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Supply Chain Jigsaw:
Piecing Together the Future Global Economy

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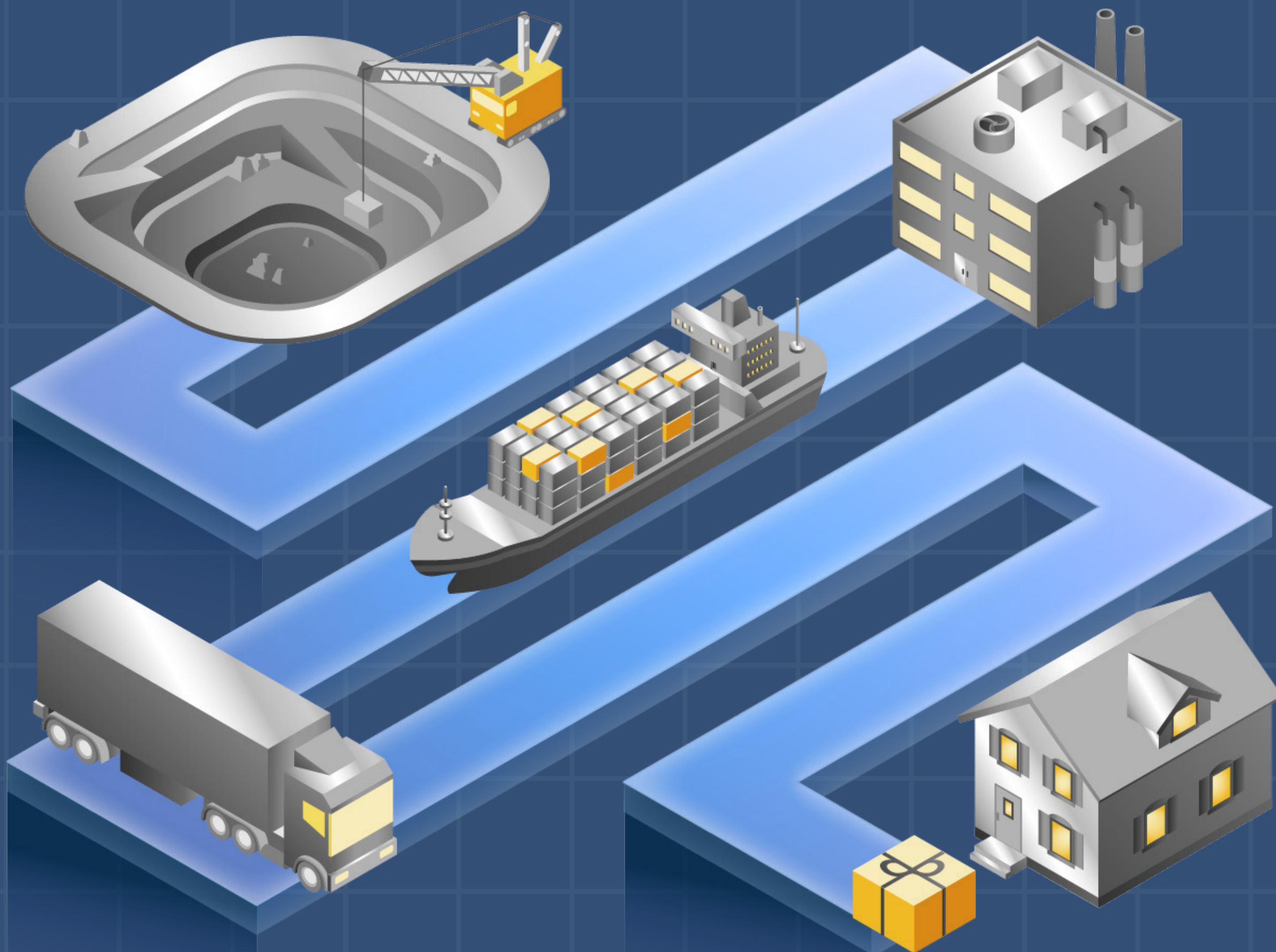

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Executive Summary

If a single device were to define the last decade, the iPhone would be a worthy candidate. Launched by Apple in the summer of 2007, the iPhone not only sparked a revolution in the consumer electronics industry, it launched new business models, services, and ecosystems. It is a device as iconic as it is ubiquitous.

But the iPhone was just the tip of a tech iceberg. During 2007-2012, when the world economy was reeling from the global financial crisis, the tech sector saw some of its best years. Among many innovations over those five years, two stand out: artificial intelligence (AI) firm DeepMind was founded (2010) and Tesla launched a best-in-class fully electric sedan (2012).

DeepMind, eventually acquired by Google, would go on to create AlphaGo, the computer program that defeated the reigning human Go champion in 2016. Tesla's Model S sedan would pave the way for a fundamental shift toward electrifying the auto industry, with major automakers now aiming to launch electric vehicle (EV) models over the next couple years.

What connects the Tesla sedan, the Apple iPhone, and Google's DeepMind is not simply the fact that they revolutionized how we work, live, and play. What makes these products possible is a set of complex inputs—lithium-ion batteries, OLED displays, and AI chips—that may prove as important in the 21st century as steel, cement, and oil were in the 20th.

Without li-ion batteries, for example, there would be no smart phones or EVs. Nor would the training of advanced AI algorithms be possible without AI chips. OLED glass displays, too, will be the medium through which we interact with the digital world via our phones, cars, and home appliances.

These inputs are not "commodities" per se—they are not as simple as steel rebar or cement blocks. But to the extent the future global economy depends on pocket-sized computers, EVs, and AI applied to virtually all industries, these inputs will likely take on "commodity-like" attributes as they become pervasive and their production costs fall.

Many countries and companies see this Fourth Industrial Revolution as a competition for technological leadership and industrial prowess. New industries have lower barriers to entry, making it easier for countries like China to establish a foothold. Moreover, many governments seek to nurture emerging industries, which means the balance between state support and market incentives can be harder to calibrate.

There is no fiercer competition in this arena than that between the United States and China. This situation should come as no surprise, since both countries have the resources, capital, and talent to lead across these industries. While their economic models are different, both countries recognize the key role of emerging technologies. Therefore, how and where each country invests today, given the long time horizons and the capital-intensive nature of these sectors, will have profound implications for their respective economies in coming decades.

But this competition is not exclusively bilateral. Many other countries are key nodes in the globalized supply chains of these industries, chief among them Japan and South Korea. In the provision of natural resources, such as cobalt and lithium, the competition extends as far as Africa and South America. Even as China and the United States compete with each other, both states are balancing their relationships with other important suppliers.

The contours of competition can be seen more clearly from the concentration of supply chains in various countries and is best viewed from a global, rather than bilateral, perspective. Supply chain ecosystems tend to develop gradually over years and decades. But once fully formed, it can be difficult to overcome first-mover advantages, because the forces of economic agglomeration and the stickiness of tech ecosystems can raise switching costs.

Therefore, simply saying one country is more competitive at the national level has little meaning without examining the global supply chains of key inputs required to make a particular industry competitive. This insight matters because various countries have established different advantages or have different risk profiles along different segments of the supply chain.

Making sense of this intertwined reality is the goal of MacroPolo's digital book, "Supply Chain Jigsaw." From upstream to midstream to downstream, each of the three chapters analyzes the markets, technology, and supply chains of 1) li-ion batteries, 2) OLED displays, and 3) AI chips.

While the full research product is best experienced in its digital form, this epilogue summarizes its main insights and findings. It synthesizes each chapter's conclusions and then offers key takeaways for policymakers to consider as part of any national strategy to ensure the United States remains competitive in the industries of tomorrow.

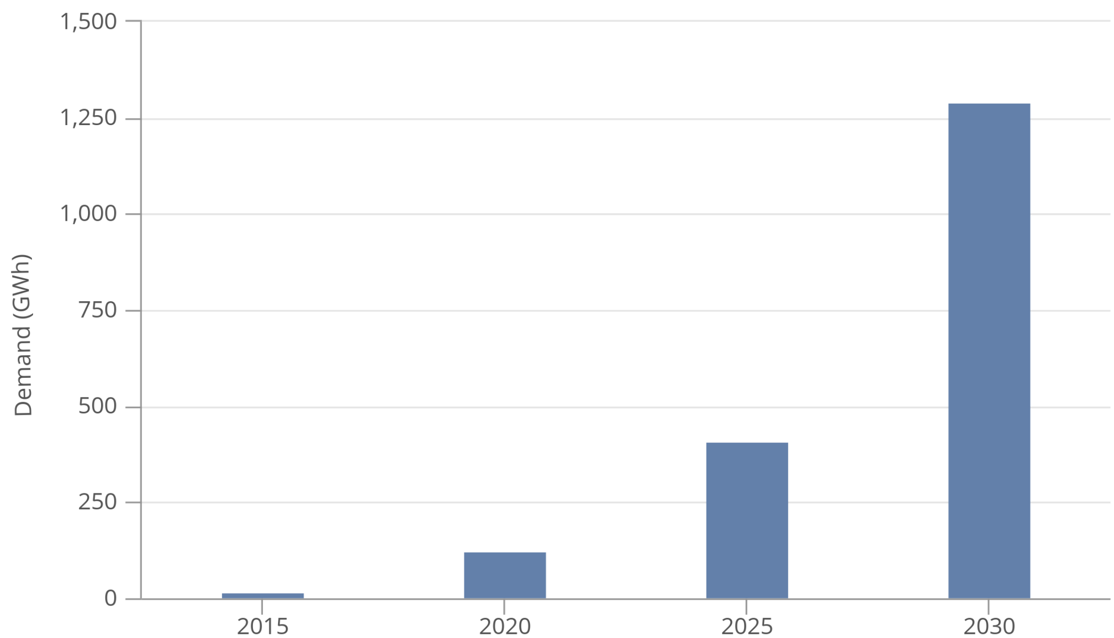
This is an Executive Summary of MacroPolo's "Supply Chain Jigsaw." The entire digital research product, including sources and references, can be viewed at our website: https://macropolo.org/digital-projects/supply-chain/

Chapter 1: Lithium-ion Batteries

Why Do Lithium-ion Batteries Matter?

Just as the internal combustion engine (ICE) made oil a crucial commodity, the continued electrification of transport will make li-ion batteries a global necessity. Since they are a significant share of total EV costs, the industry consensus is that when the cost of these batteries falls below $100/kWh—forecast for later this decade—EVs will become cost-competitive with ICE vehicles and mass commercial adoption should begin. Demand is set to jump from 19 GWh in 2015 to 1,293 GWh in 2030 (see Figure 1), and Goldman Sachs estimates that this market will grow from under $10 billion today to $60 billion in 2030.

Figure 1. Projected Demand for Li-ion Batteries for Transport



Source: Bloomberg.

Lithium-ion Battery Technology and Supply Chains

Different types of li-ion batteries are determined by their specific chemistries. But they share the same basic structure and components. All li-ion batteries have a cathode and anode at each end, while the inside is filled with electrolyte and separator for the electrons to pass through. The cathode is composed of different materials while the anode is mainly graphite.

The two main chemistries of li-ion cathode are NMC (nickel, manganese, cobalt) and NCA (nickel, cobalt, aluminum). Both these chemistries have some of the highest energy densities but are not as safe as other types, with Tesla backing the NCA chemistry to date. In general, battery makers are trying to reduce the amount of cobalt needed because it is expensive and comes from riskier countries like the Democratic Republic of Congo (DRC).

These raw materials and the main components of the battery—cathode, anode, separator, electrolyte—constitute the upstream and midstream segments of the supply chain. For inputs such as lithium, cobalt, and graphite, countries like Chile, Argentina, DRC, China, and Australia dominate. For the key components of the battery in the midstream, that supply chain is dominated by Japan, South Korea, and China, with the US playing a role in supplying separators. In terms of downstream production of battery cells, China commands a 61% global share, while the US share of 9.5% is centered almost entirely on a single company: Tesla.

Takeaways

- As the li-ion battery rises in importance, so too will the raw materials that go into it. Present concerns over lithium supply could be overcome as many reserves remain untapped, including in the United States, but the concentration of cobalt reserves in the DRC presents supply chain risks. This will likely accelerate the shift toward battery chemistries that significantly reduce cobalt content.

- Other battery inputs, such as nickel and manganese, do not face supply bottlenecks and are dispersed across more stable parts of the world. Graphite, too, is abundant, although China is a leading supplier and consumer of it, and influences its price. If advances in silicon-based anode materials become commercially successful, China could also benefit as it produces large volumes of silicon.

- China is now the world's largest producer by volume in midstream li-ion battery components such as cathodes, anodes, and electrolytes. In the downstream, too, battery cell production is increasingly shifting to China, where the domestic industry is dominated by CATL and BYD.

- China's dominance in the li-ion battery supply chain is not yet assured, however, as Japan and South Korea remain highly competitive in various segments of the battery supply chain, including downstream assembly and midstream components. These dynamics imply that, without significant investment or policy incentives elsewhere, the li-ion battery supply chain will agglomerate in East Asia in the foreseeable future.

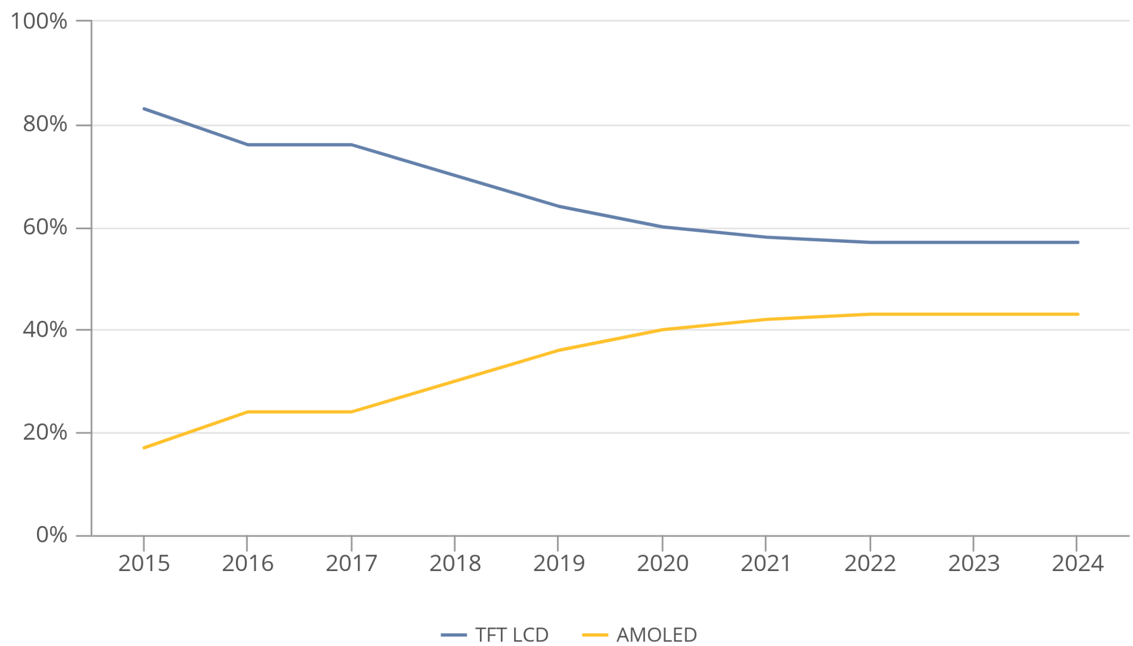
- The US li-ion battery industry depends largely on Tesla. But production tends to migrate toward end demand. If China continues to offer more effective support to its EV industry, then more global battery cell production will shift to China, further reinforcing East Asia's dominant position in the industry.

Chapter 2: OLED Displays

Why Do OLED Displays Matter?

There are more than three billion smartphones in the world, all of which are fitted with an advanced glass display. For many years, the dominant screen technology was liquid crystal display (LCD), but by 2021, more than 800 million smartphones are expected to ship with a new technology: organic light-emitting diode (OLED). OLED displays are projected to feature on 43% of all smartphones by 2024 (see Figure 2).

Figure 2. Smartphone by Type of Display (%)



Source: IHS

OLED displays are both superior to and costlier than LCDs because they are thinner and exhibit better color contrast, higher luminance, wider viewing angles, and lower energy consumption. And they are vital to the emergence of flexible and foldable displays. Displays are typically the most expensive component of a smartphone, representing about 30% of the total production cost of an iPhone X, for example.

But these costs should drop as more devices switch to OLED displays. Tablets, TVs, smart watches, and head-mounted displays are just some of the non-phone products that will drive this demand. No wonder that the market for OLED flat-panel displays is forecast to increase from $12.2 billion in 2015 to $58.7 billion in 2024, or about 40% of total flat-panel revenues.

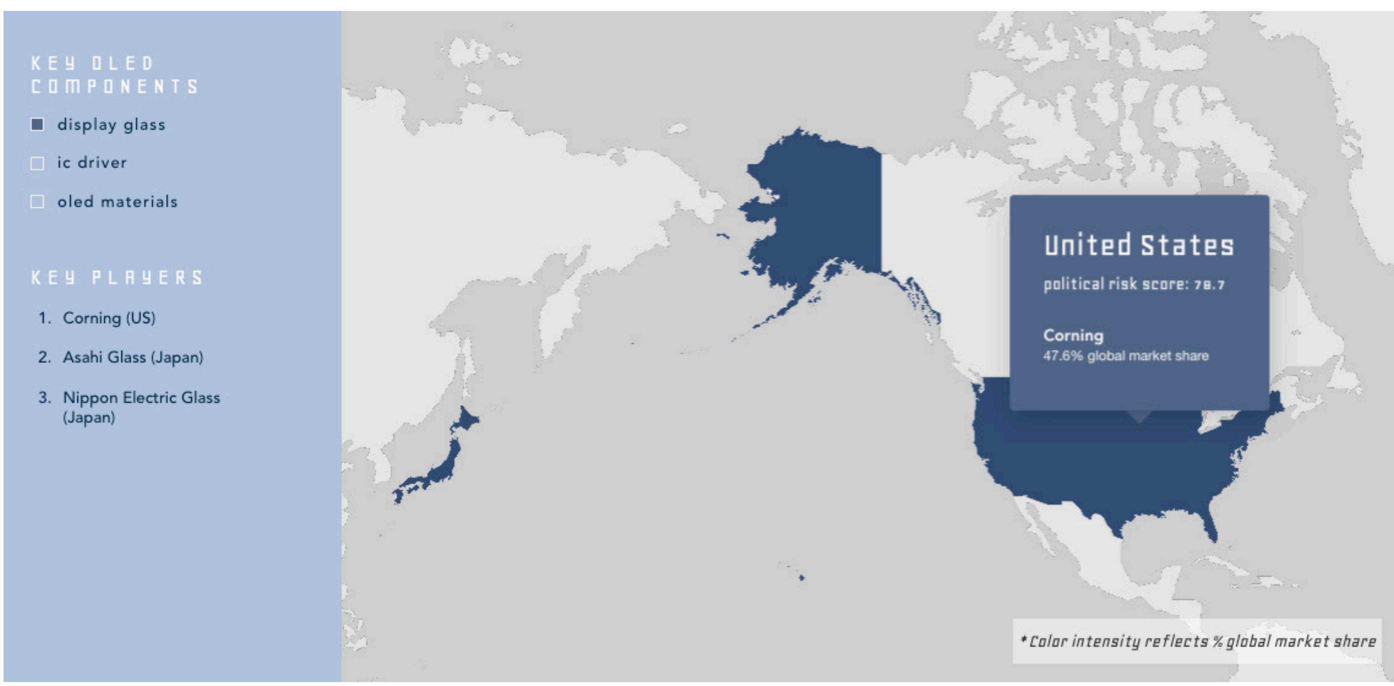
As production expands to accommodate increasing demand, the cost of OLED displays should fall dramatically. The manufacturing cost of a 55-inch UHD TV panel with an OLED display fell from 426% of LCD costs to 245% of LCD costs in the two years from 2015 to 2017. If this trend continues, then OLED technology could reach cost parity with LCDs in the coming decade, accelerating its rise to become the dominant display technology.

OLED Display Technology and Supply Chains

OLED technology is divided into two main types: passive matrix (PMOLED) and active matrix (AMOLED). The key difference is that AMOLED includes thin film transistors (TFT) that manage the pixels to allow for much higher resolution and virtually no limitation in screen size. First commercialized in 2003 by a joint venture between Eastman Kodak and Sanyo Electric, AMOLED has become the preferred OLED type for most high-end consumer electronic devices.

An important component in any OLED screen is glass, particularly the specialty Gorilla Glass that is manufactured by US-based Corning. The glass has to be light, durable, and scratch resistant, and it undergoes a special ion exchange process to fortify the glass. According to Corning, Gorilla glass can be found on six billion devices today, including those from Apple and Huawei.

Beyond the cover glass, other types of specialty glass are used in the various layers of the OLED display such as the encapsulation. Other layers of the display include the front plane, which is the emissive layer composed of organic materials, and the backplane that includes the IC driver and TFT.



These different layers constitute the upstream and midstream of the supply chain. The main raw material for glass is silica sand, which is abundant around the world, with the United States (40%) and China (27.5%) being the two leading producers. The midstream—composed of the display glass, IC drivers, and OLED materials—is dominated by South Korea, Japan, and the United States.

When it comes to display glass, the United States and Japan are basically at about 48% and 47% global market share, respectively. America is also a leading supplier of OLED materials, with roughly a 45% market share, while South Korea and Taiwan combined make up some 80% market share of IC drivers. Finally, South Korea's Samsung dominates the downstream OLED display production, accounting for 90% of the global end-use production capacity.

Takeaways

- The supply chains for OLED displays are concentrated in East Asia, and mostly in South Korea and China, with Japan a distant third. These countries are also where the consumer electronics industry, the largest source of OLED demand, is concentrated.

- The most important segment of the OLED supply chain is the midstream manufacturing of display inputs, a sector in which US firms have a significant presence. UDC, for example, is a US firm that makes organic materials needed for displays and supplies to both South Korean and Chinese OLED manufacturers.

- These American firms have competitors in Japan and Germany, but they control key technologies and far outspend their rivals on R&D. New York-based Corning, which supplies specialty Gorilla glass, is estimated to have spent 20x more on R&D than Japanese manufacturers from 2013-2017. Corning has reinforced this advantage by co-locating its facilities with customers in China and South Korea.

- One potential risk in these supply chains is the monopolization of downstream OLED manufacturing by a handful of companies in South Korea and China. With South Korea maintaining a 90% global market share in terms of OLED sales, some device-makers have sought to diversify suppliers. Recent economic skirmishes between Japan and South Korea have exacerbated this dynamic.

- To the extent supplier diversification continues, Beijing-based BOE likely stands to benefit. BOE can easily tap state financing and an enormous domestic market, making it a potential challenger for the OLED market. Although BOE still trails South Korea's domestic champion Samsung on cost and yield rates, it is catching up fast. Moreover, BOE could exploit the recent push by OLED customers to reduce dependency on South Korean manufacturers to bolster its market share.

- Although the national security implications of OLEDs are limited, OLED glass screens will become the most common digital interface in our personal and professional lives. Thus, disruptions to the supply chains for OLED displays could increase consumer prices, interrupt business operations, and even hamper certain military activities.

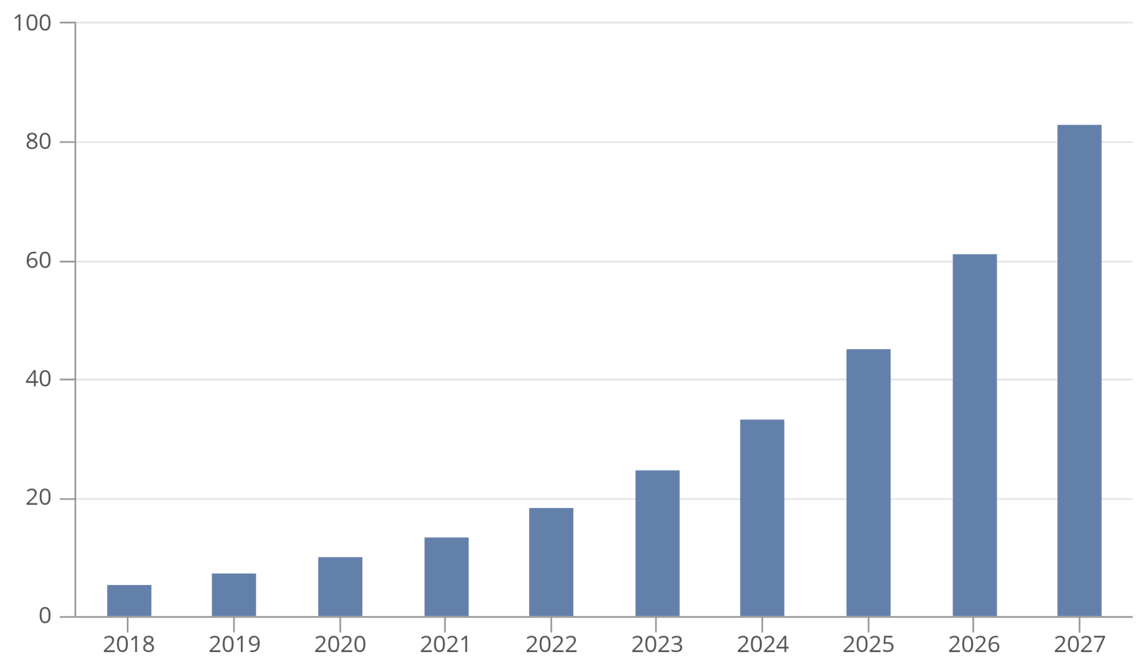
Chapter 3: AI Chips

Why Do AI Chips Matter?

Semiconductor chips are the engines of our digital lives. Fitted with billions of electronic transistors that constitute elaborate integrated circuits, these chips power everything from laptops and mobile phones to smart TVs and EVs. And the next frontier in this $450 billion industry is customized chips that support the high-order computational demands of artificial intelligence (AI) technologies. These "AI chips" are forecast to account for up to 20% of semiconductor sales by 2025.

The application of AI technologies to numerous sectors of the real economy is the key growth driver for the AI chip industry. Designed specifically for AI applications, these chips are indispensable hardware in the AI revolution. Global sales of AI chips are expected to increase more than ten-fold by 2027 (see Figure 3). As such, specialized AI chips will claim an increasing share of the global semiconductor market.

Figure 3. Projected Global Sales of AI Chips, 2018-2027 ($ Billion)



Source: Insight Partners.

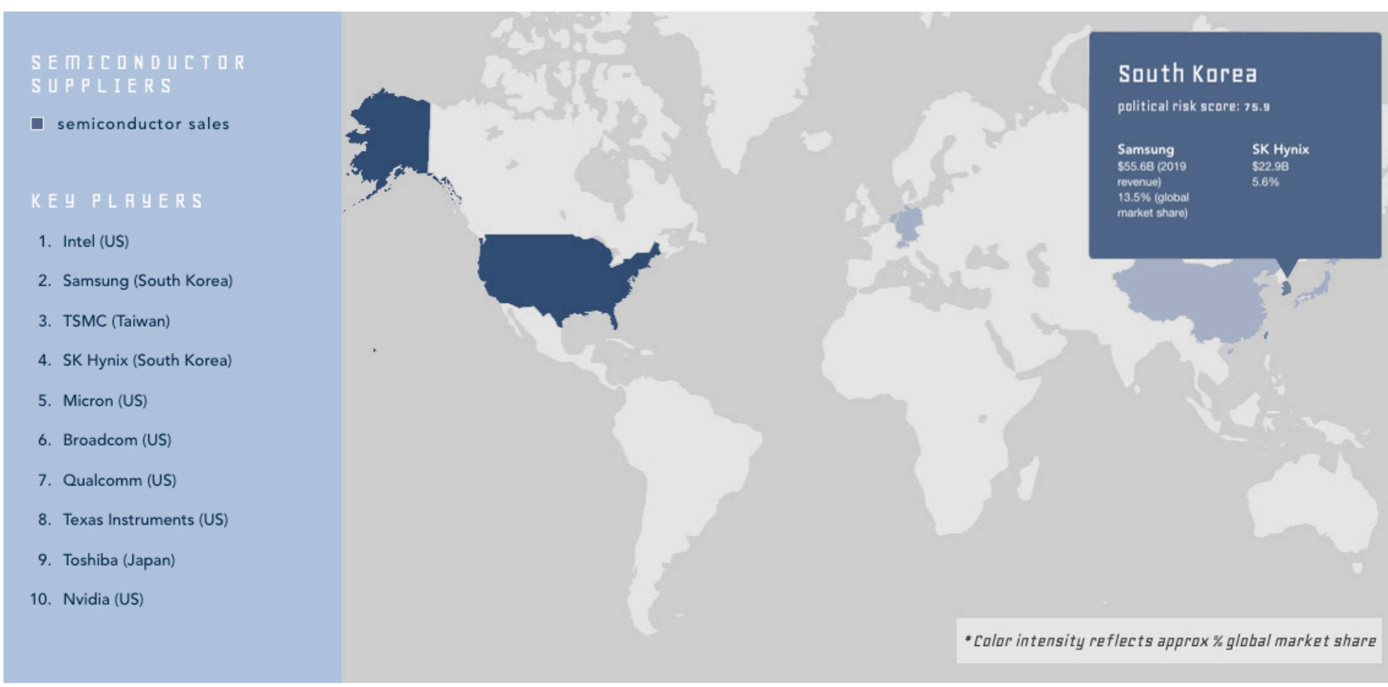
The market for AI chips is basically divided into two segments: training and inference. Training is when enormous volumes of data are fed into AI algorithms to build and refine the powerful predictive models necessary to perform complex tasks in dynamic environments. Inference, which will increasingly become the dominant market for AI chips, is when these trained models are applied and adapt to real-time decisions based on real-world stimuli. Training usually occurs in the "cloud" at data centers, while inference typically happens at the "edge," which means inside devices like phones, laptops, surveillance cameras, or autonomous vehicles.

The diverse use cases and specifications of AI chips have led to what industry insiders describe as a "Cambrian explosion" of chip design startups. Many Chinese companies, and especially Huawei, have begun to capitalize on this opening by investing heavily in AI chip design. The dynamic nature of this emerging sector could well enable them to become leading providers.

AI Chip Technology and Supply Chains

The rising generation of AI chips, mostly application-specific integrated circuits (ASICs) and field-programmable gate arrays (FPGAs), offer superior performance compared to traditional central processing units (CPUs) and graphic processing units (GPUs), the other chips that appear on a "system-on-chip" (SoC). An SoC is a "master chip" that contains multiple functions beyond the CPU, which is the workhorse of all basic computing functions. As part of the SoC, AI chips are customized for specific end-uses and programmable for narrowly-defined functions. In other words, they're optimized for discrete AI tasks and are often referred to as AI accelerators.

Most chips are built on top of core underlying architectures whose intellectual property (IP) is held by a handful of key firms, chief among them ARM Holdings. Even though there isn't a



standard AI "SoC", most have these main components: the CPU, GPU, a neural processing unit, and dynamic random-access memory (DRAM).

Manufacturing a chip requires core IP, design, fabrication, and assembly, which together form the midstream segment of the supply chain. Japan, the United States, and the United Kingdom dominate the chip IP segment, with UK's ARM holding nearly a 45% market share. China so far has one company that is competitive in this arena, but it only holds a 1.8% market share. The United States, the Netherlands, and Japan dominate the crucial market for semiconductor manufacturing equipment used in fabrication. Dutch company ASML virtually monopolizes the supply of photolithography machines, which each cost around $120 million.

Taiwan plays a crucial role in the actual fabrication of chips. Taiwan's chip foundries make up more than 80% of the global market, while mainland China's SMIC foundry has just 6.6%. But China is gaining ground on Taiwanese firms when it comes to the final stage of chip assembly, which is typically handled by low-margin outsourced contractors.

The downstream segment, which is determined by global sales of semiconductors, is dominated by the United States, South Korea, and Japan. In fact, no Chinese company yet appears in the top ten in terms of global sales. American companies occupy 35% of this market, while Korean, Japanese, and Taiwanese companies combined make up roughly one-third.

Takeaways

- The upstream segment of the AI chip supply chain is similar to that for other semiconductors, consisting mainly of silicon and boron. Both elements are relatively abundant and are not at major risk of supply disruptions. The midstream segment, however, is complex and involves suppliers across multiple continents. This segment can be divided into three stages: design, fabrication, and assembly and packaging. These three steps create roughly 45%, 45%, and 10%, respectively, of a chip's value.

- The design of AI chips typically relies on core IP licensed from a handful of American, British (e.g. ARM Holdings), and Japanese firms. Other companies then design custom chips based on this core IP, including specialized "fabless" design firms that outsource chip fabrication (e.g. Qualcomm, Broadcom), and "integrated device manufacturers" (IDMs) that also fabricate their own chips (e.g. Intel, Samsung).

- Fabrication is perhaps the crucial link in the supply chain, and the one with the most potential for disruption. Barriers to entry are high, involving enormous capital expenditure, atomic-precision manufacturing equipment, and highly skilled personnel. Taiwan's TSMC, the "Foxconn of semiconductors," dominates the contract fabrication market with an almost 70% market share in 2018. It makes the chips designed by most major semiconductor players, from Qualcomm to Apple and Huawei.

- The final segment in the midstream supply chain is "outsourced semiconductor assembly and testing (OSAT)." With the exception of IDMs, which operate their own assembly and testing operations, most chip manufacturers rely on contractors for this highly-competitive and low-margin stage of the manufacturing process. Several leading OSAT firms are Taiwanese, though mainland Chinese firms are increasingly competitive.

- The downstream segment of AI chip supply chains is the distribution of finished chips for their various end-uses in cloud servers or edge devices. While no Chinese company appears in the top ten global suppliers, the advent of custom AI chips could give Chinese firms an opportunity to move up the value chain. Despite decades of industrial policy, China has so far struggled to surmount the formidable barriers to becoming a world leader in advanced chip fabrication.

- As the world's largest buyer of semiconductors, China does hold some leverage. Shutting Chinese firms out of global supply chains for AI chips would eliminate a considerable source of revenue for Western semiconductor firms. Such a move would limit the ability of these companies to sustain the substantial capital and R&D investment—typically around 30% of revenue—needed to maintain technological leadership over competitors like Huawei. Therefore, for the United States and its allies to retain technological leadership, a more prudent approach may be more effective.

Key Lessons for Policymakers

These three technologies—li-ion batteries, OLED glass displays, and AI chips—underpin emerging industries over which countries and companies are vying for leadership. This competitive dynamic creates tension between the impulse of national governments to champion domestic industries and the market logics of openness and innovation.

Globalization sits at the heart of this conundrum. Economic nationalists argue that international supply chains make other countries more prosperous at their own country's expense, and additionally expose domestic firms to technological leakage and security risks.

But, as a detailed examination of these industries and their supply chains show, a binary framing of economic prosperity and national security is something of a false choice. Many US firms depend on global markets for revenue and have spent years, if not decades, building secure supply chains. For most companies, supply chain decisions, particularly when they concern sophisticated industries like EVs and semiconductors, are long-term ones.

This means the cost of diverting or reshoring established supply chains can be substantial because of the new uncertainties and enormous capex involved. And when it comes to core IP, the smartest firms have long found ways to protect their advantages within global supply chains.

Still, policymakers are faced with the dilemma of balancing doing what's best to ensure these emerging industries can thrive with doing what's necessary to protect national security. This is taking place in a context where strategic competitors, the United States and China, also often happen to be the most pivotal economic nodes in these industries.

Given these dynamics, the three case studies above can offer some generalizable insights that may be useful for policymakers to consider when deciding how to regulate the supply chains of high-tech products. As is evident, every industry has its own unique attributes and specific conditions, but these principles should be broadly applicable.

First, sudden disruptions to existing supply chains can cause unintended consequences that counteract the original aims of such policies. High-tech products generally comprise dozens or even hundreds of individual inputs, creating complex interdependencies between customers and suppliers around the world. For example, US semiconductor companies depend on Chinese customers for a significant portion of their profits, and trying to cut China out of the market could actually reduce the revenues, reinvestment, and competitiveness of American companies. If governments impose stringent export controls on their products, then both foreign and domestic manufacturers could be incentivized to further offshore production.

Second, innovation in emerging technologies takes many years of R&D, meaning that staying ahead of the competition is perhaps the surest way to protect both national security and economic prosperity in the long run. The key reason why the United States dominates the midstream supply chain for OLED displays, for instance, is that Corning spends up to 20 times more on R&D than overseas competitors. As such, for Western governments that traditionally played the role of referee rather than participant in the economy, they should focus more on funding basic science research, incentivizing commercialization of novel innovations, cultivating public-private collaborations, maintaining open global markets, and attracting global talent.

Third, if greater output of a certain product would achieve other important goals, like correcting for environmental externalities and other types of market failures, then governments can improve incentives without resorting to blunt instruments such as tariffs or outright bans. Many governments implement policies that nudge emerging industries into maturity—Tesla, for example, benefitted from government loans—and this strategy makes sense as industries often confront demand shortages in their infancy. An important reason why China became a leading manufacturer of li-ion batteries was that its government introduced consumer subsidies, industry regulations, and procurement guidelines that helped bolster demand and create a market for EVs.

But countries do not need to become China to compete with it, as Chinese-style industrial policy comes with its own risks. While generous state subsidies has achieved some impressive results, they have also produced bubbles, generated excess capacity, and stifled competitiveness. Indeed, China still lags the global performance and cost frontiers in many of the industries examined above. Beijing has also begun to phase out many subsidies, realizing that excessive industrial policy has its drawbacks.

How the future global economy is shaped requires a better understanding of both the benefits and costs of today's highly complex but highly functional global supply chains. If these supply chains are truly dysfunctional and exceptionally risky, then consumers would likely collectively feel the impact because that would show up in the end products. Yet for the last 70 years, as a system of US-led global commerce became more integrated and efficient, it is difficult to argue that it hasn't served its intended purpose of increasing overall global prosperity.

Of course, risks exist in any globalized supply chain, and many multinational companies are at the forefront of ensuring that their supply chains are secure and that their products are sound. And just because global supply chains largely work as intended, that does not mean the concentration of certain parts of tech supply chains in different countries is without risks. So national security should be taken into account and addressed seriously as part of the ongoing debate about economic "decoupling" between the United States and China.

But it will remain a challenge for policymakers to identify a form of decoupling that controls for security risks without undermining the enduring strength of their multinational companies. We hope these lessons can help shed light on the tradeoffs between economic progress and security concerns.

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Illustration by Corey Middleton and designed by Young Kim