's largest importer of such products, the country's imports from the US dropped from 49.0% to 28.7% between 2013 and 2022. Similarly, imports from Japan declined from 26.7% in 2013 to 20.2% in 2022. In contrast, South Korea accounted for a rising share in Singapore's imports of machines to manufacture PV cells or modules, from only 2.20% in 2013 to 16.7% in 2022.

Figure 1.23: ASEAN Member States' Imports of Machines to Manufacture Solar PV Cells or Modules, Share by Importer and Source, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

Malaysia's import trends were distinct from Singapore's. Although imports from Japan declined slightly from 30.4% to 26.8%, Japan remained Malaysia's top supplier in both 2013 and 2022. Unlike Singapore's import profile, where the US's proportion diminished, Malaysia saw a growing share of imports from the US, from 10.4% in 2013 to 21.3% in 2022. Notably, intra-ASEAN imports also doubled from 4.92% to 10.4%, reflecting a growing regional trade presence. On the other hand, China, previously Malaysia's second-largest source, dropped to third place as its share declined from 18.1% to 16.4%.

1.3.4.3.2 Machines to Manufacture Wafers

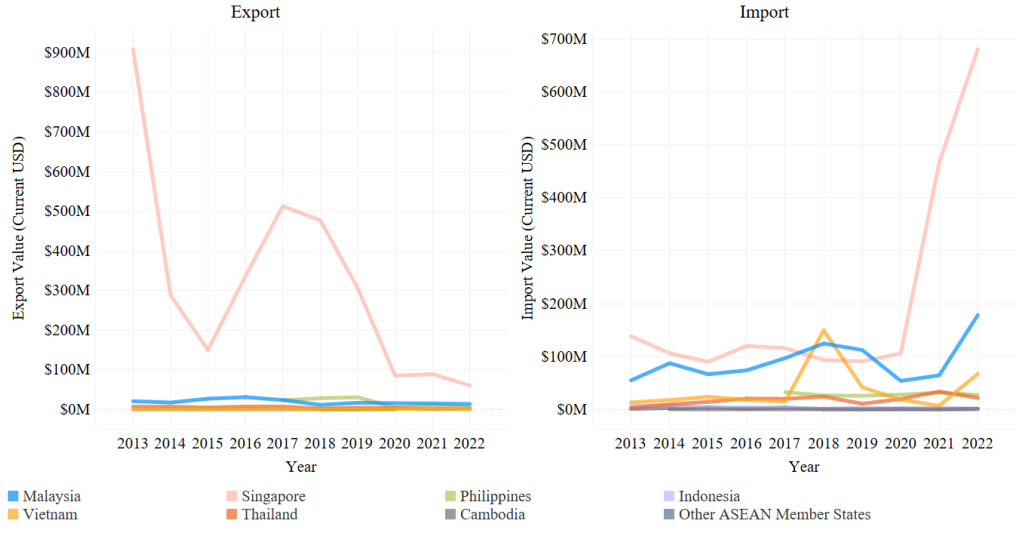
Globally, exports of machines to manufacture wafers grew significantly by 24.0%, from 2.17 billion USD in 2013 to 2.67 billion USD in 2022. Singapore, previously the top exporter in 2013, dropped out of the top three positions in 2022. Its global share plummeted drastically from 41.8% to 2.25% during this time. In contrast, Japan doubled its global share from 26.3% in 2013 to 48.6% in 2022, ascending to become the world's largest exporter. Within the same period, Germany, whose share rose from 9.27% to 19.7%, ranked second. Notably, China, which only ranked ninth with 1.27% of the market share in 2013, made impressive progress. By 2022, it had already become the third largest exporter of machines to manufacture wafers, occupying 9.82% of the global market.

From 2013 to 2022, global imports of machine manufacturing wafers tripled from 1.43 billion USD to 4.73 billion USD. China, Chinese Taipei and Singapore remained listed among the top three importers globally. China's import value surged from 369 million USD in 2013 to 1.73 billion USD in 2022, increasing its market share from 25.8% to 36.6%, solidifying its dominance. Chinese Taipei also experienced strong growth, with imports rising from 470 million USD to 1.23 billion USD, though its market share declined from 32.9% to 26.4%, indicating slower relative growth compared to China. Singapore's import value grew from 138 million USD to 681 million USD, increasing its market share from 9.64% to 14.4%.

ASEAN was the world's largest exporter of machines to manufacture wafers in 2013, accounting for 42.8% of global exports. However, by 2022, ASEAN's global market share declined significantly to 2.25%. As illustrated in Figure 1.24 (left), this sharp decline was largely driven by Singapore's export contraction. Singapore's exports of wafer manufacturing machines totalled 909 million USD in 2013, dominating 41.8% of the global market and ranking first worldwide. However, by 2022, Singapore's exports had dropped to 60.2 million USD, reducing its global market share to just 2.25% and pushing it down to sixth place globally. Malaysia was the second largest exporter in the regional exports of such machines in 2013 and 2022, but its global share (less than 1%) was far below Singapore's.

As for imports, ASEAN collectively accounted for 15.1% (21.6 million USD) of the global imports of machines to manufacture wafers in 2013. This share increased to 14.5% (797 million USD) in 2022. Similar to the export pattern, Singapore also contributed significantly to the region's total import demand. Singapore's imports grew nearly fivefold, from 138 million USD in 2013 to 681 million USD in 2022 (Figure 1.24, right). Yet, the expansion mostly occurred in the two years between 2020 and 2022. By 2022, Singapore had secured 14.4% of the global import share, reinforcing its position as the region's largest and global third largest importer.

Figure 1.24: Trade Value of Manufacturing Machines to Manufacture Wafers by ASEAN Member State, 2013-2022



Source: ACI's calculations based on UN Comtrade

Besides Singapore, Malaysia was another major importer within ASEAN (Figure 1.24, right). Malaysia's imports started from 54.8 million USD in 2013 and more than tripled by 2022, reaching 178 million USD, securing 3.77% of the global share. Following Malaysia, Vietnam was ASEAN's third largest importer. Its import value recorded a 5-fold increase from 13.2 million USD in 2013 to 67.2 million USD in 2022. In 2018, there was a one-year surge when Vietnam recorded the highest import value among all the AMS (149 million USD), although this expansion was not sustained. Globally, Vietnam's share was 1.42%, ranking ninth in 2022.

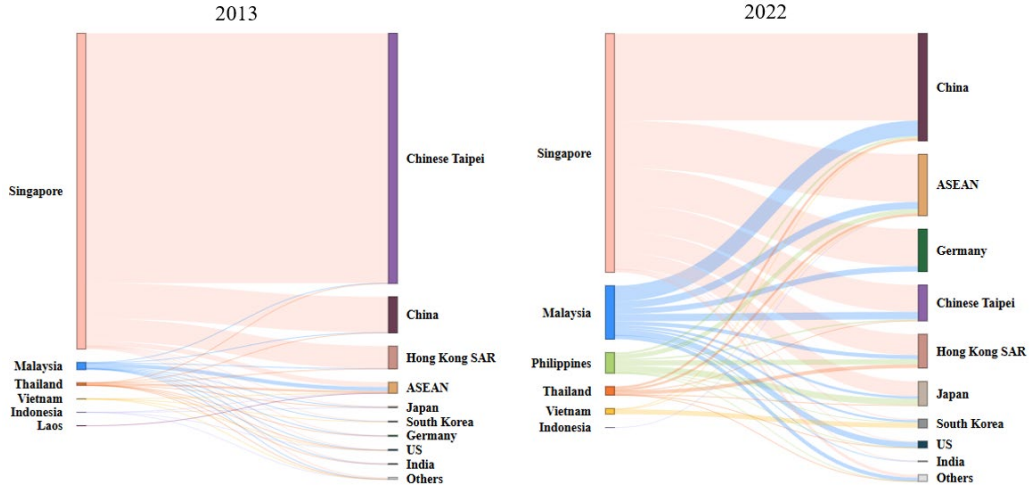
Figure 1.25 presented ASEAN's major export partners of machines to manufacture wafers. In 2013, ASEAN's export partnerships almost solely followed Singapore's because of the country's dominant position in supplying machines for wafer manufacturing. Back then, Singapore's exports were highly concentrated in Chinese Taipei, accounting for 79.1% of its total exports. Singapore's second and third largest export destinations were China and Hong Kong SAR, representing 11.2% and 7.11% of its total exports. Singapore's sales to intra-ASEAN buyers only made up 1.54% of its exports, most of which were contributed by exports to Malaysia.

In comparison, Malaysia's exports were largely focused on the ASEAN region, which made up 54.1% of its total export share in 2013. Even more reliant on intra-ASEAN trade, Thailand directed 85.0% of its exports to ASEAN, making its export structure highly concentrated within the region. But in terms of trade value, both Malaysia and Thailand were incomparable with Singapore at that time.

By 2022, there had been a trend shifting away from regional concentration towards a more globally diversified export structure. Chinese Taipei's share in Singapore's total imports decreased to 11.2%. Instead, China rose to become its largest export destination (36.3%), followed by Germany (15.4%) and ASEAN (19.9%). Among Singapore's intra-ASEAN trade, over 90.7% of exports went to Malaysia, Thailand and Vietnam. Malaysia also experienced a realignment in its trade relationships, as ASEAN's share of its exports declined sharply from

54.1% in 2013 to just 13.4% in 2022. Meanwhile, China (29.1%) and Chinese Taipei (13.8%) became major trading partners. The Philippines became the third largest exporter in ASEAN in 2022. It also exhibited a relatively diversified export structure, with Japan (31.7%), Hong Kong SAR (25.3%) and ASEAN (21.6%) being its key trading partners.

Figure 1.25: ASEAN Member States' Exports of Manufacturing Machines to Manufacture Wafers, Share by Exporter and Destination, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

Figure 1.26 highlights the shifts in import patterns between 2013 and 2022. At the ASEAN level, Japan (34.4%), the US (23.1%) and South Korea (8.85%) were the top three import sources in 2013. However, at the AMS level, the two major importers, Singapore and Malaysia, exhibited different partner profiles. In 2013, Singapore sourced most of its imports from Japan (37.8%), the US (17.8%) and the Netherlands (14.7%, under the category of "Others" in Figure 1.26, left). In Malaysia's case, the country's top two import sources were the US (42.8%) and Japan (30.6%), while none of the other suppliers secured a share higher than 7% of Malaysia's total imports in 2013.

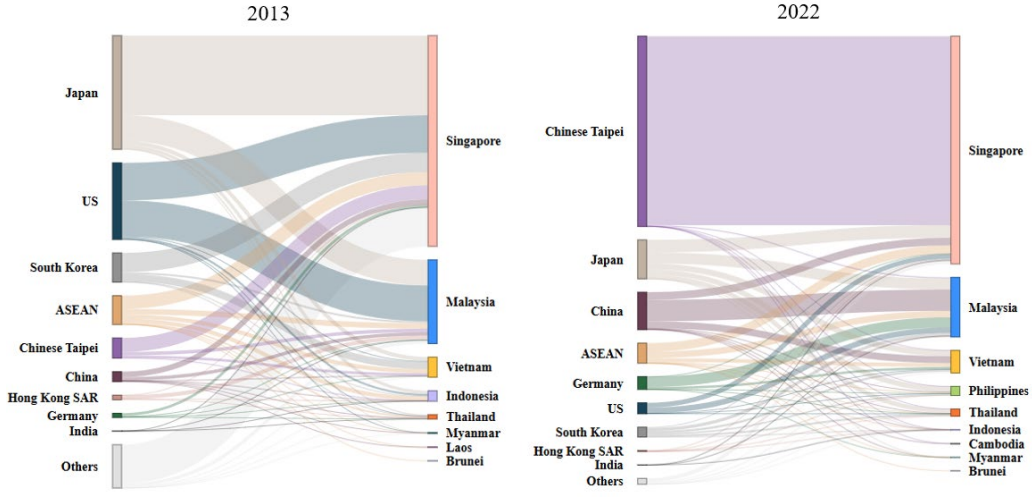
However, by 2022, Chinese Taipei had become ASEAN's largest import source, accounting for 58.2% of the region's total imports. Japan's share declined to 11.9%. Notably, China, which only supplied 3.0% of ASEAN's total imports in 2013, emerged as the third largest import source of ASEAN, with a share of 11.5% in 2022, almost on par with Japan's.

Nearly all of ASEAN's imports of machines to manufacture wafers from Chinese Taipei were attributable to Singapore in 2022, reflecting Singapore's dominant role in the region's imports (Figure 1.26, right). Singapore also had a strong import reliance on Chinese Taipei, with 83.0% of its wafer machine imports originating from there. Meanwhile, Japan's significance as a supplier to Singapore diminished, with its share dropping to 5.49% in 2022, followed by ASEAN (3.76%) and China (3.36%).

Malaysia, as the second-largest ASEAN importer in 2022, sourced 35.9% of its imports from China, which contributed to China's growing role as one of the key machine suppliers for the

region. The second and third largest import sources of Malaysia were Japan (18.5%) and Germany (17.1%).

Figure 1.26: ASEAN Member States' Imports of Machines to Manufacture Wafers, Share by Importer and Source, 2013 vs 2022



Source: ACI's calculations based on UN Comtrade

Similarly, Malaysia experienced a major shift away from the US as a key supplier. In 2013, the US accounted for 42.8% of Malaysia's imports, followed by Japan (30.6%) and ASEAN (6.58%). By 2022, however, China emerged as Malaysia's leading supplier (35.9%), while Japan's share declined to 18.4%. Intra-ASEAN trade had expanded to 10.6%. Singapore occupied around 95.0% of Malaysia's intra-ASEAN imports in both 2013 and 2022.

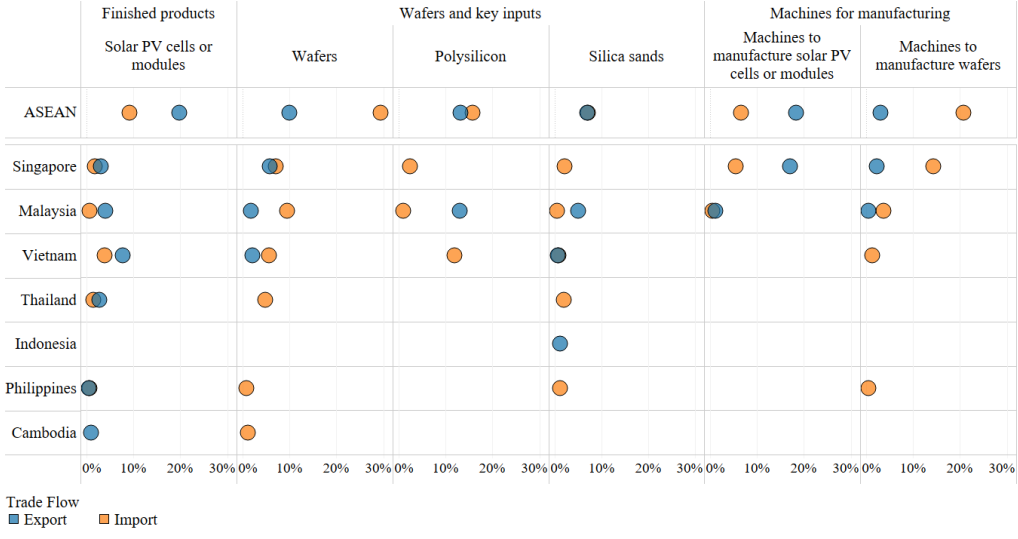
As for Vietnam, South Korea used to account for 36.6% of its total imports, followed by Japan (19.4%) and Malaysia (15.6%), in 2013. At that time, China only contributed to 0.878% of Vietnam's imports. By 2022, however, South Korea's contribution shrank to 9.72% while China became its top import source (31.0%).

1.3.4.4 Summary of ASEAN's Role in Solar PV Trade

As shown in Figure 1.27, by 2022, ASEAN has established itself as a significant player in the global solar PV supply chain, particularly in the stage of finished products. However, its position across other segments of the supply chain reveals both opportunities and challenges. ASEAN's reliance on imports for essential intermediates and machinery for manufacturing underscores its limited integration within the supply chain.

With regards to the intermediates used for cell production, ASEAN was not a key player in the extraction and preliminary processing stages of raw materials but presented a high import demand for wafers and polysilicon. The region was the world's largest importer of wafers and the second-largest of polysilicon. ASEAN was also consistently been a net importer of wafers from 2013 to 2022. As for silica sands, ASEAN did not engage much in either exports or imports.

Figure 1.27: ASEAN's and Its Member States' Global Share by Product and Trade Flow (2022)



Note: The global share of "ASEAN" means the proportion of the exports/imports of all ten AMS combined relative to the global exports/imports of the respective products in 2022. Only the data points representing global shares greater than 0.5% are shown in the figure.

Source: ACI's calculations based on UN Comtrade

In the machinery segment, ASEAN's share of the global exports of machines to manufacture solar PV cells or modules almost reached 20% in 2022, coming only slightly behind key players with established high-end manufacturing capabilities.[81] Surprisingly, in contrast to its rapid expansion in solar PV cells or module exports, ASEAN's global share in the machine-for-cell import was still limited.

At the AMS level, Singapore, Malaysia, and Vietnam contributed the most to ASEAN's solar PV trade. Singapore and Malaysia had established noticeable shares across almost all products but demonstrated different comparative advantages.

Singapore served as a key player in high-end manufacturing, as evidenced by its significant contribution to the exports of machines to manufacture cells or modules. It was also the largest ASEAN exporter of wafers, which corresponded to its substantial imports of machines to manufacture wafers.

Malaysia has been a critical trading hub of solar PV-related products. Notably, it exported the most silica sands and polysilicon among the AMS, but it was the largest importer of wafers in 2022. Given the high demand for wafers and the relatively abundant resource endowment of silica sands, policymakers have recognised the imperative for Malaysia to develop wafer production and silica sand refinement activities. For example, Malaysia's New Industrial Master Plan 2030 for the mineral industry includes a slew of strategic focuses on the mineral industry, including improving local R&D capabilities, enhancing trade balance, and attracting investors for high-

[81] The top three players were Japan, the US, and Netherlands.

value-added products in the midstream (processing, refining, and separation) and downstream segments (manufacturing and fabrication).[82]

Vietnam was the standout performer in terms of both the exports and imports of solar PV cells or modules. This reflects Vietnam's growing importance as a supplier of finished products and demonstrates substantial domestic demand incentivised by the policies boosting solar PV installations.

ASEAN's solar PV trade remained concentrated within the Asia-Pacific region, represented by China, intra-ASEAN trade, Chinese Taipei, Japan and South Korea. The US and Germany also played a key role (Table 1.6).

Table 1.6: ASEAN's Major Trading Partners on the Solar PV Supply Chain, 2022

ASEAN's Major Trading Partners	Solar PV Cells or Modules	Wafers	Polysilicon	Silica Sands	Machines to Manufacture Cells or Modules	Machines to Manufacture Wafers
ASEAN's Major Export Destinations	US ASEAN China	South Korea ASEAN Chinese Taipei China	China Chinese Taipei	China ASEAN Chinese Taipei South Korea	China Chinese Taipei US	China ASEAN Germany
ASEAN's Major Import Sources	China ASEAN Japan	China Chinese Taipei Japan	US Germany Chinese Taipei	ASEAN China Others (Belgium)	US Japan South Korea	Chinese Taipei Japan China

Note: China and Chinese Taipei accounted for a very similar share (both approximately 15%) of ASEAN's wafer exports in 2022, so both were listed as the major destinations. If the top two trade partners accounted for over 90% of the trade value for the product in 2022, the third partner will not be added to the table.

Source: ACI's calculations based on UN Comtrade

On the export side, the US was the region's top export destination of solar PV cells or modules. In 2022, over half of the region's exports of finished products were destined for the US. China was ASEAN's largest market for polysilicon, silica sands and manufacturing machines and the third-largest market for solar PV cells or modules and wafers. ASEAN was the second-largest destination for the region's exports of solar PV cells or modules, wafers, silica sands and machines for wafer manufacturing. Nevertheless, when measured by relative share, intra-ASEAN trade still remained rather limited.

[82] Ministry of Investment, Trade and Industry, Malaysia (2023)

On the import side, China was one of ASEAN's top three import sources for almost all products, except for polysilicon and machines to manufacture cells or modules. Overshadowed by China's dominance, the intra-ASEAN trade remained largely underdeveloped, except for products like silica sands and solar PV cells or modules.

This reliance on the US market for solar PV cells or modules, and wafers supplied by China, exposed ASEAN to global geopolitical dynamics, particularly the US tariffs targeting solar PV products associated with China, potentially jeopardising the sustained development of the region's solar PV industry.

1.3.5 Conclusion

Expanding the adoption of renewable energy is critical to supporting global sustainability efforts. Solar PV is one of the prevalent renewable energy sources both in the world and ASEAN. In order to capitalise on the opportunities that come from the increasing adoption of renewables, ASEAN needs to understand the global landscape of the solar PV supply chain and its position in it. This paper assessed ASEAN's position on the global solar PV supply chain from two perspectives: its performance in R&D and trade.

Our study finds that ASEAN presented a limited presence in solar PV R&D activities globally, as measured by both publishing high-quality papers and the ownership of solar PV patents. Within the region, Malaysia and Singapore were major contributors to R&D. Malaysia recently surpassed Singapore as the top contributor of high-quality papers, while Singapore remained the leader of patenting activities.

From the trade perspective, ASEAN collectively ranked as the second-largest global exporter of solar PV cells or modules in 2022. ASEAN was also the world's largest importer of wafers and the second-largest importer of polysilicon, underscoring its reliance on external sources for critical intermediates. At the AMS level, Singapore, Malaysia and Vietnam were key players in the production of most products, while the remaining AMS were only present in the manufacturing of some products, with negligible shares in the global trade. As for trade partners, ASEAN presented a strong reliance on extra-regional partners, while intra-ASEAN trade remained limited across most solar PV products. The strong reliance on the US as its largest export market for finished goods and on China for key inputs, especially wafers, exposed the region to risks from trade tensions between the two great powers. Potential higher tariffs on solar PV products from some AMS, due to their ties with Chinese manufacturers, could deter Chinese companies from operating in the affected AMS, potentially undermining local industries in these AMS.

This highlights the importance for AMS to diversify their export markets and import sources. For instance, ASEAN could consider expanding its export of solar PV cells or modules to European countries such as Germany or other emerging markets like India; both were ASEAN's traditional export markets.

Establishing manufacturing capabilities locally and strengthening regional integration within ASEAN also helps reduce reliance on China for intermediate inputs. For example, wafers can be imported from Singapore, while polysilicon and silica sands can be imported from Malaysia. Additionally, more machinery can be exported to Malaysia and Vietnam, the region's leading exporters of solar PV cells or modules, from Singapore.

In conclusion, while ASEAN has made significant strides in establishing itself as a major exporter of finished solar PV products, addressing its reliance on imported intermediates and machinery is critical for long-term growth. By fostering regional collaboration, diversifying trade partners, and strategically investing in upstream capabilities, ASEAN can strengthen its position in the global solar PV industry while mitigating vulnerabilities arising from geopolitical tensions and external dependencies.

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