zvei
electrifying ideas

From chips to chances
The importance of and the economic case for supporting microelectronics

In collaboration with strategy& Part of the PwC network

German Electro and Digital Industry Association (ZVEI e.V.)

Contents

Summary of findings

The microelectronics industry is a central pillar of the European economy, and forms the backbone of digitalisation and electrification. It drives innovation and strengthens economic growth in Europe's key industries and across the entire value chain. Through its products and innovations, it enables end-application industries to develop high-performance, cost-efficient and competitive systems and position themselves successfully in the market. As such, it is a critical factor for Europe's future competitiveness and technological sovereignty.

This study underlines and quantifies the importance of the microelectronics industry for the European economy, society, and technological sovereignty.

Chip shortages cause significant harm to the European economy

The chip shortage in 2021-2023 led to an estimated loss of GDP in Germany alone of some EUR 102 billion, corresponding to 2.4% of annual German GDP in 2022. The analysis demonstrates the dependence of the European applications industries on microelectronics. In addition, the after-effects of the chip shortage and of the coronavirus pandemic have altered global market relations, due to high inventory levels and the subsequent price collapse in the microelectronics industry. This has particularly affected European PCB (printed circuit board) manufacturers and EMS (electronic manufacturing services) service providers in competing globally. Due to the dynamics of the microelectronics industry, shortages will occur again in future. Measures to improve demand transparency and to strengthen the value chain are still needed, to reduce the negative effects as far as possible in the event of similar situations recurring.

The current support for microelectronics as an initial step for economic growth in the EU

The current funding programmes will contribute to an annual increase in gross value added of EUR 33 billion in the EU. If all planned projects are implemented, this leads to additional tax receipts of EUR 7.9 billion per year which can be invested in future growth. In addition to this, the funding will generate 65,000 new jobs across the value chain and in other industries – for every job with a semiconductor manufacturer, there are around 6 further jobs in associated enterprises and across the value chain. However, the study also clearly shows that the measures currently planned are not sufficient to achieve the ambitious EU targets. If no further investments are forthcoming, the share for European production capacities is likely to fall from 8.1% today to 5.9% by 2045. Perpetuating the current funding measures could possibly enable Europe to maintain its global share of manufacturing capacities at a near-constant level, given that it has continuously fallen in the past.

Sustainability as an opportunity and a challenge

In order to achieve full climate neutrality in Europe by 2050, up to 25% of European production capacities for semiconductors or chips is needed for domestic consumption. For Germany alone, electrification of industry and society will require up to 6% of European production capacities. At the same time, this presents a massive opportunity: Europe can not only decisively shape the development and production of climate technologies, but can also act as a global trailblazer for sustainable semiconductor production. The high proportion of renewable energies and the environmental standards create the ideal preconditions for this. But to exploit these opportunities, measures targeted on the energy infrastructure and close collaboration across the value chain are needed, to avoid creating a location disadvantage in global competition.

Strengthening microelectronics as a necessary condition for Europe's technological sovereignty

Technological sovereignty is the key to ensuring national prosperity and self-determination. It means being able to understand, manufacture and further develop key technologies, and actively shape them on an international footing. Microelectronics plays a key role in this, since it offers critical control points for the EU's technological sovereignty. Europe has strengths in the semiconductor design and manufacture, specifically in the areas of power semiconductors, micro-controllers and sensors, with global market shares of up to 54%. In addition, European companies have sizeable market shares in the stages of the value chain relating to equipment and tools, along with materials.

These strengths need to be supported in a targeted manner to secure and enhance Europe's position in the global value chain. At the same time, these strengths need to be exploited for their future differentiation potential. This will be achieved by combining them with additional technologies and requirements. In some places, existing strategic gaps still need to be closed, for example in the areas of design and advanced packaging. This is also true with regard to competences in the area of semiconductor manufacturing for AI and high-performance computing, so long as this is either delivered via the market and demand situation in Europe or of particular importance for future strengths.

Additionally, there is a need to catch up for PCBs and EMS. Particularly when it comes to materials, Europe is heavily dependent on imports from South-East Asia, and as a result it has lost a key control point. Moreover, PCB manufacturing and EMS capacities in Europe have contracted significantly over recent years, putting resilience at risk in the long term. It is only through a combination of further developing existing competences and targeted investment in new strategic skills that Europe can secure its technological sovereignty for the long term and guarantee its future competitiveness in an increasingly digitalised and connected world.

Introduction

It is no longer possible to imagine our economy and our society without microelectronics. Whether in the automotive industry, in mechanical engineering, in medical technology, in the defence industry, in aviation and space travel or in the electronics industry – it is the basis of innovation in practically every branch of industry, as an essential primary product. To guarantee technological progress and to meet with the other global actors on an equal footing, in the coming years the European states are planning to invest over EUR 32 billion[1] in the domestic microelectronics industry. As such, they are joining in with a global trend which is also being pursued by regions such as the U.S., China and South Korea. The aim is to secure their technological sovereignty and to strengthen long-term competitiveness, cost efficiency and speed of innovation.

The potential of microelectronics is particularly apparent in the green transformation. Here, it is used in climate technologies such as heat pumps, photovoltaic systems, wind farms and electromobility. As the backbone of digital and ecological change, it enables the transition to a climate-neutral and digital society.

In Europe, the semiconductor shortage in the course of the coronavirus pandemic heightened political awareness of secure supply and support for innovation. This led to measures such as the second IPCEI (Important Projects of Common European Interest)[2] and the EU Chips Act[3]. These funding instruments are intended to bring long-term benefit and societal value added to both the microelectronics sector and the economy as a whole.

But how assured are these measures? This study examines this question, putting a particular focus on the economic and social benefits of microelectronics as a key technology.

Objective of the study

As part of this study, the effects of funding support for microelectronics in Germany and Europe are to be analysed and quantified comprehensively. The aim is to evaluate the effectiveness of previous measures and to identify potential additional steps to strengthen Europe as a base for microelectronics. The results re intended to stimulate an informed discussion of the further development and adaptation of funding instruments, and to illustrate the value added from microelectronics for the European economy and society.

Opening the study, Chapter 1 offers a comprehensive **overview of the microelectronics industry** and its central role in the modern economy. It illuminates the components of the microelectronics ecosystem across the value chain, along with its interactions. Additionally, it presents the trends in demand for microelectronics, based on the various product categories.

Chapter 2 is devoted to **global supply chains and the effects of the chip shortage** between 2021 and 2023, which had a considerable impact on the German economy. Alongside this, the damage to gross domestic product (GDP) in the German economy caused by this shortage is quantified, future risks for the supply chain are assessed, and possible risk reduction measures listed.

Chapter 3 looks at **return on investment (ROI) from microelectronics subsidies**. The increased production capacity due to subsidy also leads indirectly to higher tax receipts. In the study, the expected growth in tax receipts per euro invested in semiconductor subsidies is calculated. The anticipated growth in production capacity in Germany and Europe for semiconductor products is estimated per amount of subsidy, and considered in relation to the anticipated, additional tax receipts. A similar quantification is undertaken with regard to creating new jobs.

In Chapter 4, the focus in on analysing the **importance of microelectronics in achieving climate goals** in Germany and Europe. Microelectronics is essential for climate technologies such as heat pumps, photovoltaic systems and electric vehicles. Based on the German and European climate goals, the demand for corresponding technologies is determined and the volume of microelectronics production needed for this is estimated. In addition, the advantages of Europe as a base for sustainable semiconductor production are analysed and the necessary framing conditions for further supporting Europe's economic competitiveness are discussed.

Lastly, Chapter 5 examines which **parts of the microelectronics value chain** are critical for a state's technological sovereignty. For this, the current strategic positioning of the EU in these areas is analysed and, based on this, possible areas for action are identified which could contribute to strengthening both Europe's resilience and its long-term competitiveness.

1 The microelectronics industry and its development

Technological developments alter the economy and society fundamentally. The irresistible push towards the digital era is transforming business models and production processes, as more and more data is processed and connected systems are integrated into all areas of life. Many sectors, such as energy and mobility, are also relying on increasing electrification. Automated systems and artificial intelligence (AI) have long become a fixed component in modern industrial and societal structures, encouraging efficiency and innovation. Microelectronics is playing a key role in this – it is the basis of the digital transformation and electrification.

1.1 The role of microelectronics for applications industries

Microelectronics encompasses a wide range of electronic components that are essential for practically all technological applications. These components form the backbone of modern systems – from consumer goods to cutting-edge industrial technologies. One example showing the key importance of microelectronics is the automotive industry (see Figure 1.1). Modern vehicles are heavily dependent on electronics and software. Systems such as infotainment, driver assistance and engine control are based on electronic components which process quantities of data in real time. Safety, efficiency and convenience can be guaranteed as a result. The components needed for this consist of semiconductors, passive devices and circuit boards

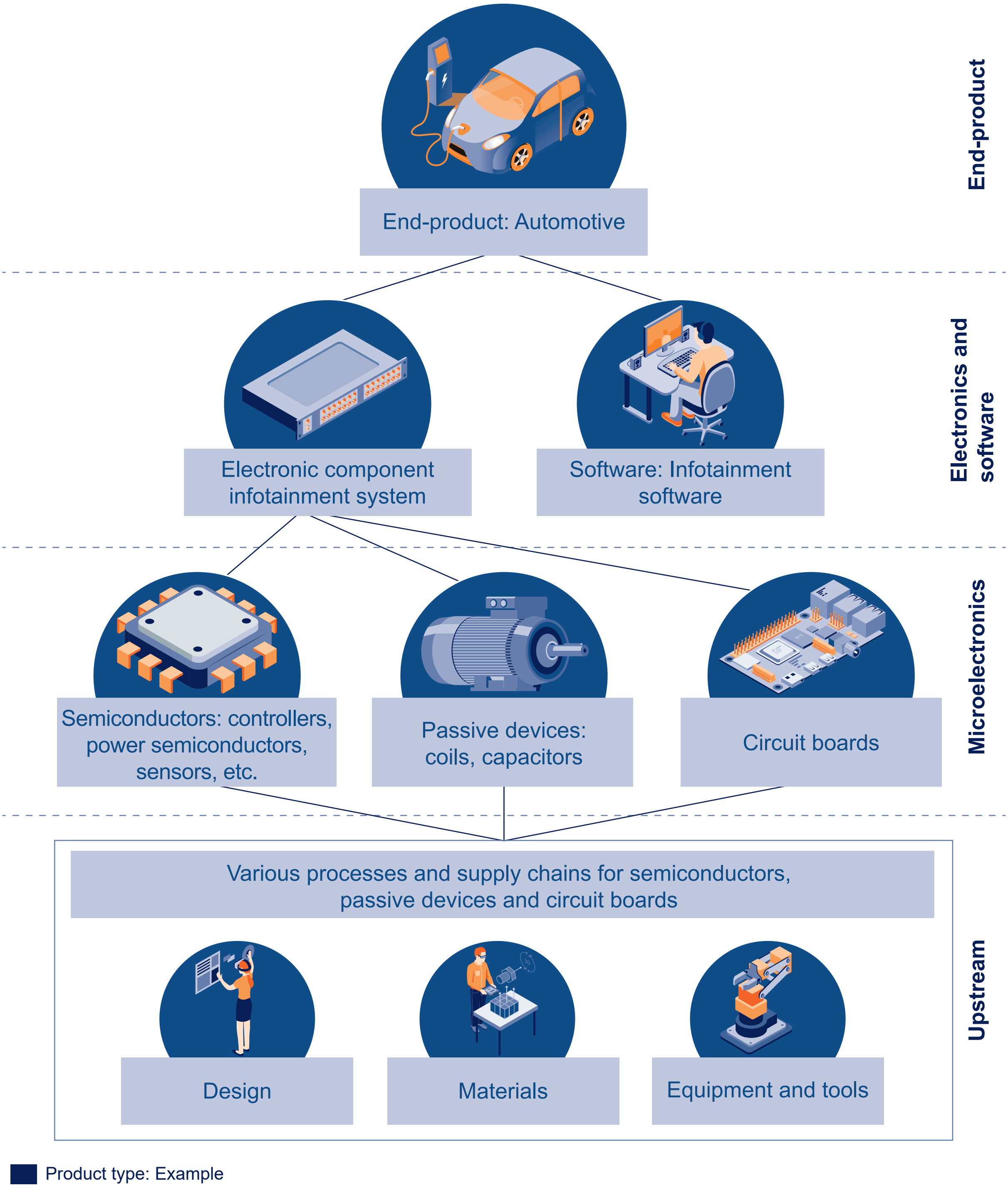
- Semiconductors are key components in electronics and electromechanics. They control, switch and measure electrical signals and are responsible for the functionality of electrical and electromechanical systems. Computing and communications systems, sensor systems and actuator systems would be unimaginable without semiconductors.

- Passive devices such as resistors and capacitors regulate electrical currents and voltages, without actively amplifying or controlling them.

- Circuit boards (or PCBs – printed circuit boards) serve as the carrier for electronic components and connect them via conductive conduits. They enable the transfer of current and signals between individual components, thereby ensuring that they work smoothly together.

The manufacture of these components requires special materials, challenging designs, and complex equipment and tools. However, microelectronics not only plays a key role in the automotive sector, but is also vital for numerous other sectors such as telecommunications, aviation and space travel, defence, and industrial automation. Their key function in these industries makes them an engine for future competitiveness and technological sovereignty.

Fig. 1.1: Microelectronics as a constituent part of the European economy



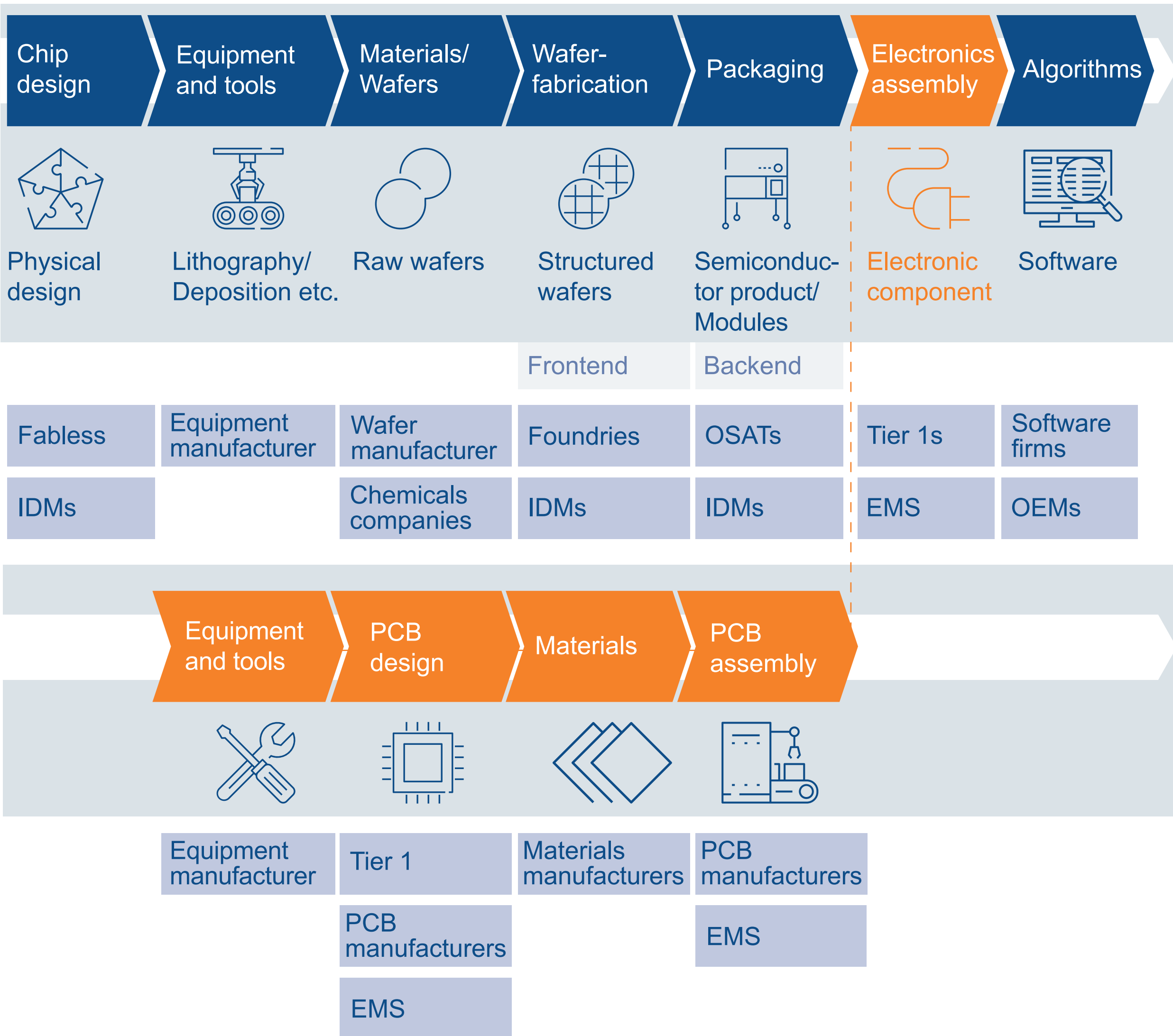
Source: Strategy& analysis

1.2 The microelectronics value chain

The microelectronics ecosystem is a highly complex network with various segments and actors along the value chain. Each individual module plays a vital role in the development, production and integration of microelectronic components and systems (see Figure 1.2). Moreover, the microelectronics industry is heavily globalised: the various areas of the value chain are distributed worldwide and with varying degrees of regional presence. This means that end-customers of electronics products are reliant on materials and process steps from various regions of the world (more on this in the chapter on technological sovereignty).

The chip design forms the first step of the value chain in microelectronics, and comprises detailed design and development of semiconductor circuits, which define the function of a chip. The design influences the performance capability, energy efficiency and manufacturability of a chip. In this area, companies produce blueprints for later production. Fabless companies in particular, such as NVIDIA or AMD, specialise in development, while their partners handle production. Integrated manufacturers (integrated device manufacturers, IDMs), by contrast, combine design and production in their company. The most important representatives of this segment include Intel, Infineon, NXP, STMicroelectronics and Texas Instruments.[4]

Fig. 1.2: Overview of the microelectronics ecosystem



Source: Strategy& analysis

A range of special raw materials are needed for the manufacture of semiconductors, with wafers and process chemicals in particular being essential. Wafers are thin discs of high-purity silicon or a combination of silicon with other materials (see technology trends in Chapter 5), which serve as the basis for the production of microchips. Since even the smallest of contaminations can impair the functionality of a chip, elaborate procedures are needed in manufacturing to ensure the necessary purity and precision. Process chemicals and gases are used in various stages of semiconductor manufacturing, for instance to clean the wafers or to structure circuits on the wafers. The quality of the raw materials is decisive for the performance and reliability of semiconductors. Leading suppliers of silicon wafers include Siltronic, Shin-Etsu Chemical and SUMCO[4], while BASF and Linde play an important role in the field of process chemicals and gases.

Front-end production, where the semiconductor chips are manufactured on silicon wafers, is a highly complex and technologically challenging process, involving up to 800 production steps. This massive complexity distinguishes semiconductor production significantly from the manufacture of other industrial goods (further details in Chapter 2). Production is undertaken on the one hand by specialist contract manufacturers (foundries), or alternatively by IDMs who manufacture their own chips. Foundries such as TSMC, Samsung Electronics, GlobalFoundries or X-Fab concentrate on manufacturing chips for external customers, whereas companies like Infineon, NXP, Texas Instruments and STMicroelectronics focus on production of their own products.[4] The technologies and production processes used in this vary depending on the application and the specific requirements of the respective chips.

Following front-end production, the semiconductor chips undergo the back-end process (packaging). Here, the individual chips – known as bare dies – are cut out from the silicon wafer and then integrated into a protective housing. This protects the chip against external influences and mechanical damage. In addition, the package plays a key role when manufacturing the electrical connections to other components. The packaging ensures that the chip can be integrated into end-products and perform its function in the optimal manner. In the back-end area, the market is dominated above all by Asian companies such as ASE Group or JCET, but also by some US companies such as Amkor.[4]

In the next step, the packaged semiconductor chips are mounted onto PCBs (printed circuit boards). PCBs are carrier materials for electronic components such as passive elements and semiconductor chips, and they provide the basis for connections and communications between them. Leading PCB suppliers are Zhen Ding Technology, DSBJ and Unimicron.[4]

Passive devices such as capacitors, coils and resistors, which unlike active devices cannot be actively controlled, are similarly essential for the manufacture of electronic systems. They regulate electrical currents and signals, which is fundamental for the functional capability of every electronic device. Leading companies in this area are Murata Manufacturing and TDK Corporation.

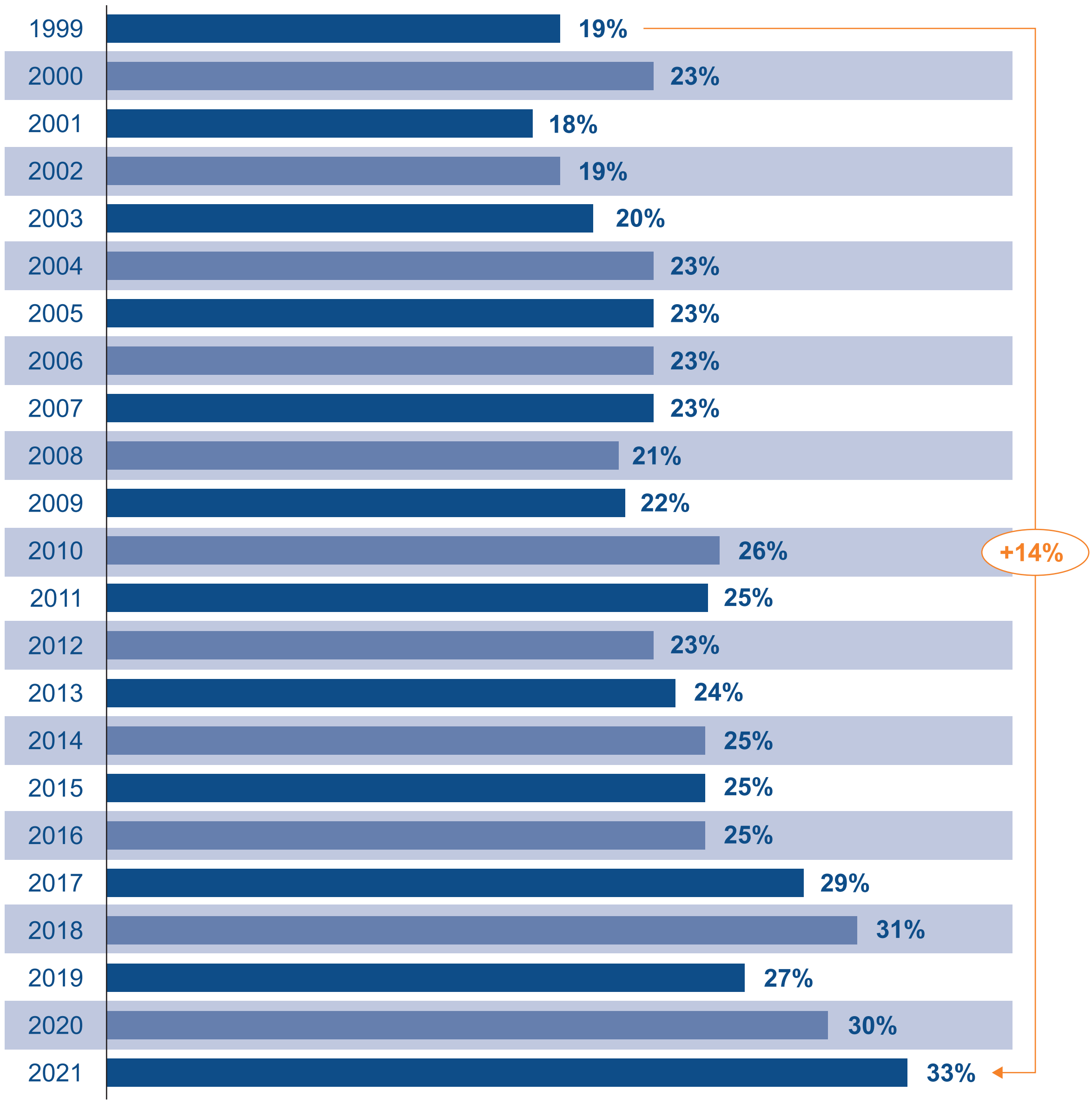
The assembly of the PCBs and their integration into electronic systems are often handled by electronics manufacturing service (EMS) companies, acting as contract manufacturers. This step is highly relevant, since the quality of the assembly and integration exert a decisive influence on the reliability and performance of the end-products. Major global EMS providers include Foxconn (known for manufacturing the iPhone), together with Jabil and Flex.[4] In parallel with this, either end-customers or third-party suppliers develop the necessary algorithms and software that control the functionalities of the end-products.

By the time the semiconductor chip has eventually undergone all its production stages, on average it has covered a distance equivalent to travelling 2.5 times around the world. Thus the value chains in the semiconductor industry extend over numerous countries and continents.

1.3 The semiconductor market grows into a trillion-dollar industry

In recent years, microelectronics has steadily gained in importance, since it represents the technological basis for many global developments. Megatrends such as digitalisation, electrification and automation, and the use of technologies such as AI, are driving this change. These key technologies, used for instance in renewable energies, electric vehicles or smart industrial applications, cannot be imagined without semiconductors. A clear sign of the growing importance of microelectronics is the rising share of semiconductors in electronic systems, which has increased from around 20% in the early 2000s to over 30% in this decade (see Figure 1.3).

Fig. 1.3: Share of value for semiconductors in electronic components, 1999-2021, as a percentage



Source: Statista 2023: Share of value for semiconductors in electronic systems from 1999 to 2021

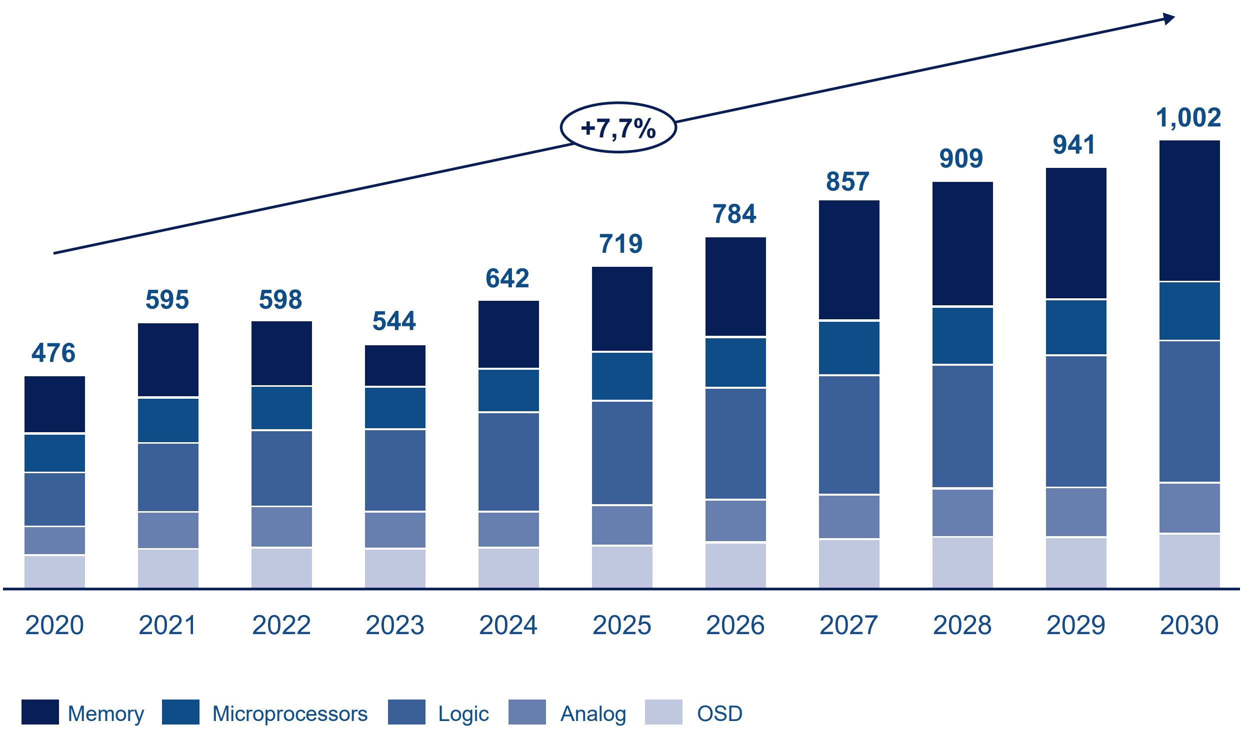
This is also reflected in the development of the semiconductor market. The megatrends cited above are driving demand for semiconductors and ensuring constant growth in the sector. According to the technology research and consultancy group Omdia, in 2024 the global semiconductor market will total around USD 650 billion, and by 2030 it will grow to over USD 1 trillion (see Figure 1.4).

The semiconductor market comprises seven types of components: memory, logic, microcomponents, analog, optoelectronics, sensors and discrete components. Of these, memory and logic products continue to make up the largest share in semiconductor sales, since the demand for computing power in data processing is continuing to increase, as is the demand for faster and more efficient storage solutions. The increasing spread of AI, the Internet of Things (IoT), data centres and cloud-based solutions require the processing of large volumes of data in real time. This significant demand for high-powered logic and memory chips is correspondingly reflected in the costs of manufacture and sales prices, and explains their dominant share in the overall market.

When it comes to quantities, other components are still dominant, such as discrete components, which play a key role in the increasing rise in electrification and which are exhibiting steadily-growing demand. Discrete semiconductors such as diodes, transistors and power switches are vital for efficient energy conversion and control, and are therefore essential for applications in electromobility and in the fields of renewables and industrial drive technology.

The same applies for sensors and analog semiconductors, which are key to the development of autonomous vehicles, IoT and modern communications applications. These components enable precise recording and processing of data in real time, which is vital for safety, connectivity and efficiency in an increasingly digitised and connected world. The persistent progress in these areas will continue to boost demand for these technologies.

Fig. 1.4: Development of the semiconductor market by component, 2020-2030 in USD billion



Source: Omdia Q3 2024

1.4 Semiconductors as the key component of modern technologies

One example of the many areas in which microelectronics is being applied can be found in the private home, with its progressive development towards increased efficiency and connectivity (see Figure 1.5). The use of microelectronics starts with the power supply itself – whether through green energy generated at home using PV panels on the roof or via electricity from the public grid, which is increasingly turning to renewable energies such as photovoltaics or wind power. Here, microelectronics enables the control, monitoring and optimisation of power generation and distribution.

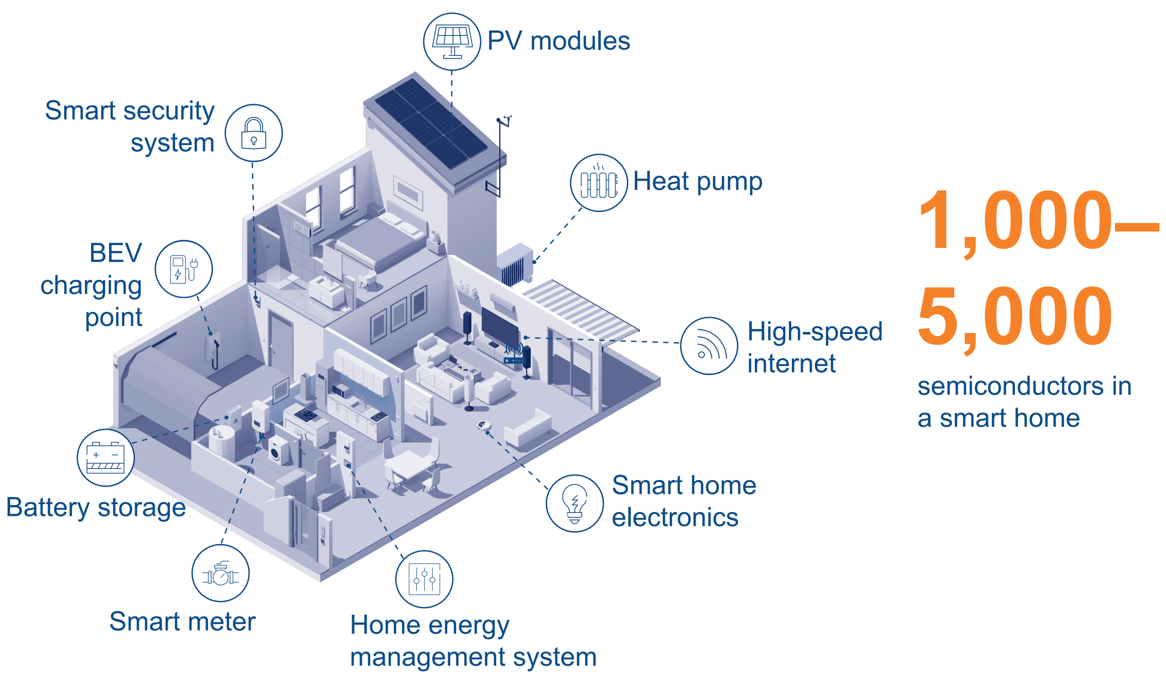
Battery storage systems store surplus energy and use semiconductors to control energy management and charging. This ensures reliable and efficient energy supply. Smart meters record and analyse energy consumption in real time, with energy management systems using this data to optimise energy consumption.

Modern heating solutions too, such as heat pumps which provide efficient heating and cooling, integrate microcomponents for precise temperature control and adjustment. Security systems in the home, including cameras and alarm systems, are similarly based on microelectronics, which is vital for image processing and data communications. Many households nowadays also have connected devices such as smart fridges and washing machines, and semiconductors are used for their functions, such as remote control and energy efficiency.

In addition, charging points for battery-electric vehicles (found in increasing numbers of homes) are similarly controlled by semiconductors, to ensure safe and efficient power transfer. These wide-ranging applications show that microelectronics is already playing a key role in many modern households. Microelectronics is contributing in a vital way to convenience, security, sustainability and energy efficiency, and will further gain in relevance in the years ahead.

A further example of the growing influence of microelectronics is modern vehicles, which are increasingly digitalised and connected (see Figure 1.6). Even today, many electronic systems are in use, essential for a variety of functions. Infotainment systems are based on high-performance microcontrollers and processors, and integrate various media and navigation services. Modern driver assistance systems – such as adaptive cruise control, lane assist or emergency brake assist – process data recorded by sensors in real time, to ensure safety.

Fig. 1.5: Overview of electronic components in smart home applications



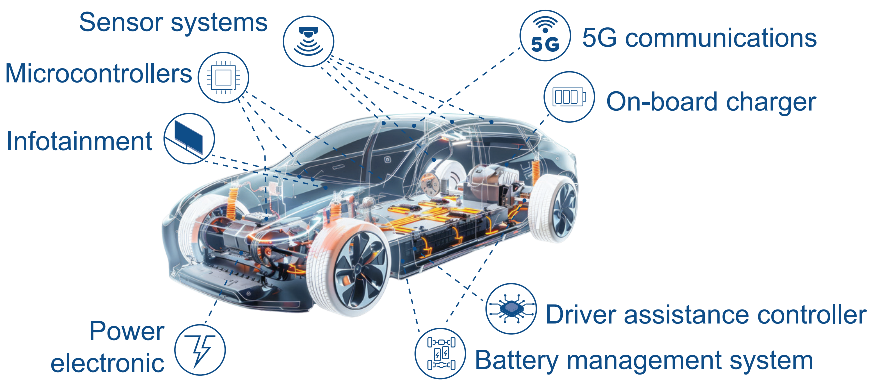
Source: Strategy& analysis

5G communications are also becoming increasingly important, since they enable fast, low-latency connectivity – which is a key precondition for the further development of autonomous vehicles. These technologies are vital for efficient management of the complex data flows between vehicles and their environment.

The influence is even more strongly apparent when it comes to vehicle electrification. In electric vehicles, the flow of energy from the battery to the motors and other systems is controlled by the power electronics. Alongside the on-board charger, which converts alternating current (AC) into direct current (DC) to charge the battery efficiently, the main converter plays a key role. It converts the direct current fed from the battery into alternating current, which drives the electric motors and thus makes it possible for the vehicle to move at all. During operation, the battery management system (BMS) monitors and optimises battery performance and ensures battery safety.

This trend towards digitalisation and electrification is being further boosted by the introduction of software-defined vehicles (SDVs). SDVs make it possible to implement vehicle functions largely through software, which can be regularly updated and improved. This is leading to stronger personalisation, greater flexibility for consumers, and faster innovation cycles, as hardware and software are largely developed independently of each other.

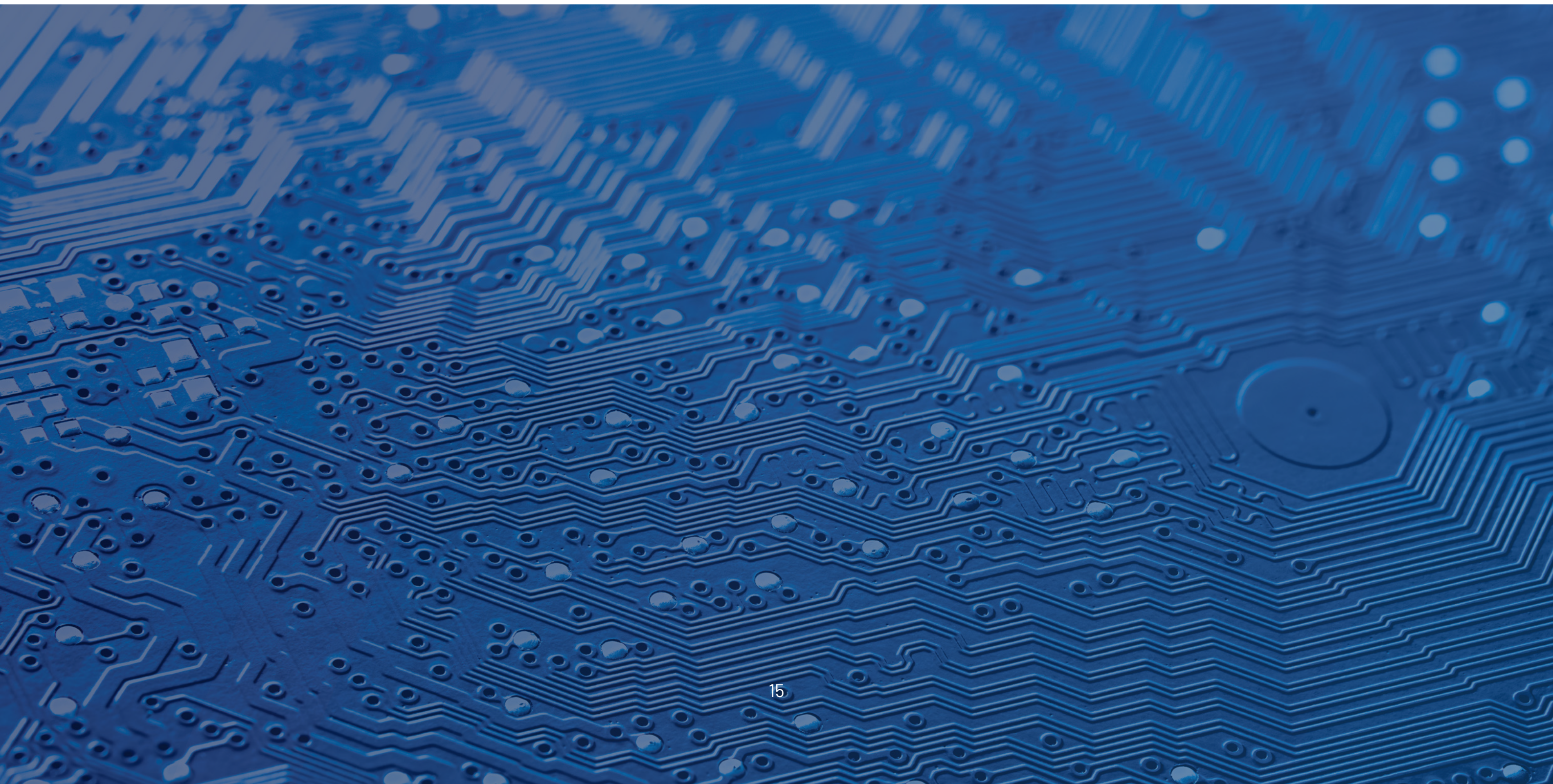
Fig. 1.6: Overview of semiconductor applications in an electric car



1,000–3,000

semiconductors in a vehicle

Source: Strategy& analysis



2 Chip shortages and their effects

The microelectronics industry is marked by a high need for investment. This starts with the building of semiconductor factories (fabrication plants, or fabs for short): from planning to commissioning a new production plant, the process usually takes three to five years. The costs for this range from single-digit to double-digit billions. Companies thus need to take investment decisions upstream, without being able to reliably predict future market developments.

Key factors for this high investment expense are the massive complexity of the manufacturing processes, and the infrastructure associated with this. Semiconductor factories need to be operated under strict cleanroom conditions, in order to avoid contamination during production. The cleanroom requirements for this exceed those of operating theatres several times over. Moreover, the facilities require the use of special chemicals and are reliant on a high degree of automation. The comparison with other industries demonstrates this: a modern semiconductor factory, such as the planned plant for the European Semiconductor Manufacturing Company (ESMC) in Dresden, costs around ten times as much as an ultra-modern car production facility, such as the Tesla Giga-Factory in Brandenburg (see Figure 2.1).

Fig. 2.1: Comparing a state-of-the-art automotive and semiconductor production facility

Automotive production in Brandenburg

TESLA

Area 700,000 m²

~ €1 bn investment

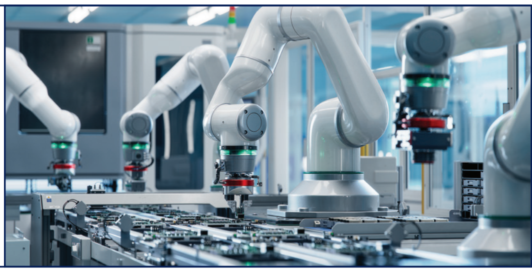
€1,500/m²

500,000 cars p. a.

12,000 employees

ESMC Dresden Fab

esmc



Area 40,000 m²*

~ €10 bn investment

€250,000/m²

>200 million chips p. a.

2,000 employees

*Cleanroom area (production area for chip fabrication);
Source: Press releases by TESLA, NXP, Infineon, Bosch, TSMC

The many innovations in the semiconductor industry extend the planning time-frames. New technologies not only call for financial resources, but also years of research and development. For instance, chips undergo extensive testing and optimisation phases before they can be manufactured in mass production. This is also reflected in the costs for semiconductor design, which can range from the two-digit to three-digit millions, depending on the technology.

These factors force the manufacturers to sell large volumes of a product in order to be profitable. The massive development, investment and production costs make it difficult for the semiconductor industry to respond flexibly to short-term fluctuations in demand, which strongly depend on the automotive, consumer electronics and industrial automation sectors.

The dynamics outlined here lead to the typical pork cycles in the semiconductor industry. In phases of high demand, capacities rapidly run up against their limits, potentially leading to supply bottlenecks and price increases. As soon as new capacities are built up and demand slackens off, cyclical over-capacities arise, leading to price corrections in individual technologies. In these adjustment phases, production is reduced or market corrections occur, in order to restore the balance between supply and demand. In addition, during economically strong phases companies often build up their stocks, and as a result demand for semiconductors continues to climb in the short term. In weaker periods, these companies initially look to run down their inventories before placing new orders, thereby triggering additional fluctuations in the market.

The global connectivity of the semiconductor industry brings further challenges with it, since geopolitical tensions and trade restrictions exert considerable pressure on global supply chains. Local constraints, such as natural disasters or pandemic-induced lockdowns, place additional burdens on supply chains and heighten existing market effects.

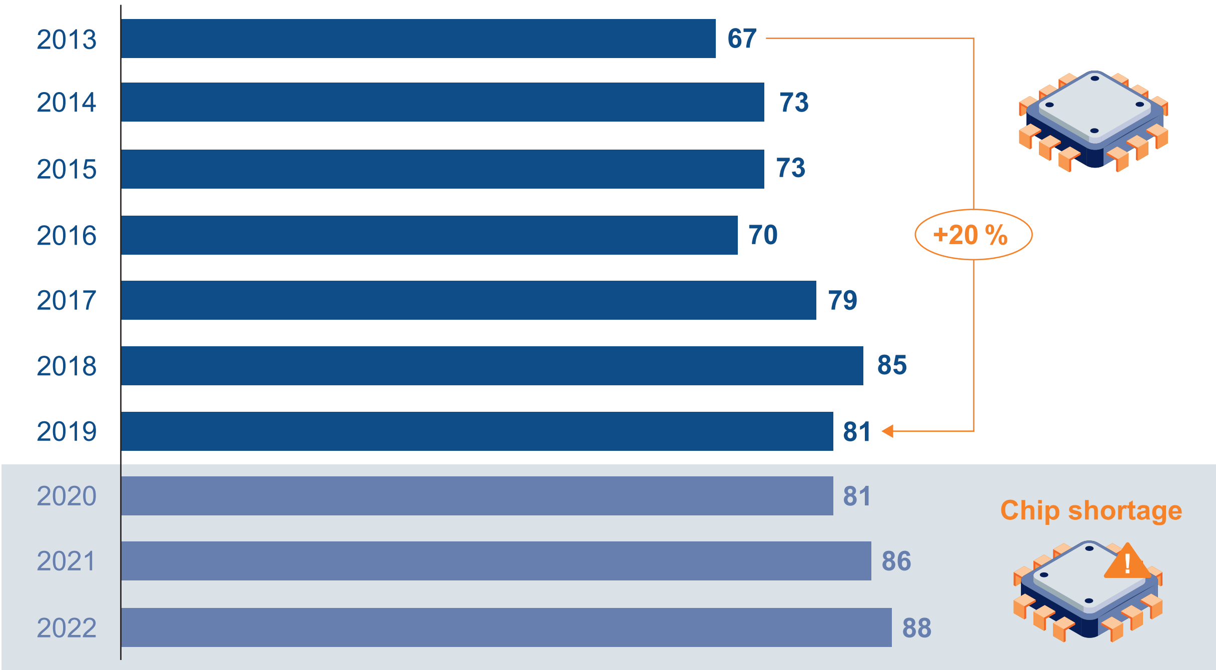
2.1 Chip shortages, a recurring phenomenon

Chip shortages are not a new phenomenon, and have already hit the semiconductor industry several times in the past: every time technological breakthroughs or global events unexpectedly triggered strong demand for semiconductors, supply chains came under pressure. For instance, the boom in personal computers in the 1980s[5] and the rapid spread of mobile phones in the 2000s led to considerable bottlenecks.[6] Natural disasters, too, like the earthquake and tsunami in Japan in 2011[7], have had an impact on supply chains in the past.

The most serious chip shortage to date lasted from the end of 2020 to 2023.[8] Due to the massive increase in demand, there was a worldwide shortage of semiconductor chips during this period. This led to far-reaching interruptions to production in various industries, and had deep impacts on the global economy. The automotive industry and, to some extent, the industrial products sector were particularly badly affected by this shortage.

But even before this chip shortage, the supply of semiconductors was gradually running up against capacity limits, due to the constantly growing demand in various sectors. This development was accelerated by growing digitalisation and electrification (see Figure 2.2). The COVID-19 pandemic acted alongside this as once-in-a-century shock, and as a result global GDP fell in 2020 more dramatically than at any time since the end of World War 2. In anticipation of a marked downturn in automotive sales, this collapse caused many car manufacturers to release significant parts of their allocated semiconductor capacities in early 2020.

Fig. 2.2: Average capacity utilisation of US semiconductor companies, 2013-2022, as a percentage



Source: Federal Reserve 2024

At the same time, more work was being done from home, and during the lockdowns consumers made increasing use of streaming services and video games. This led to a disproportionate demand for chips for data processing and communications technologies. The rapid growth of the IoT also meant that connected devices and sensors were increasingly used in homes and businesses. The semiconductor manufacturers reacted to this by allocating the released capacities to other industries, such as consumer electronics, in order to maintain capacity utilisation in their fabs. However, and contrary to expectations, the collapse in demand for semiconductors in the automotive sector proved to be more modest. Instead, the rapidly-growing interest in electric vehicles led to a sustained increase in demand for semiconductors. An important aspect to note in this regard is that European core industries, like the automotive industry and industrial products industry, constitute only a small part of global semiconductor demand. For instance, the global automotive sector is only responsible for less than 10% of semiconductor volumes.[9]

But geopolitical factors, too, contributed to intensifying the chip shortage. Trade disputes hampered the procurement of semiconductors and led in some countries and companies to the holding of a strategic reserve, which further increased the global pressure on supply chains. Natural disasters like the drought in Taiwan, several factory fires in Japan and a winter storm in the U.S. between 2019 and 2022 further exacerbated the shortage.

However, the chip shortage did not affect all product categories in equal measure, but was concentrated on specific segments, albeit ones that are particularly critical for many applications in the automotive and industrial sectors. One primary reason for this is that these chips are frequently based on what are called “mature nodes”. These chips are optimally suited to their respective applications, but due to lower investments in production capacities in recent years they were not available in sufficient quantities and thus were not able to cover the dramatically increased demand.

There were significant bottlenecks, particularly in microcontrollers and processors, even though these are essential for the control and processing of a wide variety of devices and systems. Power semiconductors, needed for efficient energy transfer and management in applications such as electric vehicles and industrial machines, were also heavily affected. Field programmable gate arrays (FPGAs), which provide for flexibility and adaptability in hardware development, experienced considerable shortages – as did current supply management components such as gate drivers and LED drivers.

In contrast to this, other categories of semiconductor remained largely available. For instance, analog semiconductors used to process continuous signals, and standard transistors and diodes (fundamental switching elements in many electronic circuits) were less affected by the shortage. Standard logic modules and memory chips, too, were also supplied largely without significant interruptions.

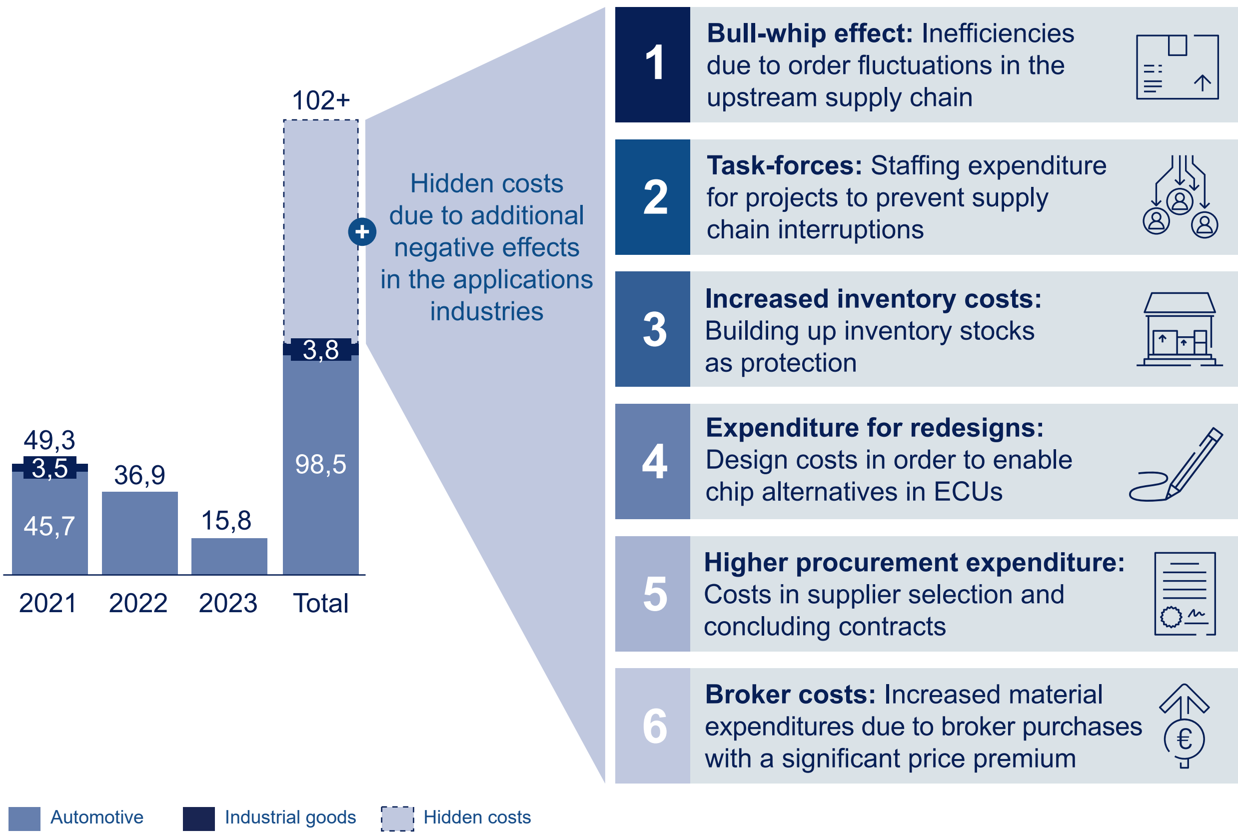
2.2 Economic effects of the chip shortage

The chip shortage particularly affected the industrial goods and automotive sectors. Other sectors of German industry, such as consumer electronics, were less badly affected by comparison and were therefore not considered in this analysis. In the aviation and space travel sector, the pandemic-induced fall in demand led to cancellations of aircraft orders, superimposed over the effects of the chip shortage in that sector. In other areas such as the service sector, the chemical industry or in medical technology, no economically measurable chip-related losses were recorded.

Analysis of the loss of GDP
To calculate the loss of GDP, 2019 was taken as the base year, since this year was untouched either by the effects of the COVID-19 pandemic or by the chip shortage. With regard to the automotive industry, the number of commercial vehicles produced in the years 2021 to 2023 was compared with the production volume in 2019. This difference was multiplied by the gross value added per vehicle produced, as calculated by the Federal Statistical Office, in order to determine the loss of GDP. With regard to the industrial goods sector, the contribution to GDP in 2021 to 2023 was compared to that of 2019, in order to calculate the corresponding losses.

The analysis of the losses of GDP which have come about due to supply bottlenecks in the microelectronics industry shows that the automotive sector, in particular, was badly affected from 2021 to 2023. In this sector, the loss of production resulted in a loss of GDP totalling EUR 99 billion for the German economy. However, the result of the analysis is heavily dependent on the underlying figure for production losses. The methodology used in this study relates to the production figures of the German Association of the Automotive Industry (VDA) and assumes that the decline after 2019 is primarily attributable to the shortage. Accordingly, the calculated loss of GDP is at the upper end of the possible range of results. On the other hand, these figures do not reflect the full extent of the loss, since hidden costs have also arisen in the end-application industries. In addition to the production losses in the automotive industry, economic losses in industrial products have also resulted, totalling around EUR 4 billion (see Figure 2.3). The total loss – based on the underlying methodology – thus amounts to at least EUR 102 billion, corresponding to 2.4% of German annual GDP in 2022.

Fig. 2.3: Quantification of GDP loss due to the chip shortage, 2021-2023 in EUR billion



Source: Strategy& analysis

Hidden costs due to the bull-whip effect, warehousing of stocks, and other expenses

A central factor for the additionally hidden costs is the bull-whip effect, where uncertainties and delays in the supply chain lead to disproportionate fluctuations in order volumes. Companies responded to the semiconductor shortage by attempting to offset their under-supply through disproportionately increased orders. However, this led to additional uncertainties on the semiconductor manufacturer side and made it more difficult to estimate the actual needs of companies accurately.

In order to manage the shortage, many companies assembled task forces to work specifically on the procurement and management of semiconductor deliveries. These specialised teams worked intensively on identifying alternative sources of supply and on optimising existing supply contracts. However, setting up such task forces was also associated with considerable costs. Seconding staff from regular departments impaired productivity in other areas, and in addition external consultants or experts were often called in, leading to additional expenditures. Moreover, the immediate measures initiated by the task forces often required near-time investments in logistics and in optimising supply chains to relieve the situation.

One of these measures was building up inventory stocks – companies procured sizeable stocks of critical components in order to anticipate possible future bottlenecks. This led to considerable additional costs for warehousing and logistics. The expenditure for redesigns and the procurement of alternative components also increased sharply, as companies needed to adapt their products in order to be able to use other semiconductors or replacement parts. These adaptations were often time-consuming and costly, since they required extensive testing and validation. At the same time, alternative semiconductor manufacturers needed to be qualified, which caused additional administrative costs. Companies were increasingly reliant on middlemen to procure urgently-needed chips. However, these brokers often demand high premiums, and as a result production costs rose even further.

Companies under pressure due to the chip shortage

The combination of these factors led to a considerable burden on the industries affected. Production capacities were restricted, while cost structures rose at the same time – and this was reflected in higher end-consumer prices. Beyond this, the after-effects of the chip shortage and the coronavirus pandemic led to a shift in global market relations. The high stock levels built up during the chip shortage subsequently led to a heavy price collapse in the microelectronics industry. These cost reductions caused European companies, particularly in the areas of PCBs and EMS (which were already under pressure), to experience an even greater squeeze. At the same time, this market trend boosted the dominance of Asian actors in these areas, as European companies in the end-application industries have increasingly qualified Asian alternatives during re-designs to combat the chip shortage. This development has strengthened the position of Asian market players in some areas, and weakened the European market for the long term. The massive effects of the chip shortage demonstrate the urgency of building up a more robust and more flexible supply chain, in order to be able to cushion future disruptions better.

Necessary strengthening of the semiconductor supply chains

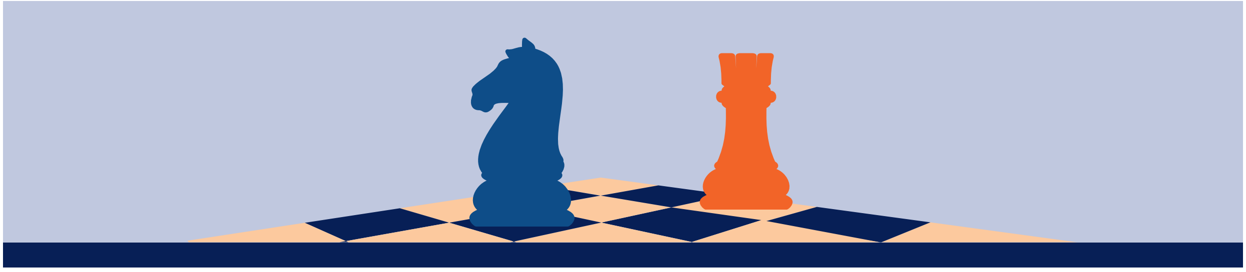
Looking to the future, it is reasonable to suspect that there will continue to be bottlenecks in the semiconductor sector, since such shortages are a recurring phenomenon. While future shortages in the semiconductor industry are probable, they might occur as more isolated instances, and with less serious consequences. This development is the result of targeted investment decisions, enabled in part by state funding programmes and contributing to the diversification and flexibility of global semiconductor production.

Nevertheless, widespread risks such as geopolitical tensions, natural disasters, trade wars and military conflicts continue to represent a considerable threat. The growing importance of microelectronics in practically all branches of industry and the progressive increase in applications, from AI to IoT to autonomous vehicles, are amplifying the effects of such risks. This increasing dependence is making the global economy more susceptible to interruptions in the semiconductor supply chain. The recent chip shortage from 2021 to 2023 was of global significance. It affected regions worldwide, although US and European industry in particular – and especially the automotive industry – had to deal with the biggest effects from it.

In the event of a local shortage affecting Europe alone, the effects would be even more serious. Europe is heavily integrated into the international semiconductor supply chain – both as a customer, and as a provider of specialised technologies and equipment. Interruption to supply could lead to considerable production losses, and indirectly to the loss of market shares in key industries such as the automotive sector, industrial products and other key sectors.

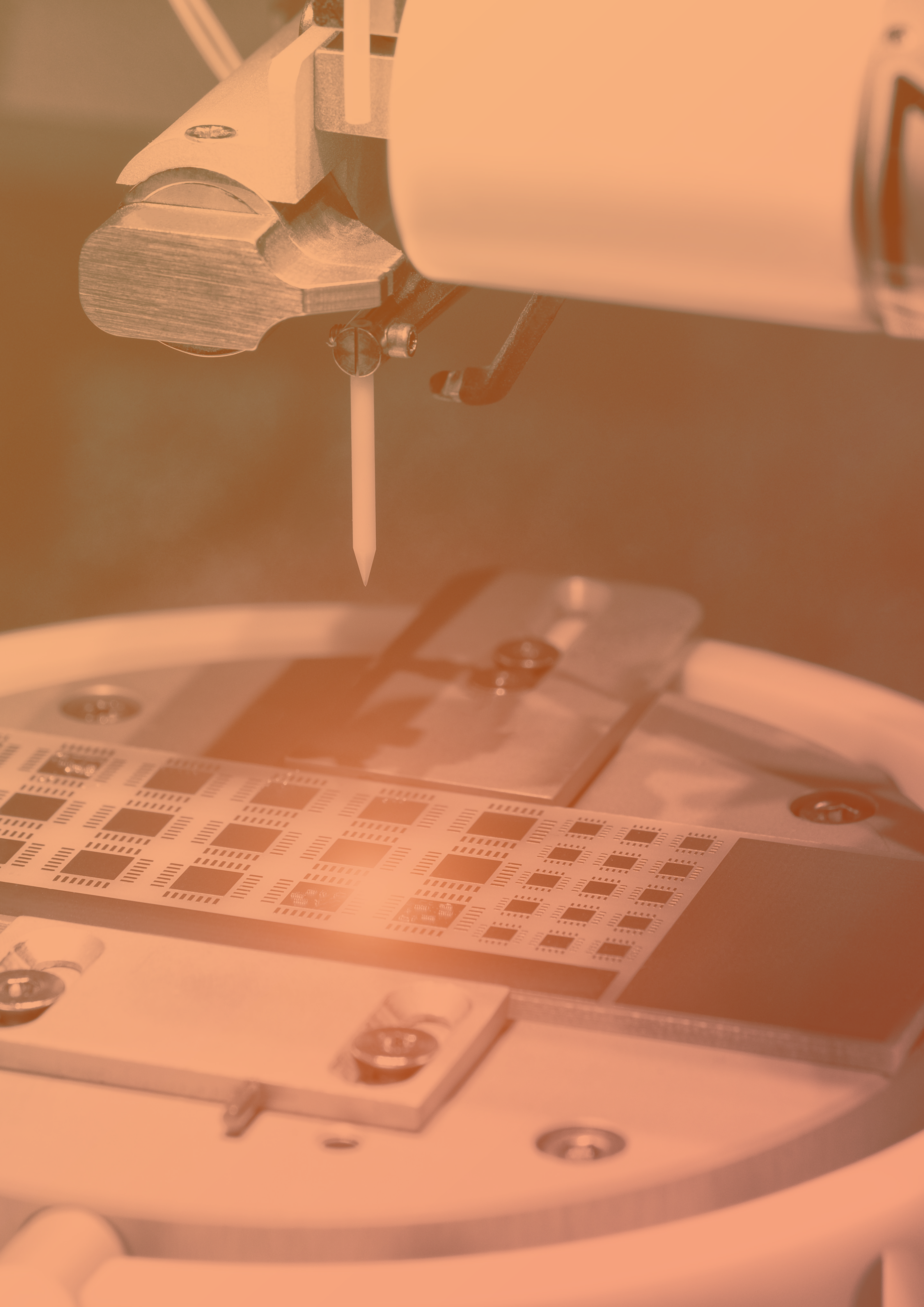
Several lessons which can contribute to minimising risk can be drawn from the chip shortage. Figure 2.4 shows and explains an overview of possible measures which could contribute to reducing problems in the semiconductor supply chains. By implementing these measures, future crises can be better overcome and industry resilience strengthened. Given the structural challenges for the microelectronics industry, more reliable forecasting of demands by the customer industries is becoming increasingly relevant.

Fig. 2.4: Measures for long-term, holistic semiconductor management



Measures	Effect
1 Improving transparency on demands	Improved demand planning can contribute decisively to avoiding shortages. More precise plan data makes it possible to better estimate the need for future investments and to ensure sufficient capacities.
2 Investments in production capacities	Comprehensive investments in production capacities, particularly in the area of key technologies, contribute to reducing the dependence on non-European suppliers and being able to minimise geopolitical risks.
3 Design for resilience/ sourcing	Through the cross-area collaboration by R&D, Purchasing and Supply chain management in collaboration with the suppliers, end-consumer industries are able to ensure greater design flexibility.
4 Building up long-term partnerships	Long-term partnerships across the microelectronics value chain ensure better exchange and early forwarding of key data.
5 Building up workforces	The growing demand for microelectronics will continuously increase the need for trained specialists. A robust strategy to encourage and develop these skilled workers is therefore essential.
6 Multi-fab/Multi-sourcing	Multi-fab and multi-sourcing strategies can help to minimise interruptions in the supply chain. Diversifying production sites and suppliers can reduce the risk of geopolitical events hampering business processes.

Source: Strategy& analysis



3 ROI from microelectronics subsidies

Due to the global chip shortage from 2021 to 2023 and given geopolitical challenges, many nations decided to support their microelectronics industry to a greater extent using state funds. Their aim is to reduce dependencies, in order to avoid becoming the plaything of geopolitical developments. The positive effects of state subsidies to the microelectronics industry include:

Economic growth and jobs	Targeted subsidies stimulate economic growth and create new jobs by generating more value added within the country.
Boosting research and development	Supporting R&D drives innovation. These innovations strengthen both the technological sovereignty and the competitiveness of the microelectronics industry and of global end-markets. The research-intensive microelectronics sector in particular, which is characterised by a high degree of innovation and extensive investments in R&D, can benefit considerably from such measures.
Digital and green transformation	One important goal for the EU is to drive forward the digital and green transformation. With this in mind, the focus is on developing innovative microelectronics and communications solutions and on energy-efficient and resource-saving systems and manufacturing methods. These advances will drive progress decisively in key technologies such as 5G/6G, autonomous driving, AI and quantum computing. At the same time, they are contributing to the green transformation – both in the production of renewable energies and by electrifying sectors of industry and both personal and public life.
Strengthening national security	Funding programmes support national security by developing new technologies for the defence industry. It therefore ensures that states remain competitive in technology, and reduces the risk of data manipulation and espionage. To promote data security, investment in the communications industry and hardware security is also relevant.

3.1 Subsidies in the microelectronics industry

The term “Important Projects of Common European Interest” (IPCEI) designates strategic funding measures in close coordination between the Member States and the European Commission. The aim is to support sustainable economic growth, to create new jobs, and to boost competitiveness, resilience and autonomy in the EU. To do so, innovations and infrastructure projects need to be facilitated as part of a cross-border collaboration with positive spillover effects on the internal market and on the whole of society. The focus here is on supporting highly innovative production processes and products, to be developed and implemented through to first industrial deployment (FID).

2018: the first IPCEI on microelectronics

The first IPCEI on microelectronics was launched in 2018, to promote the development of energy-efficient chips and power semiconductors, smart sensors, optical components and compound materials. A total of 32 companies from five Member States (Austria, France, Germany, Italy and the United Kingdom) pursued 43 projects to boost product innovations in microelectronics. The companies receiving support included leading enterprises such as STMicroelectronics, Bosch, Infineon, NXP, GlobalFoundries and OSRAM. The volume of state funding was EUR 1.9 billion, intended to trigger a further EUR 6.5 billion in private investment.

2021: innovation and technological progress through IPCEI ME/CT

The positive resonance and success of the first IPCEI on microelectronics meant that, in 2021, a further IPCEI on microelectronics and communications technologies (IPCEI ME/CT) was initiated, and approved in 2023. The aim of the IPCEI ME/CT is to simulate innovation and technological progress, to shape society in the EU to be greener, more digital, more secure, more resilient and more sovereign. To that end, companies in the following areas were supported: new sensor systems, cybersecurity, energy-efficient chips for data storage and processing, microelectronic systems performing actions, and fast, secure and reliable data transfer. A total of 56 companies from 14 Member States are participating in the IPCEI ME/CT, driving 68 research and FID projects. The Member States involved are Austria, the Czech Republic, Finland, France, Germany, Greece, Ireland, Italy, Malta, the Netherlands, Poland, Romania, Slovakia and Spain. For the IPCEI ME/CT on microelectronics and communications technology, the participating EU states are making EUR 8.1 billion available, and hope to trigger a further EUR 13.7 billion in private investments. Once again, well-known companies across the entire value chain are involved in the IPCEI ME/CT – from materials manufacturer Soitec to IDMs such as STMicroelectronics, NXP and Infineon or innovative foundries like X-FAB and GlobalFoundries, through to companies in the applications industries such as the automotive suppliers ZF Friedrichshafen and Valeo.[2]

2023: The European Chips Act

The European Chips Act (ECA) was adopted in 2023. This law represents the EU's response to increasing dependency on other global nations in semiconductor manufacturing, as became evident in the years 2021 to 2023. An applications industry survey conducted by the European Commission revealed that the sector is anticipating a doubling in demand for microchips by 2030. With the European Chips Act, the EU is aiming to strengthen its leading role in technology and either prevent future disruptions to supply chains or be better able to respond to them.

This includes earlier projects announced as part of the ECA. For instance, an STMicroelectronics project for the manufacture of silicon carbide substrates in Catania, Italy, was approved. The volume of investment is EUR 750 million, of which over EUR 290 million is from state subsidy. In addition to this, STMicroelectronics has planned a further fab in Catania to manufacture silicon carbide power electronics, which is attracting subsidies of EUR 2 billion. A further STMicroelectronics project, jointly with GlobalFoundries, is to be established in Crolles in France: a joint fab is proposed, at a cost of EUR 7.4 billion including EUR 2.9 billion in subsidies, to manufacture 300mm silicon chips for automotive, industrial, IoT and telecommunications applications. In addition, a TSMC fab is being built in Dresden, to be operated as a joint venture under the name ESMC together with NXP, Infineon and Bosch. This new factory will cost a total of EUR 10 billion, of which EUR 5 billion is coming from state funding. Here, too, it is planned to operate a 300mm silicon fab, intended to supply products for the European and global automotive, industrial and telecommunications sectors.

Another major project in Dresden is the new module for Infineon's smart power fab, which is similarly set to receive support under the European Chips Act. With an investment volume of EUR 5 billion and a targeted subsidy of around EUR 1 billion, the plant will contribute to strengthening European semiconductor manufacturing. The fab is set to produce semiconductors from 2026, supporting key industries such as the automotive sector and renewables. According to information from the semiconductor company, 1,000 new jobs will be created there.

In 2022, Intel also announced construction of a mega-fab for 2nm technologies in Germany. However, the project was initially paused and postponed for two years, due to the company's current situation. In a first phase, Intel was planning to invest around EUR 30 billion, of which EUR 10 billion was coming via subsidies, in the manufacturing site in Magdeburg, Germany.

To date, the promised public funding for European microelectronics programmes amounts to over EUR 32 billion.[1] In the officially-announced EUR 43 billion by 2030 to mobilise public and private investments via the ECA, there is no definition as yet to indicate what share of this will fall to public subsidy.[3] Accordingly, in the study the figure of EUR 32 billion is taken as the reference value.

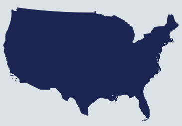
3.2 The global competition for funding in microelectronics

But, as already mentioned, other nations are also aware of the relevance of the microelectronics industry and are investing at significant scale. These include the U.S., China, South Korea, Japan, Taiwan, Singapore and India – these countries have developed various funding programmes, with differing areas of focus.

For instance, Taiwan and South Korea are primarily looking to tax incentives in the form of tax credits for R&D, and for the procurement of production plants (tooling). Japan is putting its focus mainly into development and production of chips for applications in AI and high-performance computing. This is to be enabled, for instance, through the state-sponsored chip venture company Rapidus, which amongst other things is developing the production of semiconductors smaller than 2nm.

The U.S. is providing USD 53 billion, China as much as USD 143 billion, and Japan a planned USD 65 billion to support the semiconductor industry (see Figure 3.1), with part of the Japanese investments also set to go into supporting the AI industry.

Fig. 3.1: Overview of microelectronics funding programmes in the leading semiconductor regions (as at Q3 2024)

US	EU	China	South Korea	Japan	Taiwan
Chips for America	**EU Chips Act and IPCEI**	**Semicon package**	**K-Chips Act**	**Semicon ecosystem strategy**	**Taiwan chip act**
					
>$53 bn by 2026[1]	>$30 bn by 2030	$143 bn[2] by 2028	Tax benefits by 2032	$65 bn by 2030[3]	Tax benefits by 2029
Additional tax credits and incentives					
Credit 20% of investment costs		**Relief** Income tax relief for 2-10 years depending on the technology	**Credit** 20% of investment costs 50% of R&D costs		**Credit** 15-25% of R&D 5% of tooling No restriction for state expenditures

1) Quantification of national, regional and district level with collaboration of private investments; subsidies still in the planning phase;
2) Figure includes public direct investments and a small share of joint investments with the private sector;
3) Includes funding for semiconductor and AI industry (programme currently being finalised)
Source: Strategy& analysis based on publicly-available information (Q4 2024)

3.2.1 A comparison between the U.S. and the EU

European support for the semiconductor industry is frequently compared with the “CHIPS for America Act” in the U.S. The reason for this lies in the similar starting conditions: both regions are having to combat a decline in their market shares, and are pursuing comparable aims in supporting the semiconductor industry. Figure 3.2 compares the European and American funding programmes, looking at their key features.

In the CHIPS for America Act, the U.S. is seeking a global share of 30% in semiconductor manufacturing by value, and in an initial move is providing USD 52.7 billion for this. Of this, USD 11 billion is intended for R&D.

By comparison, the EU originally committed to an ambitious target of 20% of global production capacity and, to date, has set aside something over EUR 32 billion for new projects in semiconductor development and manufacture. However, it should be emphasised that the funds are coming from the EU Member States and not from the EU itself. The EU merely specifies the framing context allowing the Member States to support the microelectronics sector.

Fig. 3.2: Comparison of European and American funding programmes for microelectronics

	EU Chips Act and IPCEI 1+2	US chips for America
Total funding Subsidies in € bn	**>$ 30 bn** (from member states)	**$ 53 bn**
Tax incentives Tax incentives in € bn	**Theoretically possible** (to date none)	**$ 24 bn** Investment tax credit
Coverage of initiatives along value chain	Equipment manufacturers, materials and semiconductor manufacturing	Equipment manufacturers, materials, semiconductor manufacturing and design
Restrictions Trade restrictions with non-EU states	Priority for EU orders for crisis-relevant products; exclusivity of IP	No new capacities in China, Russia, Iran, North Korea; exclusivity of IP
Administration and process Administrative effort for application	Tracking of spending, appropriateness of aid; At the start, under administration with EU: individual negotiations	Individual negotiations, tracking of funding monies, proof of foreign activities
Requirements Requirements beyond project plan and business case	“Beyond-state-of-the-art” technology or “First-of-a-kind” fab, spillover effects	“Community Benefit Plan”, both leading-edge and legacy technology, investments and capacity expansion
Support State support measures	Accelerated processing of applications (priority)	Dedicated Chip Office staff, accelerated processing of applications

Low — High

Source: Strategy& analysis based on public data and own extrapolations

This also means that certain aspects of the conditions for subsidy are specified to a large degree by the Member States. A precise division between support for R&D and supporting new manufacturing capacities is problematic in the EU, since IPCEI projects often cover both areas. Apart from the amount of the funding, the US CHIPS Act and the ECA also differ with regard to the funding instruments employed. Whereas the U.S. largely uses tax credits, the funding instrument of choice in the EU Member States is primarily direct subsidy. Even if theoretically possible, to date there have been no tax breaks approved by the European Commission. By contrast, the U.S. grants tax credits for 25% of expenditures for semiconductor factories and manufacturing equipment. As a result, companies can offset 25% of expenditures directly against taxable income and thus reduce their tax burden.

The US CHIPS Act also aims to establish a "USA Semiconductor Institute", which on the one hand is set to shape the framework for partnerships between the industry, universities, government and research institutes, and on the other hand to drive research into virtualisation of semiconductor equipment. In addition, joint projects are set to further strengthen the U.S.'s capabilities in assembly, testing and packaging. Looking to the EU, the European Chips Act established a European Semiconductor Board[10], which supports the European Commission in implementing the Chips Act and encouraging collaboration between the Member States. Beyond this, the European Semiconductor Board will monitor production and supply of semiconductors and ensure that, in the event of a crisis, information from the Member States is rapidly available in order to introduce possible measures.[11]

One big difference is apparent when it comes to trade restrictions. In the US CHIPS Act, it is prohibited for subsidised companies to build up further production capacities in China, Russia, Iran or North Korea for first-of-a-kind technologies for a period of 10 years following the subsidy. In addition, new factories for mature technology nodes should only be built up in these countries if these production capacities are primarily destined for the market of the country of manufacture. Furthermore, subsidised companies are prohibited from entering into joint research projects or technology licensing arrangements with institutions with links to these states. The EU has pursued a different approach in the European Chips Act, aimed at protecting the quality of free trade on world markets and freedom of investment. Thus in general there are no restrictions concerning the building up of additional production capacities in other countries, and in the event of a crisis the EU is permitted to intervene in the semiconductor supply chains. For example, subsidised companies are obliged – in the event of serious disruption to the supply chain or an incident concerning national security – to accept orders for crisis-relevant products as a priority and to manufacture these as a priority, in order to ensure the stability of the supply chains within the EU.[12]

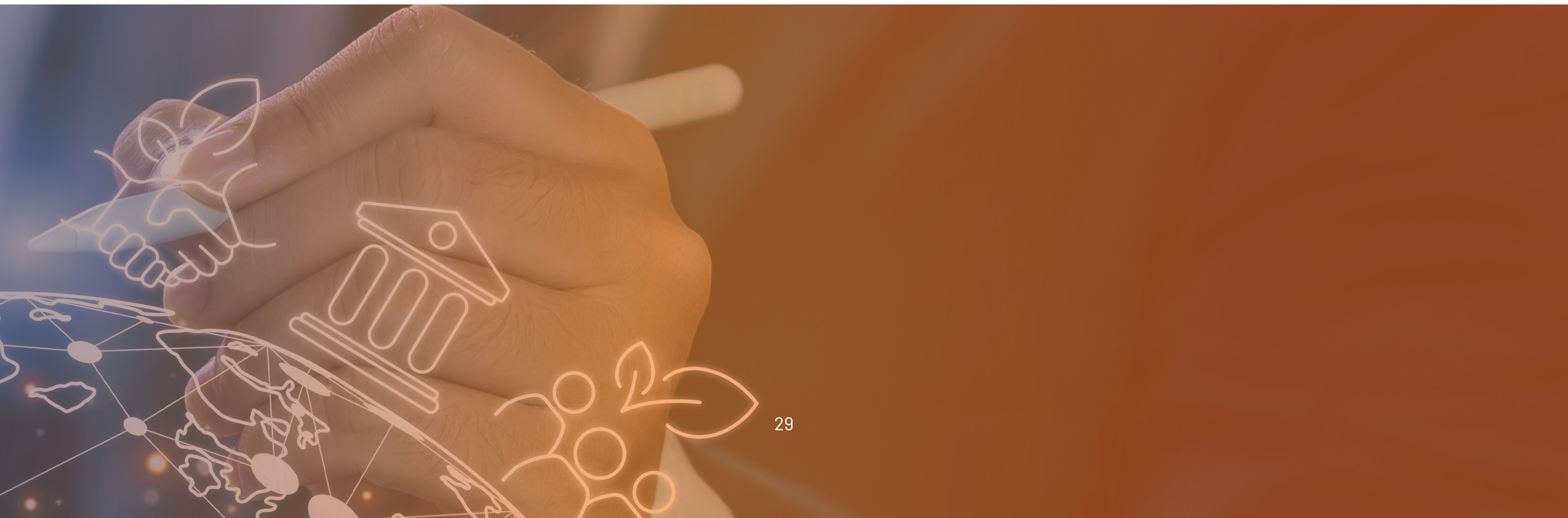
Both the EU funding programmes and the US CHIPS Act give rise to considerable administrative expense for subsidised companies, albeit in different ways. One key difference is that companies need to demonstrate for the U.S. that no activities are planned in countries like China which contravene the conditions for subsidy. In both funding programmes, detailed tracking of the monies paid in subsidies is necessary over the entire project period. For the EU, an additional requirement is that the subsidies need to be applied for and correspondingly approved under the applicable law of the respective Member State, and as a result the duration of the application processing period varies across Europe.

There are different requirements for eligibility for support in the two programmes. In the U.S., a "Community Benefit Plan" is needed, which ensures that the company being subsidised has a positive influence on marginalised and disadvantaged communities. The applicant is therefore required to demonstrate that disadvantaged communities are supported through value creation, new jobs and offers of training, and are better integrated into society. Furthermore, companies need to show how they enable their factory employees and construction workers to have access to childcare, in order to support their families in that way. For the EU funding programme, partnerships and spillover effects need to be demonstrated along the value chain. The latter include – comparable to the Community Benefit Plan – the positive effects of the project, such as the creation of jobs and training opportunities, the boost to the regional economy, increased access to innovations, and support to R&E establishments, universities and technical universities. Moreover, there is a strong focus on stipulating a "first-of-its-kind in the EU" technology. Thus far, the biggest hurdle and the biggest expense in applying for funding has been in demonstrating the incentive effect, which calls for an in-depth analysis of a possible "counterfactual scenario" and detailed evidence relating to the decision-making process for the chosen European location.

A further difference between the US CHIPS Act and the European Chips Act is the support for talents and training. The "Chips for America Workforce and Education Fund" makes explicit provision for targeted funding of USD 200 million, intended to mitigate the shortage of specialists in the semiconductor industry. In addition, the US CHIPS Act includes investment of USD 12 billion in Science, technology, engineering, and mathematics (STEM) education in key areas of microelectronics. In the European Chips Act, it is planned to develop "Centres of Excellence" to strengthen the training network in Europe in order to combat the shortage of specialists. However, the European Chips Act does not plan for any explicit funds to invest in STEM education. Instead, the emphasis here is on spillover effects, to encourage training in these areas directly by the companies.

Both in the U.S. and in the EU, applications for funding go hand-in-hand with time expense and a commitment of resources. The complexity of applications can hamper SMEs and young companies, in particular, in seeking financial support. The U.S. has set up a "CHIPS Program Office", comprising experts and specialists who can support applicants in designing and implementing subsidised projects. For this, an employee is made available to accompany the entire application process. In the EU, state organisations at the national level handle these tasks – however, the number of available staff, according to industry information, is lower than that in the U.S., thus restricting the opportunities for support.[13]

The comparison shows that both funding mechanisms each have strengths and weaknesses, but many things in common. The EU funding measures have already significantly strengthened the European semiconductor industry. However, to date there has been no comprehensive strategy across all Member States for industrial policy in supporting the microelectronics industry. Stronger meshing of major projects within the EU, and closer alignment with the strategic aims for Europe as a location for microelectronics, could bring additional advantages. In addition, more intensive support in making applications, for example by establishing a Chip Office along the lines seen in the U.S., could contribute to assisting SMEs and start-ups, in particular, in seeking subsidies.



3.2.2 Funding programmes for PCBs and electronics manufacturing

There are also national funding programmes for PCBs and EMS. In 2021 India approved a "Production Linked Incentive Scheme for Large Scale Electronics Manufacturing" with funding of around EUR 4.9 billion to manufacture mobile telephones and electronic components, along with assembly, testing and packaging.[14] Beyond this, there was a second programme to support IT hardware with grants totalling EUR 860 million, focusing on the laptop, tablet, all-in-one PC and server segments.[14] To obtain these grants, companies need to show that they undertake the assembly of circuit boards in India. In addition, India has a "Scheme for Promotion of Manufacturing of Electronic Components and Semiconductors (SPECS)", which reimburses 25% of the investment costs for buildings and equipment and 25% of the R&D costs.[14] Another programme is the "Modified Electronics Manufacturing Clusters Scheme", benefiting the building of factory premises and manufacturing sites by reimbursing up to 50% of the construction costs. This funding programme has a volume of around EUR 400 million and is aimed at supporting the build-up of manufacturing clusters in India.[14]

The United States, too, is investing in the PCB industry. In 2023, US President Joe Biden declared PCBs to be a critical technology for national security. As part of the Defense Production Act (DPA), a need for action was identified to encourage domestic production. Initially, USD 52 million was made available as short-term assistance.[15]

China is supporting its PCB industry as part of its "Made in China 2025" strategy, and is channelling subsidies in a targeted fashion into key sectors such as medical technology and electrical transmission technology. Countries such as Thailand are offering "investment incentives" to attract Taiwanese PCB manufacturers looking to relocate their production out of China.[16]

To date, the EU has not established any comparable programmes, and is currently concentrating its funding measures solely on the semiconductor supply chain through to packaging.

3.3 Not all semiconductors are the same

Before undertaking an analysis of the economic effects of subsidies for semiconductors, we first offer an overview of the types of semiconductor products. There is a wide variety of different types, which vary in their physical composition, in the underlying manufacturing process and in equally in their functionality.

To understand the product categories to which funding measures primarily relate and the extent to which these measures influence the manufacture of the individual product categories, the study offers an overview below of the individual semiconductor types and their functionalities (see Figure 3.3). In addition, the study looks at how demand is trending and at which technology is normally used to manufacture the products.

The concept of process size, also referred to as the process node, is a key aspect of the production technology. It describes the smallest structure which can be reliably manufactured on a semiconductor wafer. To put it simply, the smaller the width of the structure, the more components can be manufactured on the same area – this enables either smaller or chips with a higher performance within the same surface area.

The spectrum of the semiconductors used today ranges from process nodes of several micrometres down to 2 nanometres – a size that is smaller than one ten thousandth of the thickness of a human hair. However, it should be emphasised that smaller process nodes do not automatically equate to better or more innovative products. The choice of suitable technology to develop and manufacture a semiconductor depends on numerous factors. For instance, power electronics call for bigger structures in order to switch electrical currents and voltages efficiently and to reliably dissipate the heat generated. Moreover, innovations can equally be achieved through innovative manufacturing technologies and materials or intelligent product design. Below, the term "medium node" is used for semiconductors manufactured using process sizes of around 180–40 nm. Anything smaller than this is referred to as "small node" and above it as "large node".

Fig. 3.3: Overview of semiconductor product types and their functions

	Semiconductor type	Function
Memory	**Memory**	Storage and access of data within an electrical system
Microcompo-nents	**Microprocessors/ Microcontrollers**	Processing data, controlling programs in electronic/ digital devices
Logic	**Logic**	Controlling devices and processing digital signals, performing calculations
Analog	**Power management**	Monitoring, control and distribution of electrical currents and voltages within an electronic system
	Other analog	Processing, amplifying or filtering analog signals such as voltages, currents and frequencies
	Communication	Receiving, processing and sending data within communications systems
OSD	**Optoelectronics**	Converting electrical signals into optical signals and vice versa
	Non-optical sensors	Measuring non-optical signals such as ultrasound, pressure, temperature, humidity, gas, health data, etc.
	Power semiconductors	Switching, controlling and converting high electrical voltages and currents
	Other discrete	Basic elements (e.g. diodes and transistors) for switching, controlling and amplifying electrical circuits

Source: Strategy& analysis

Memory chips	Memory chips enable the storage and access of data within an electronic system. They are used in practically all systems, and vary in size and complexity. Applications such as those in the automotive or industrial products industry frequently use memory components produced on medium nodes. Particularly small memory chips are critical for compact devices such as laptops or smartphones. At the same time, demand for high-performance and energy-efficient memory chips on the smallest nodes is growing, due to the growing requirements of AI applications and data centres, which increasingly require bigger quantities of memory.
Microprocessors and microcontrollers	Microprocessors and microcontrollers are designed to control and execute specific tasks or applications. They are used in practically all fields – from controlling motors, brakes, airbags or infotainment systems in the automotive sphere through to smart home systems and automated systems in production. Normally, they are produced on medium nodes, although the most recent are moving towards 22/16 nm.
Logic	Logic components such as CPUs and GPUs control and process the basic operations in electronic devices. Thanks to the boom in AI and the increasing importance of high-performance computing applications, for instance in data centres, they are rapidly gaining in relevance. These chips are primarily produced on small nodes, due to the high demands in terms of performance and miniaturisation. In addition to universal logics such as CPUs, there are specialised variants such as ASICs (application-specific integrated circuits), which are optimised for specific applications, and FPGAs (field programmable gate arrays), capable of being programmed flexibly and used in prototype development, industrial automation and in communications systems such as 5G networks.
Analog semiconductors	Analog semiconductors process and amplify electrical signals. They play a key role in applications where signals like sound, light or temperature need to be converted into analog voltages and processed. One category within this covers power management chips, which control and distribute currents and voltages. These are essential for battery-operated devices in consumer electronics and play a key role in electrification. They are generally manufactured on medium nodes. Another sub-category is communications chips, which can receive, process and transmit data. They are produced on both medium and small nodes. With increasing internet penetration, the development of new generations of mobile telephony such as 5G and 6G, and the growing need for higher bandwidths, the demand for communications chips is growing constantly, since they form the basis for communication between an ever-expanding number of connected devices.
Optoelectronics	The term "OSD" subsumes optical, sensor and discrete semiconductors. Optoelectronics convert electrical signals into optical signals, or vice versa. They are vital for consumer electronics, for instance for displays, high-quality sensors and efficient lighting systems. Optoelectronics are also used in the automotive industry – for instance, in displays or lighting. In healthcare, optoelectronics represents the sectoral standard for imaging procedures. Optoelectronics are typically manufactured on larger nodes, and the demand for this process is continually growing, as ever more complex electrical systems are integrated.
Non-optical sensors	Non-optical sensors are semiconductors which can record physical and chemical environmental data. For instance, they measure ultrasound, pressure, temperature, gas concentrations, humidity or specific health parameters. These sensors are frequently manufactured on larger nodes. Due to their wide-ranging scope for uses in sectors such as industry, automotive, defense and healthcare, the demand for non-optical sensors is high. With the increasing use of data-driven business models and algorithms in these areas, the demand for such sensors is growing worldwide. Miniaturisation plays an ever-greater role in this, since the number of sensors per device is increasing and the devices are getting smaller.

Power semiconductors	Power semiconductors belong to the category of discrete semiconductors, and they assist in switching, controlling and converting high electrical voltages and currents; as such, they are a key technology for electrification. They are mainly manufactured on medium to large nodes. The expansion in climate technologies and electric cars is markedly driving demand for power semiconductors, since they are a vital component in these applications.
Other discrete semiconductors	Discrete semiconductors such as diodes and transistors are basic components for controlling, switching and amplifying electrical circuits. These relatively simple semiconductors are produced mainly on medium and large nodes. With the growing number of electrical systems and components worldwide, demand for these basic semiconductor components is also growing continuously.

3.4 Input-output model: calculating the effects of funding projects

To examine the economic effects of subsidising microelectronics on Germany and the EU as an economic location, the input-output analysis process is used. This methodology is used in empirical business research to quantify the effects of changes in economic activity within a national economy. Such changes can come about, for instance, through subsidy measures.

The methodology makes it possible to measure the effects of economic activities on income and employment within a national economy. To that end, economic activities across the entire value chain are considered and analysed to establish how different sectors in a national economy are connected via production interdependencies.

In connection with subsidising microelectronics, fundamentally three effects can be quantified – direct, indirect and induced effects:

- Direct effects relate to changes occurring directly in a sector that is affected by a measure. An example of this is increased production value due to the investments made using subsidies.

- Indirect effects concern the effects of the investments on other sectors connected to the subsidised sector as a supplier or service provider, such as increased demand for machinery for semiconductor production. It also includes the associated increased demand from these suppliers and service providers for goods and services.

- Induced effects result from the additional incomes linked to the additional employment and arising through the direct and indirect effects of the subsidy. These additional incomes lead to changes in consumption and in general economic activity.

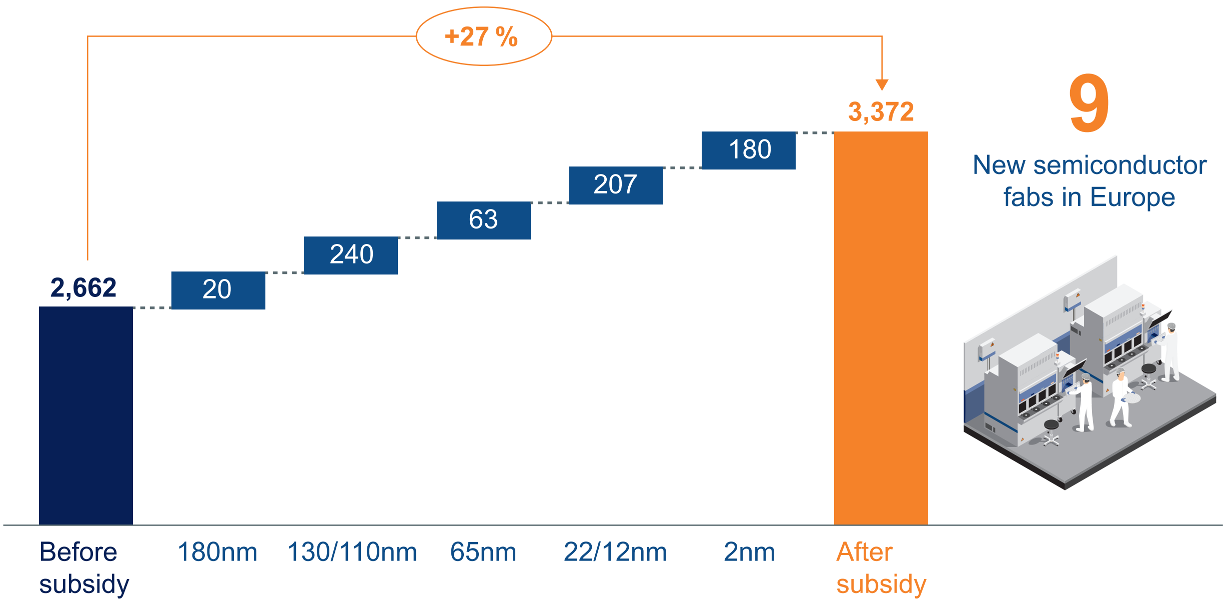
Using the input-output model, it is possible to determine various key ratios. This study focuses on the effects on the overall economy of subsidising microelectronics, and particularly on the change in gross value added and the associated effects on tax revenues.

The data for the analysis was gathered in collaboration with the ZVEI member companies. This was supplemented with publicly-available information on the levels of subsidy, production capacities and price structures, along with some own assumptions. On this basis, an approximated production value per funding project was determined. The total of the approximated production values in connection with the subsidies served as the basis for calculating the indirect and induced effects. These were derived using the domestic production interdependencies shown in the Federal Statistical Office's Input-Output Table for 2021.[17] The input demand for the semiconductor sector according to the official statistics was adjusted to map the specific demand for the companies in receipt of subsidy.

3.4.1 Trend in European production capacities

For the analysis of the economic effects, the planned major projects to build or expand semiconductor production capacities under the IPCEI on microelectronics and the European Chips Act were taken into account. These include the subsidised projects for Bosch, Infineon, NXP, ESMC, STMicroelectronics, GlobalFoundries, Analog Devices and Intel. The planned subsidies for these projects total around EUR 21.4 billion, including the EUR 10 billion intended for the Intel project or a comparable alternative. If these funds are used in some other way, the total reduces to around EUR 11.4 billion. Since it was not possible to include further subsidised projects due to a lack of data on the level of the subsidy, this total represents a minimum value which could rise further in future. The project planned by Wolfspeed was not included in the calculation, since here the likelihood of a stop on the project is very high, in part given the recently-received subsidy via the US CHIPS Act.

Fig. 3.4: Growth in European semiconductor production capacities from subsidised projects under the IPCEI and ECA by technology node, 2020-2040 (in thousand of wafer starts per month, 200mm equivalent)



Source: Strategy& analysis based on data from ZVEI member companies and public sources

The measures initiated via subsidised projects will increase European production capacities by around 27% by 2040, compared with the level before the start of subsidy (see Figure 3.4).

The biggest growth in capacity will occur in the power electronics sector (130/110nm), particularly owing to the STMicroelectronics silicon carbide projects and the Infineon project in Dresden. Adding to this, the projects for ESMC and the cooperation between STMicroelectronics and GlobalFoundries are making a vital contribution to strengthening European competences and production capacities in the areas of micro-controllers, power management and analog and communications technologies. Realising the planned Intel project would also provide Europe for the first time with a production facility for 2nm technologies, enabling the manufacture of the latest components for AI and high-performance computing. In the event of a complete stop on the project and without possible alternatives, growth in production capacities would only hit 20%.

The question remains as to whether current investments are sufficient to achieve the target sought by the European Commission, of a 20 per cent share of global production capacities. This is because other leading and emerging semiconductor nations are investing significantly in expanding their local manufacturing capacities. Against this background, the study analyses the development in European semiconductor production using three possible scenarios:

- Scenario 1 – No subsidy: In this comparative scenario, the assumption is that, without state subsidy, European production capacities would have grown at the same rate as prior to 2019. For the period after 2030, a modestly-increased growth rate is assumed, to take account of the accelerated demand from electrification and computing.

- Scenario 2 – Current funding programme: This scenario is based on the current programme of subsidies. After conclusion of the planned expansions, around the mid-2030s, capacities develop with the growth rate assumed in the first scenario.

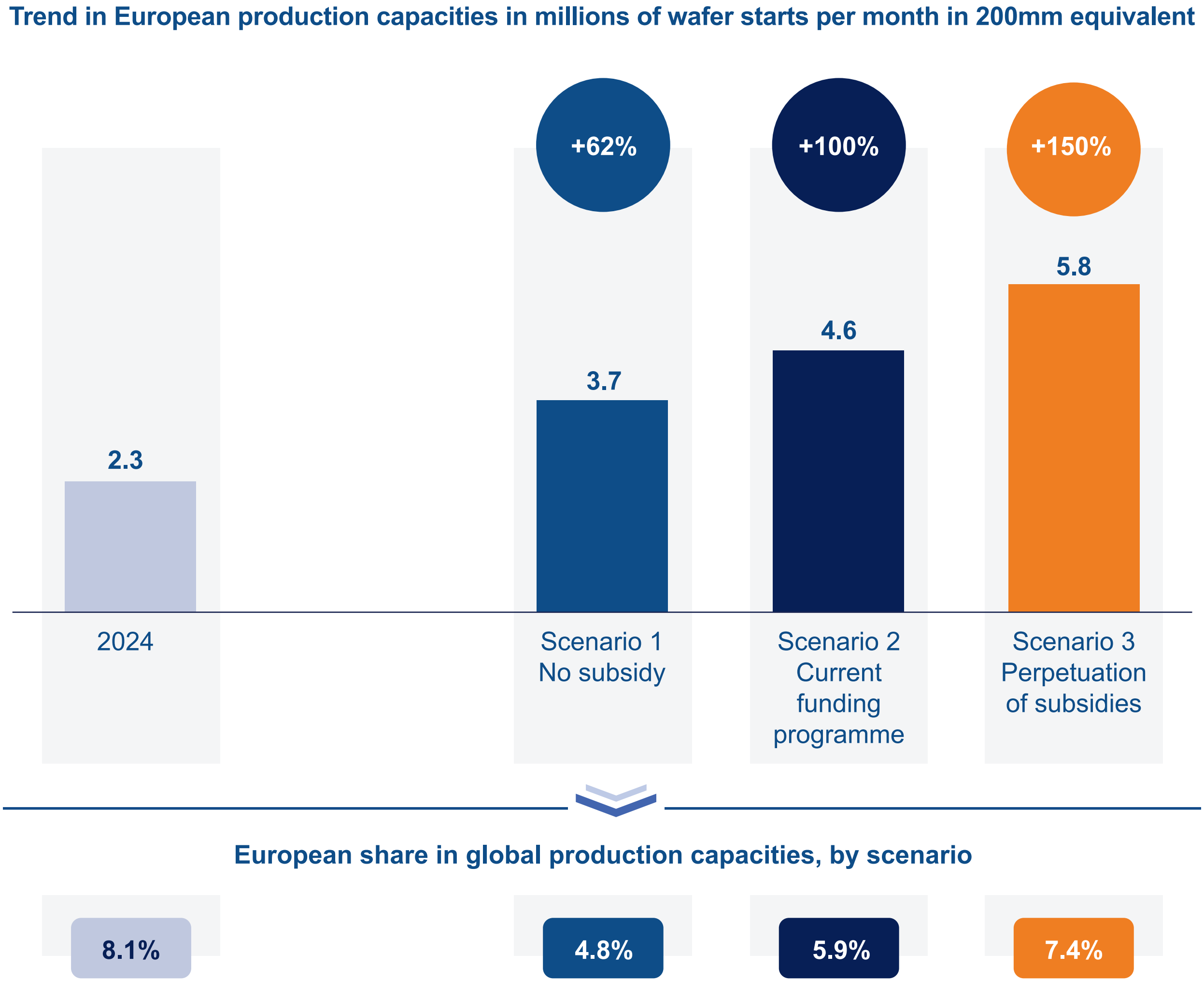
- Scenario 3 – Perpetuation of subsidies: In this scenario, the assumption is that following conclusion of the current projects additional subsidies will support further major projects in Europe and drive the expansion in production capacities for the long term. The level of the assumed investments corresponds proportionately to those in the current programmes, and leads to a similar growth rate.

The results of this analysis are shown in Figure 3.5. Perpetuating the current funding measures is the only approach that could enable Europe to maintain its global share of manufacturing capacities at a near-constant level, given that it has fallen over a long time in the past. The share would then reduce only modestly, from the current 8.1% to a projected 7.4% in 2045. Without additional measures and based on the currently-planned subsidised projects, however, the share could fall to slightly below 6%. The decline would have been even more dramatic without the investments already made, as it would have seen Europe's share falling to below 5%. This illustrates the decisive contribution that state subsidies can make in a capital-intensive and strategically important area such as microelectronics, in terms of the future competitiveness of this industry. Through such measures, equal conditions for competition can be created and thus a "level playing field" reached, in terms of an international comparison.

3.4.2 National economic growth through subsidising microelectronics

Two scenarios were considered in the study for the input-output analysis: the national economic effects for Germany and the overall effects for the EU. For this, the assumptions on the distribution of domestic input demand on the supplier industries are largely based on the data in the Federal Statistical Office's input-output table. The effects at EU level were extrapolated, based on this. Despite possible deviations at European level compared to the production interactions in the German economy, the methodology offers a valid approximation. This is attributable above all to the fact that almost 80% of the value added effects relate to German projects. A comparable situation also pertains in relation to corporation tax rates: a value of around 24% was assumed for Germany[18], while the rates for France (just over 30%) and Italy (just over 29%) only deviate slightly.[19]

Fig. 3.5: Trend in European semiconductor production capacities under 3 scenarios and share of global capacities, 2024-2045 (million wafer starts per month, 200mm equivalent and share in percent)



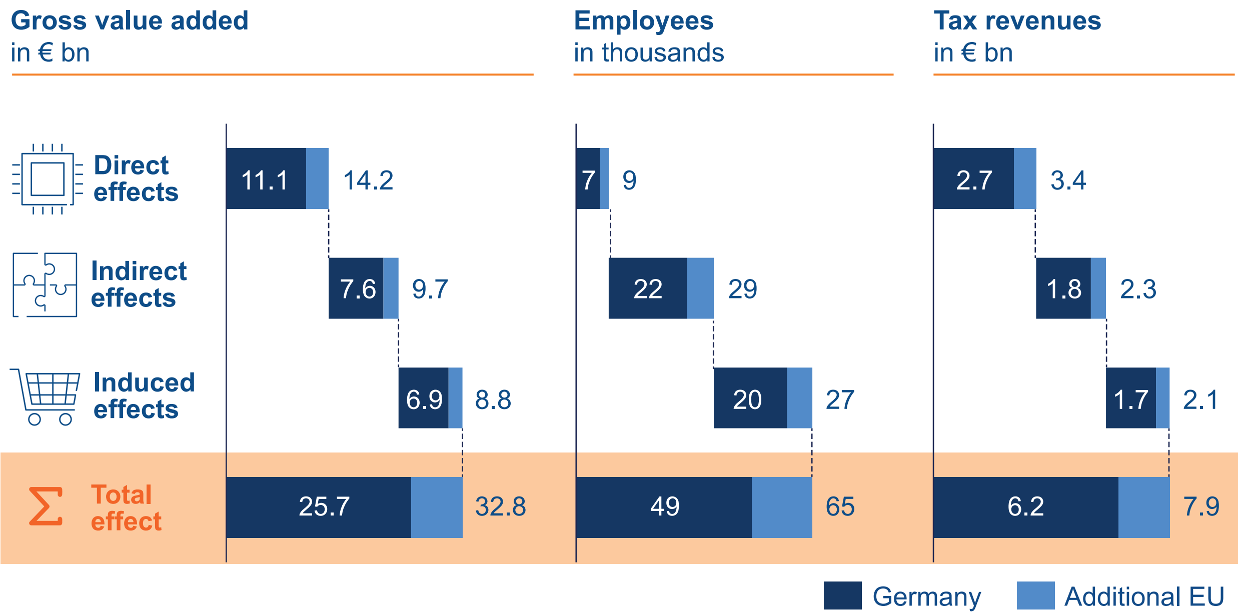
Source: Strategy& analysis

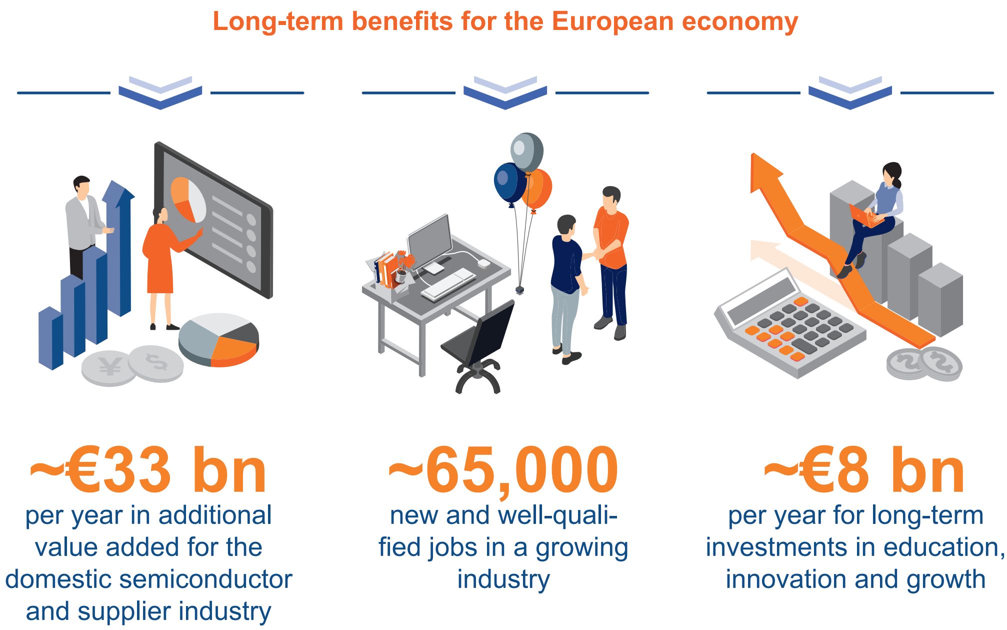
Growth in gross value added

The results of the analysis show that subsidised projects, if successfully completed, result from 2036 in an annual increase in gross value added of EUR 25.7 billion in Germany alone (see Figure 3.6). During the ramp-up phase of the projects the value is initially lower, but it already reaches around half of this amount by the start of the next decade. The importance of the major project for Intel in Magdeburg should be particularly emphasised: without a comparable project, the annual growth in gross value added would only be around EUR 8.3 billion, corresponding to just one-third of the total value.

Of the total of EUR 25.7 billion in annual gross value added, 43% is attributable to direct effects, resulting from increased value added as part of production in the subsidised fabs. For the IDMs, this value also includes value added from chip design, where the share – based on historical empirical values – is estimated at between 10% and 30%. In addition, the calculation also assumes a decline in product prices, expected particularly for products using 2nm technology and in silicon carbide power electronics. This price reduction is attributable to significant efficiency improvements in production processes and the associated cost reductions in the years ahead.

Fig. 3.6: National economic effects of microelectronics subsidies per year, following completed expansion, for Germany and Europe





Source: Strategy& analysis

A further 30% of the gross annual value added linked to subsidy relates to the increased value created in the supplier sectors, including semiconductor equipment and tools, materials and services. This corresponds to a significant sum of nearly EUR 7.6 billion per year, in the fully built-out state. Beyond this, 27% – or around EUR 6.9 billion – relates to induced effects in other industries, generated in connection with consumption by employed workers.

If all projects at EU level are considered, the value of the additional value added runs to just under EUR 33 billion. Here, too, around 42% is due to direct effects resulting from the increased gross value added in the subsidised production facilities.

Growth in employees

To examine the creation of new jobs, a two-pronged approach was adopted. The figures for directly-arising additional employees are based on data provided by the member companies, and supplemented with publicly-available information. The indirect effects within the supplier industry and the induced effects from increased consumption were determined using empirical values calculated for the semiconductor industry.[20] In Germany alone, subsidies give rise to around 7,000 new jobs with semiconductor manufacturers. Through input demand from semiconductor manufacturers, a further 22,000 jobs arise in the supplier industry (indirect effects) and a further 20,000 from increased consumption (induced effects). In total, this produces a factor of around six – meaning that each direct job brings with it more than six further posts along the value chain. In total, this generates around 49,000 long-term jobs in Germany and 65,000 in Europe from the subsidised projects. In the long term, this helps to offset the loss of jobs in other areas affected by the structural change.

Thus the microelectronics projects make a vital contribution to building up and preserving jobs, and promote the development of innovative know-how in the EU. In addition, the increased demand for trained specialists increases the attractiveness of offering targeted education and training programmes in the field of microelectronics. Due to scale effects, the growing number of employees in the sector makes it more efficient for educational establishments to offer customised trainings. This dynamic is particularly important in view of the threatened shortage of specialists in the EU, a problem further exacerbated by demographic change. The microelectronics sector is similarly challenged by this, and by 2030 it could be facing a shortfall of around 350,000 skilled employees.[21] To counteract this bottleneck, targeted measures in education, training and talent promotion are needed to secure European competitiveness in the microelectronics sector in the long-term. These include not only adapted courses of study, but also suitable apprenticeship routes, particularly in the areas of mechanical engineering and machine maintenance. In addition, it is essential that courses of study and training programmes are better coordinated with the industry's technological roadmap, in order to clearly define the future requirements and to promote the necessary skills in a targeted way.

Additional tax revenues

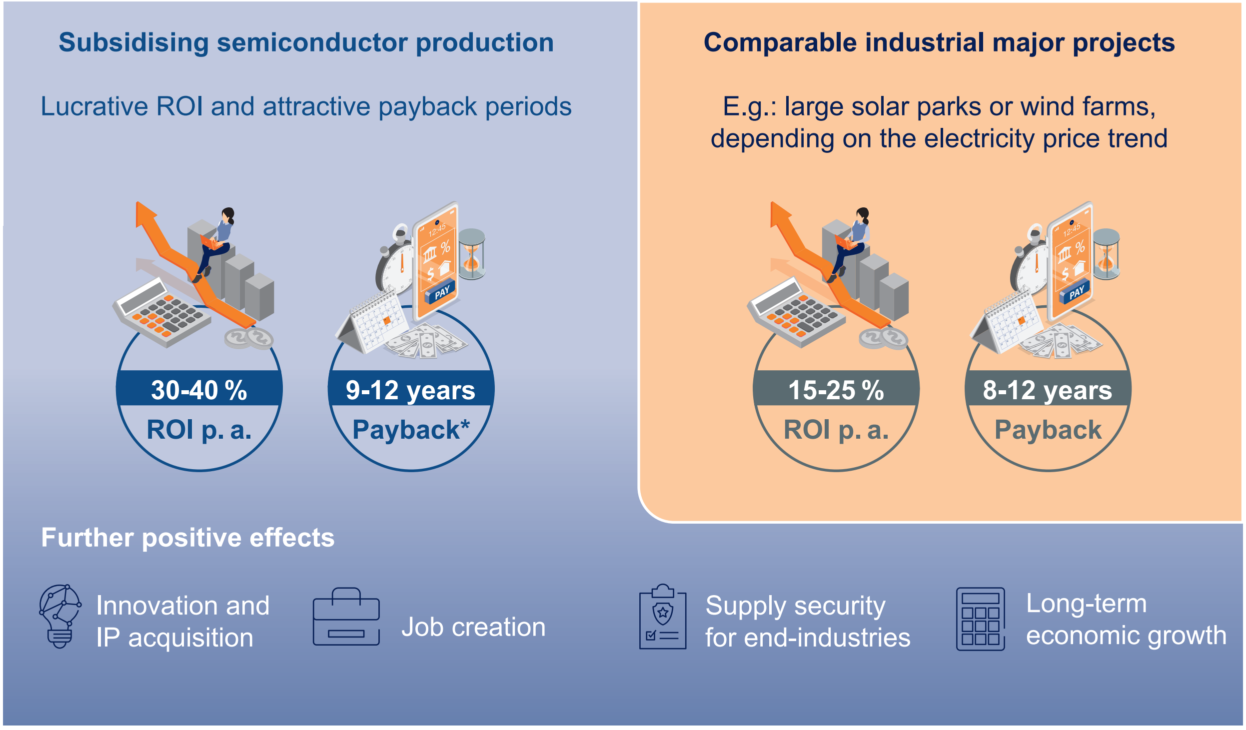
Following successful ramp-up of all projects, the direct, indirect and induced effects on value added lead to additional tax revenues of around EUR 6.2 billion p.a. in Germany.[21] At the European level, the additional tax revenues total as much as EUR 7.9 billion annually. In this regard, it is important to emphasise that these values will probably only be achieved in the mid-2030s, and will be lower during ramp-up.

3.4.3 Microelectronics investments with high returns

If the anticipated tax revenues are compared with the volume of state subsidy invested, the resulting return on investment (ROI) is between 30 and 40% p.a., in the fully built-out state (see Figure 3.7). For comparison purposes, on projects with high investments and corresponding risks companies generally look for ROI of 15 to 25%. The analysis therefore confirms the economic attractiveness of the subsidised projects. Incidentally, the loss of the Intel project would not have a major influence on ROI, since the level of the subsidy funding would then be significantly lower.

As mentioned previously, the return on investment is to be anticipated following successful implementation of the projects. Within this, the ramp-up of large semiconductor fabs represents a complex and elaborate process. To calculate the amortisation period for the state investments, a detailed ramp-up curve at project level was adduced, supplemented by an assumed discount rate of around 10%.[22] Based on these assumptions, the resulting amortisation period is between 9 and 12 years. Although this time-frame appears high on first viewing, it corresponds to the usual values in the semiconductor industry for comparable projects, and therefore lies in the expected range. It should be particularly emphasised that after this period the profits kick in, which exceed the original investments several times over within a very short time.

Fig. 3.7: Positive effects of European microelectronics subsidies, including ROI and amortisation period



*Depending on the precise time of the project starts;
Source: Strategy& analysis

3.5 The contribution from microelectronics to global value added

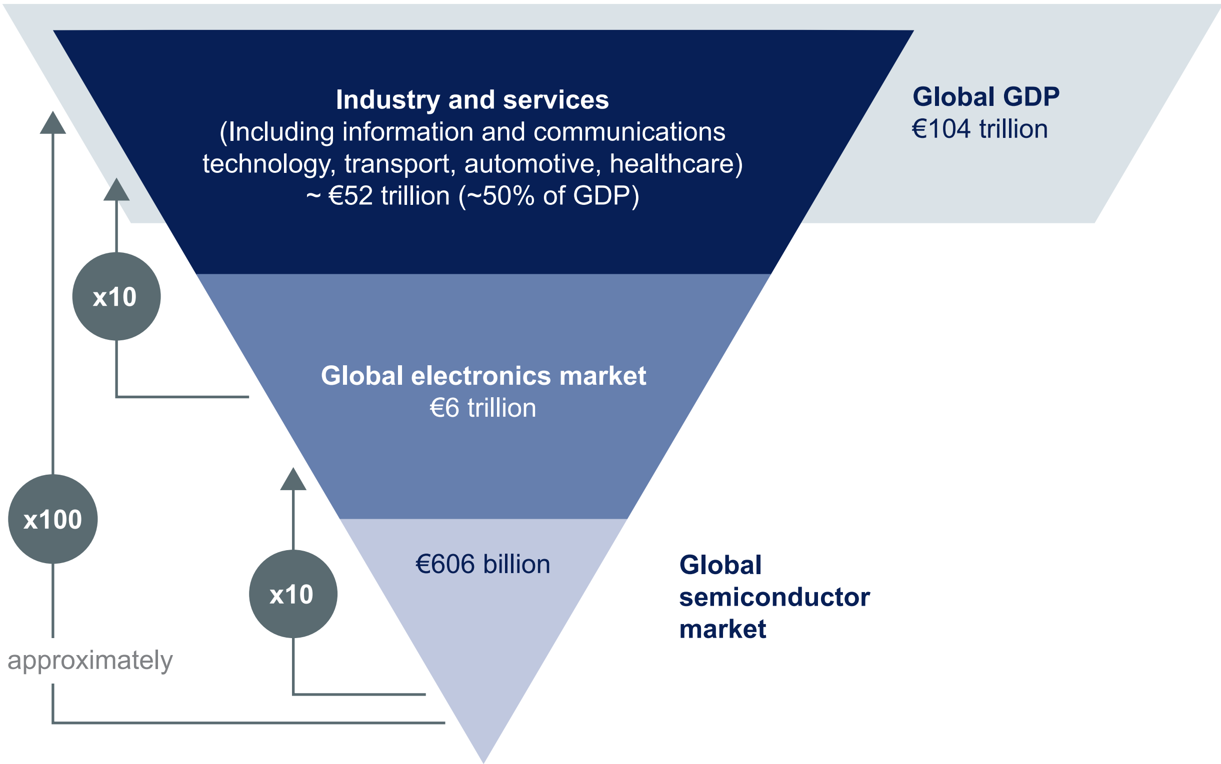
In addition, microelectronics represents a key lever for value added in downstream applications industries. According to an analysis by industry representatives, direct and indirect microelectronics products contribute around 50% to global GDP (see Figure 3.8). They enable sales of EUR 55 trillion, thus generating a hundred times their own value added in applications industries such as information and communications technology, transport, automotive, healthcare, and aerospace.

This immense influence underlines the strategic importance of microelectronics as the foundation for economic growth, technological innovation and social progress. This close connection with the applications industries shows that investments in microelectronics not only boost the competitiveness of individual regions, but also stabilise global value chains and facilitate transformative technologies in key sectors of our society.

Supporting microelectronics is more than an economic measure – it is an essential component in Europe being fit for the future. The results of the analyses performed show how far-reaching the effects of this subsidy are: it strengthens European industry along the entire value chain, creates new jobs and generates tax revenues at a level which justifies the investments in the long term. Moreover, the subsidy addresses key challenges such as the increasing dependence on non-European semiconductor manufacturers and is the basis for innovations in key industries such as mobility, communications and power supply. For without a European subsidy, there is a high probability – given the global competition in funding – that companies will favour locations outside Europe offering higher incentives. The specific requirements of the microelectronics industry, particularly the massive investment sums and the long project lifetimes, increase the risk for new investments considerably. Such projects will be implemented with far greater probability if the demand is assured or if there is support via funding programmes.

The analysis clearly shows that these investments are not only sensible in economic terms, but also have a transformative effect overall on industry, society and the European economy. They enable Europe to position itself as a leading region for technology in an increasingly global competition, and to create a long-term basis for prosperity and resilience.

Fig. 3.8: Positive economic effects of the microelectronics industry in the applications industries



Sources: DECISION Etudes & Conseil, Deutscher Bundestag, Infineon, S&P Global, WSTS, ZVEI, Omdia Q3 2024

4 Microelectronics as an engine for sustainability goals

The effects of climate change have long been felt globally, and find expression in destructive fires, devastating storms and catastrophic floods. These extreme weather events are impacting national economies and societies worldwide with increasing severity, and causing immense damage. Given these developments, the urgent need to create a climate-neutral economy is increasingly becoming the focus of global measures.

On 12 December 2015, 197 countries reached agreement at the UN Climate Conference in Paris (France) on a new, global climate protection treaty.[23] The states set themselves the global target of limiting global warming by comparison to the pre-industrial age to "well below" two degrees Celsius, and to make efforts to limit it to 1.5 degrees Celsius.

To achieve this, national governments have set targets for climate neutrality. The European Union is looking to become climate-neutral by 2050.[24] Other major economies, too, are pursuing similar goals: Japan and South Korea are looking to achieve this by 2050[25,26], while China wants to reach it by 2060.[27] As things stand currently, the U.S. is similarly planning to be CO_2-neutral by 2050.[28] These provisions, however, are not just political in nature, but also send a clear signal to the industry that far-reaching changes are unavoidable.

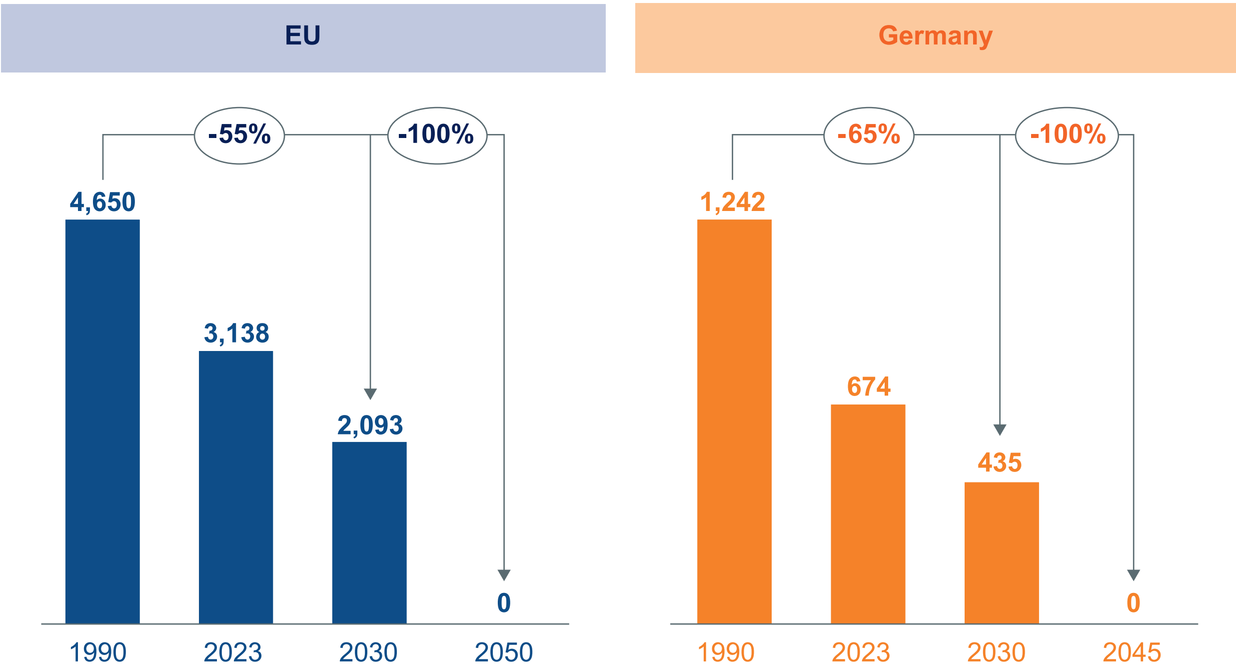
Microelectronics plays a central role, as a catalyst for the European and German climate goals. The aim is to highlight this relevance in this chapter, and to examine and discuss the advantages of Europe as an economic location for sustainable semiconductor production, along with the framing conditions that are needed to further promote its competitiveness as a location.

4.1 Ambitious EU and German climate targets

On the path to European climate neutrality, by 2030 the EU wants to achieve a reduction in greenhouse gas emissions of at least 55% compared to the 1990 level (see Figure 4.1). This interim target is part of the "European Green Deal", a comprehensive strategy which not only places an emphasis on reducing emissions, but also on promoting a sustainable economy and strengthening European industry.[18]

Germany, as the biggest industrial country in the EU, is pursuing similarly ambitious targets. By as early as 2045, the country is aiming to become climate-neutral, five years ahead of the target date set by the EU.[29] This means that Germany not only needs to reduce its emissions drastically, but must also make major steps forward towards carbon-free energy supply, mobility and industry. By 2030, Germany is planning to lower emissions by at least 65% (see Figure 4.1), which necessarily leads to comprehensive changes in energy production, transport and industrial manufacturing.

Fig. 4.1: German and European climate goals to reduce greenhouse gas emissions, in million tons CO_2 equivalent



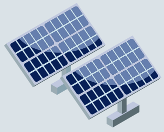
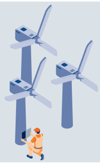
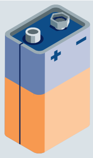
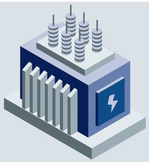
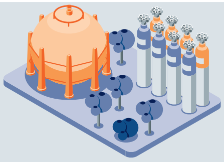
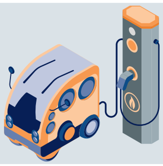
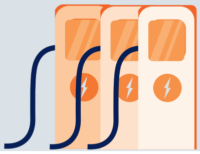
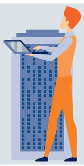
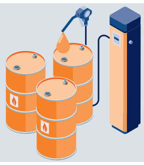
Source: Federal Environment Agency (UBA); EEA greenhouse gases

4.2 Achieving sustainability with the help of climate technologies

The targeted change in industry and society is predicated on a comprehensive transformation of the energy, heating and mobility systems. Climate technologies such as photovoltaics, wind power plants, battery storage, heat pumps, electric vehicles and smart home systems play a key role in this. These make it possible to reduce CO_2 emissions, replace fossil fuels and at the same time ensure security of supply in an increasingly electrified world.

However, the importance of climate technologies goes well beyond individual applications – as they are catalysts for long-term innovation. They create the conditions for new business models and promote the integration of renewable energies into existing systems. Below, key climate technologies are illustrated in greater detail, along with their respective areas of application and their interaction (see Figure 4.2.). In this study, the focus is on technologies that make a direct contribution to electrification. But other systems too – such as autonomous applications or digital solutions – will contribute to reducing emissions in the long term. However, they have deliberately not been included in the study, in order to define clear boundary conditions for quantification and to minimise uncertainty in the analysis as far as possible.

Fig. 4.2: Overview of climate technologies and a selection of illustrative applications

Climate technology		Applications (examples)
	**Photovoltaics**	• Residential electricity and heat generation • Commercial power generation including PV plants
	**Wind**	• Commercial energy generation on land (onshore) and at sea (offshore)
	**Battery storage**	• Battery storage in combination with a PV system • Central battery storage for grid regulation
	**Heat pumps**	• Heat pumps for residential heat generation • Large-scale heat pumps for district heating and industrial processes
	**Electrolysis**	• Hydrogen production for industrial processes and industrial heating, the transport sector, energy production, etc.
	**Electric vehicles**	• Electric cars, trucks, and buses • Electric commercial vehicles
	**Charging points**	• Wall-boxes • Public (fast) charging points
	**Smart home**	• System for energy management • Smart meters and distribution boxes
	**Control systems for industry**	• Power control systems in industrial production
	**E-drives for industry**	• Electric drives in production for autonomous systems, conveyors, tooling machines, pumps, fans, compressors and other machines

Source: Strategy& analysis

Photovoltaics and wind power: the basis of renewable power supply	Photovoltaic and wind power plants form the backbone of an emissions-free energy infrastructure. Thanks to the modular design, PV systems can be adapted flexibly to a wide range of requirements – from smaller, localised home systems to large industrial PV plants. Wind power plants supplement photovoltaics ideally, by frequently producing electricity at times when sunshine is at low levels, such as in the evenings or during the winter months. They can be realised either onshore or offshore. Offshore wind farms, in particular, offer massive potential, since the constantly high wind speeds there can be exploited. Both technologies offer not only the possibility of using renewable sources of energy, but are essential to cover the growing demand for electricity from more sustainable sources.
Battery storage: flexibility for renewable energies	Battery storage supplements the volatile power sources that are wind and sun, by storing surplus energy and releasing it again as needed. This stabilises the power grid and makes efficient use of renewable energies possible. Battery storage is used both in private homes and in large-scale storage facilities.
Heat pumps: decarbonising the supply of heating	Heat pumps make it possible to produce heat efficiently and with low emissions. While smaller heat pumps are primarily an alternative to fossil fuel for residential heating, large-scale heat pumps are employed in district heating systems and in industrial applications. They can use waste heat from industrial processes or heat from geothermal sources to heat whole districts or to supply industrial processes with the required thermal energy. Their use is particularly attractive in the food, chemicals and paper industries, where large quantities of process heat are needed.
Electrolysis plants: hydrogen as energy source	Electrolysis plants make it possible to produce green hydrogen, which serves as an adaptable energy source in industrial applications, mobility and energy storage. Hydrogen offers a sustainable alternative to fossil fuel energy sources, particularly in areas that are hard to electrify, such as the steel industry or heavy goods transportation.
Electromobility and the charging infrastructure: the future of mobility	Electric vehicles and the associated charging infrastructure form a key pillar in climate-friendly mobility. They reduce the dependency on combustion engines, and make it possible to significantly reduce greenhouse gas emissions in the transport sector. In doing so, the connection between e-mobility and renewable energies, such as via vehicle charging using solar power, is becoming increasingly relevant.
Smart energy management systems: efficient use of resources	Smart home systems and smart energy control systems in production ensure more efficient use of energy. They analyse and control energy consumption in real time, and enable optimum distribution of renewable energies. Smart meters and distribution boxes, in particular, are creating the basis for smart grids that design energy flows more efficiently.
Electric drives: supporting sustainable production	Electric drives are increasingly replacing mechanical or hydraulic systems, offering advantages such as greater energy efficiency, lower maintenance expense, and reduced emissions. Particularly in energy-intensive industries such as metal or chemicals production, but also in automotive manufacturing and in packaging processes, electric drives enable precise control and adjustment to variable production requirements.

Moreover, the increasing connectivity of climate technologies is boosting their impact. For instance, PV systems can be linked with battery storage and heat pumps to provide energy for heating or cooling of buildings. Electric vehicles can be used as mobile energy storage, storing surplus solar power and feeding it back into the grid as required (smart charging and vehicle-to-grid). These synergies create an integrated and flexible energy system that not only reduces CO_2 emissions, but also increases the efficiency and stability of the power supply.

4.3 The role of microelectronics in climate technologies

Microelectronics is a fundamental component of the climate technologies mentioned, since it enables the control, adjustment and optimisation of energy flows. This process starts with data recording by sensors, measuring key parameters such as temperature, electric current, solar radiation or speed of rotation. The recorded data forms the basis for adapting the systems to different requirements. For instance, in a PV system sensors record the solar radiation and simultaneously measure the ambient temperature in a heat pump, in order to regulate the energy demand dynamically. In production facilities, sensors monitor the status of electric drives, to manage their operations efficiently and safely.

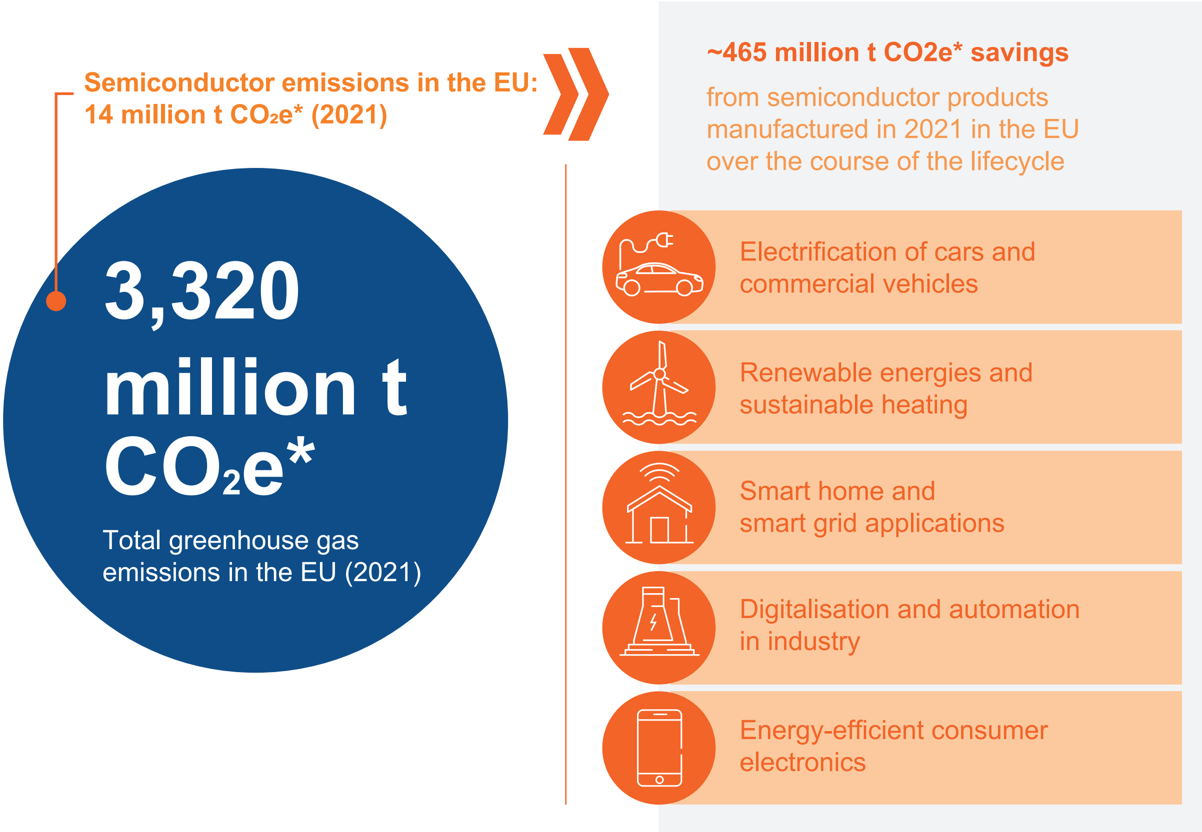
The data gathered is then processed by microcontrollers, memories and other logic components that handle the central control of the technologies. They coordinate the charging cycles of electric vehicles, control energy conversion in PV and wind plants, or optimise the operation of electric drives in production. Microcontrollers ensure that these processes are controlled accurately and specific to the application.

For energy conversion and management, power semiconductors and other discrete semiconductors play a vital role. For instance, they convert the direct current produced by solar cells into alternating current that can be fed into the power grid, and regulate the energy supply in electric vehicles or electric drives. Power semiconductors contribute decisively to the efficiency and adaptability of these technologies.

In addition, logic semiconductors in combination with the power semiconductors control the actuators, which in turn translate the electrical signals into mechanical movements. They open and close valves in heat pumps, drive production machines or control mechanical processes in industrial applications. In this way, digital controls are translated into practical applications.

The interaction and coordination between different technologies is made possible using communications semiconductors. These ensure that individual systems can be connected and coordinated with one another. In smart home, for example, PV systems, heat pumps and battery storage work together to optimise energy consumption. Electric vehicles can also be integrated into a smart grid for this purpose, and provide interim storage for surplus solar or wind power. Connected systems of this kind support efficient energy distribution and promote the sustainable use of renewable energies. Linking sensor systems, controllers, power converters and communications enables effective collaboration between climate technologies. Microelectronics thus creates the conditions for embedding these technologies into integrated systems which support the transition to a more sustainable energy supply.

Fig. 4.3: Greenhouse gas emissions in the EU and from European semiconductor production and the savings within end-industries from using semiconductor products manufactured in 2021

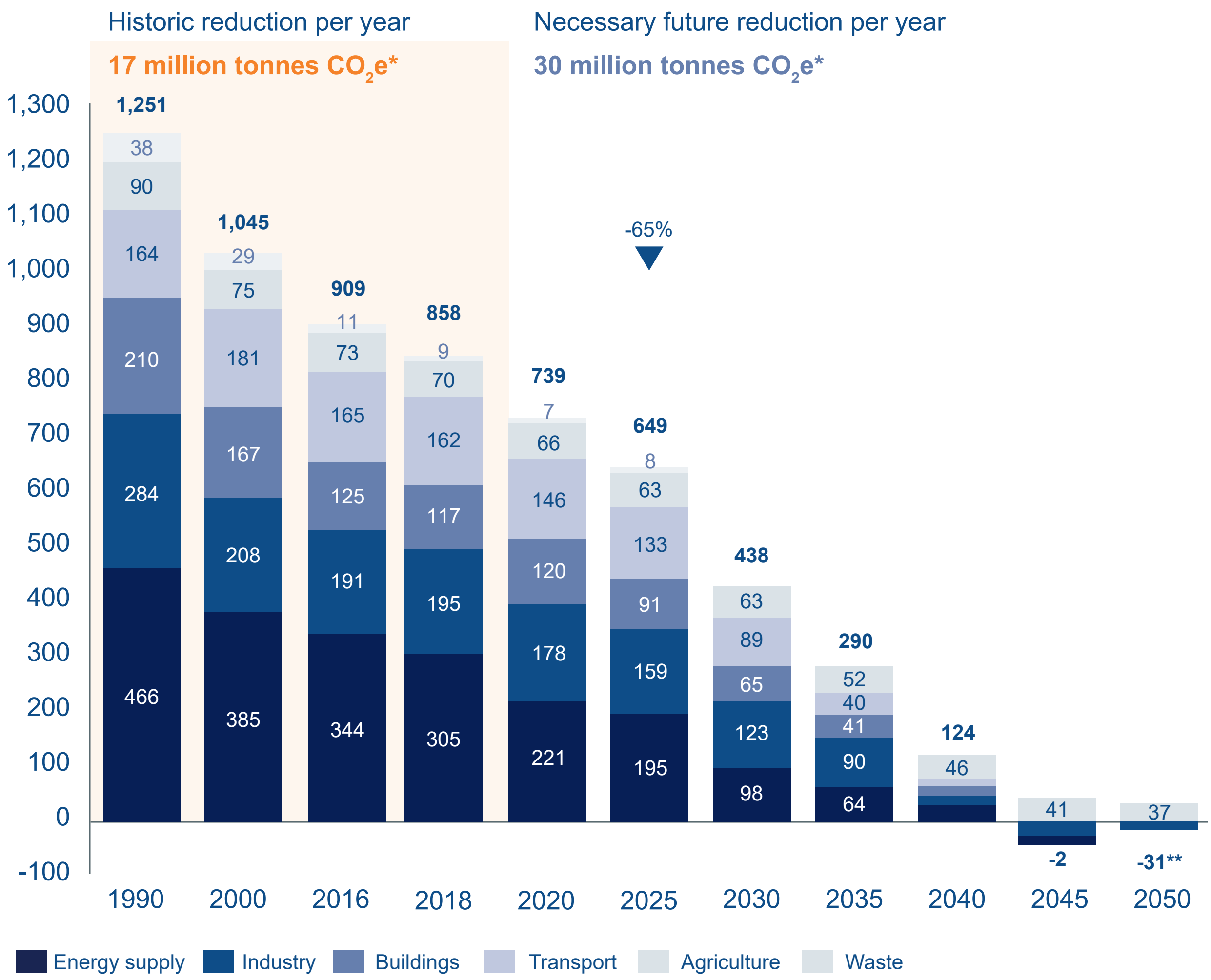


* Million tonnes CO_2 equivalent

Source: Strategy& analysis based on Stiftung Neue Verantwortung (2024) in Julia Christina Hess 2024: Chip Production's Ecological Footprint Mapping Climate and Environmental Impact, EEA (2024)

Overall, the microelectronics industry and its products are already contributing significantly today to reducing European greenhouse gas emissions. According to a study by Stiftung "Neue Verantwortung" ("New Responsibility" Foundation), European semiconductor production in 2021 was responsible for emissions of up to 14 million tonnes CO_2 equivalent, representing around 0.4% of total European greenhouse gas emissions. At the same time, microelectronics products are making a considerable contribution towards lowering emissions in the end-industries. Based on estimates by semiconductor industry experts, microelectronics products are saving 34 times more emissions than are caused during their production.[30] Purely considering European semiconductor production for 2021, this means a saving of 465 million tonnes CO_2 equivalent that can be achieved over the lifecycle of the products. Given a lifetime of 10 to 20 years, depending on the product, this corresponds to an annual saving of up to 50 million tonnes CO_2 equivalent. This constitutes 1 to 2% of total annual emissions in Europe, and underlines even today the relevance of microelectronics with regard to pursuing the sustainability goals. With progressive electrification and the increasing spread of climate technologies, this effect will become even more significant in future.

Fig. 4.4: Reduction under German climate goals



Negative emissions are taken directly into account in the respective sectors

* Million tonnes CO_2 equivalent

** After 2045 the trend is simply extrapolated, and a further reduction in emissions is possible

Source: Agora Klimaneutrales Deutschland 2045 and Prognos, Oka Institute, Wuppertal Institute (2021)

4.4 The path to climate neutrality

Achieving German climate neutrality by 2045 requires comprehensive measures in all sectors of the German economy. The necessary reductions are distributed across the energy supply, industry, buildings, transport and agriculture. For the analysis in this study, the basic assumptions of the Agora study "Klimaneutrales Deutschland 2045" ("Climate-neutral Germany 2045", hereinafter KND2045) are adduced and supplemented with own models to evaluate the development of key technologies in the individual areas. The trend in emissions for Germany according to KND2045 for each sector is shown in Figure 4.4. In 2023, Germany's greenhouse gas emissions were 673 million tonnes CO_2 equivalent – a trend that falls within the parameters of the KND2045 study.

Energy supply
With a 30% share of total emissions, the energy industry was the biggest cause of greenhouse gases (GHG) in Germany in recent years. According to the scenarios in the Agora study, electricity consumption in Germany is set to continue rising, from 575 TWh in 2020 to 882 TWh in 2045, due to increasing electrification. Since the assumptions in KND2045 date from 2021, this figure could increase further due to the growth in data centres and AI applications which has become apparent in recent years. At the same time, the biggest reduction in GHG emissions is expected in this area – a reduction by 235 million tonnes CO_2 equivalent between 2020 and 2045. This transformation is set to be achieved through an increase in installed PV capacities by a factor of over four, along with a tripling of wind power plants. The use of battery storage, too, will increase considerably in the course of expanding renewable energies.

Industry
Industry is the second-biggest emitter, with 178 million tonnes CO_2 equivalent in 2020, accounting for a 24% share. Electric drives and large-scale heat pumps are set to decarbonise industrial processes in this sector. In addition, the use of green hydrogen in energy-intensive industries is being driven forward, in order to replace fossil fuels. Smart energy management systems are also optimising more accurate management of power flows, contributing to increasing efficiency.

Residential and commercial
The residential and commercial sector is responsible for around 16% of German GHG emissions in 2020, and is challenged to deliver a reduction of around 120 million tonnes CO_2 equivalent by 2045. A key measure in lowering emissions is a massive expansion in heat pumps: by 2045, 14 million heat pumps will be required in residential properties. In addition, large-scale heat pumps are to ensure supply via district heating, in both urban and industrial settings. Intelligent smart home systems are optimising energy consumption by dynamically coordinating the use of photovoltaics, battery storage and heat pumps.

Transport
Transport is now the third-biggest emitter in Germany, with 146 million tonnes CO_2 equivalent in 2020. However, that was not always the case: over the past decades, transport's share in overall emissions has grown steadily. The switch to electric vehicles, the expansion in the charging infrastructure and the development of emissions-free drive technologies are key measures for reducing emissions. Connected mobility solutions and autonomous vehicles can also contribute to increasing efficiency and lowering emissions.

Agriculture
In agriculture, emissions fell, notably during the 1990s due to the decline in livestock numbers. Compared to the other sectors, emissions in 2020 were at a relatively low level, with 66 million tonnes CO_2 equivalent. Further reductions are being achieved, inter alia, by reducing animal stocks and digesting high volumes of manure in biogas facilities.

4.4.1 The number of climate technology systems needed

Based on the assumptions in the KND2045 study, models for the development of climate technologies were created. In order to enable a detailed calculation, reference systems were defined for each technology. This is particularly clearly demonstrated in the case of PV facilities: these come in various size classes, from small roof systems with an peak output of less than 10 kW through to large PV farms with an output of over 750 kW. For the models, corresponding categories were formed per climate technology. Future demand was determined on the basis of current market forecasts from studies, along with estimates by experts. The assumptions in KND2045 served as a boundary condition for the total capacity required by 2045, set out in 5-year increments. A comparable approach was also applied for other climate technologies.

For specific technologies (such as charging infrastructures, smart home or electric drives for industry), complementary market models by Strategy& were used, since no base data was available for these in KND2045. These individual approaches allowed for a differentiated assessment of the respective technologies.

The calculations were carried out under two scenarios:

- Scenario Min: This scenario describes the minimum necessary demand for climate technology systems, based on the energy requirements in KND2045, and thus forms the lower limit of the requirements.

- Scenario Max: In this scenario, the assumption is of a significantly higher number of climate technology systems, in order to offset possible inefficiencies in the system. Particularly in the area of renewable energies, it takes account of the fact that overcapacities might be needed in order to bridge energy bottlenecks. In addition, in this scenario a higher degree of electrification is assumed in new production facilities, compared to redeveloped sites.

Similar principles apply in the areas of hydrogen and heat production. Here, the assumption is of increased adaptation of these technologies in order to offset inefficiencies and to close potential gaps in the development of synthetic fuels. The Scenario Max thus takes account of greater flexibility and adaptability to cope with the growing requirements.

The analysis shows that by 2045 a total of 365 to 552 million climate technology systems of various types will be needed in order to achieve the German climate goals (see Figure 4.5). In the area of photovoltaics, the installed capacity needs to grow from 2025 to 2045 to around four to five times the number of plants in place in 2025, in order to meet future demand. This corresponds to 11 to 16 million new PV systems, of which the majority will be installed in the private sector.

When it comes to wind power plants, considerable growth is again expected: somewhere between the same and twice the number of new turbines will be needed, with 80% of this expansion to come via onshore plants. The increase in battery storage is particularly striking: the number of such units will increase from just over 500,000 in 2025 to between 10 and 16 million by 2045. The main driver of this growth is the increasing spread of battery storage in combination with residential PV systems.

Fig. 4.5: Total demand for climate technology systems to achieve the German climate goals by 2045, assessed using two scenarios and with a comparison to the number of installed systems by 2025, in thousands

	2025	2045 Scenario Min	2045 Scenario Max
PV systems	3,294	10,642	15,963
Wind	33	48	97
Battery storage	483	10,413	15,619
Heat pumps	2	14,001	21,005
Electrolysis		0.4	18
EVs	2,162	132,517	150,218
Charging points	3,658	22,450	33,674
Smart home	2,063	106,591	177,652
E-drives for industry	11,742	68,594	137,188
Control systems	49	103	206
Total	23,486	365,358	551,640

Source: Strategy& analysis

In relation to heat pumps, Scenario Min adopts the assumptions in KND2045, which envisage installation of a total of 14 million systems by 2045. Under Scenario Max, this rises to 21 million, based on greater spread of heat pumps and significantly higher use in district heating and in industrial applications.

For hydrogen, the number of new plants to be added is relatively low by comparison, a fact largely attributable to their size. Based on the hydrogen projects announced, the study primarily assumes the new construction will be of very large, central hydrogen facilities. By 2045, these are set to reach a total capacity of 96 TWh, according to the assumptions in KND2045.

Electric vehicles constitute a large part of the technologies being considered. Starting from around 2 million vehicles in 2025, by 2045 an accumulated total of 130 to 150 million will have been sold in Germany – representing an increase by a factor of 60. Around 10% of these will be electric trucks and commercial vehicles. This growth will significantly increase the demand for home charging boxes, public charging points and rapid charging stations. The underlying model takes into account both the energy requirement in this sector and also a distribution based on forecast charging patterns amongst the general population.

Comparable growth is shown in smart home applications: by 2045, it is estimated that 107 to 178 million units will be needed. Home energy management systems and smart meters are the particular focus here. Likewise, the number of electric drives for industrial manufacturing is set to rise considerably, with an expected demand of around 69 to 137 million new devices until 2045.

4.4.2 Semiconductor capacities for the green transformation

In the next step, the semiconductor demand for the defined climate technologies was forecast. Together with the member companies, for each climate technology the specific semiconductor content was estimated on the basis of the reference systems. To illustrate this, we can again use the PV system as an example: for each PV system size class, the semiconductor content per semiconductor product category was determined. Thus, for example, one analysis looked at a 40-kW system to see how many power semiconductors (measured by the chip area) are typically installed in a system of this size. The same methodology was applied for all other categories of semiconductor (an overview of the categories considered can be found in Figure 3.3 in Chapter 3).

This approach was transferred by analogy to the other PV system size classes, and to the other climate technologies. After this, the calculated chip area was converted into the number of semiconductor wafers needed, with the calculations being based on the two defined scenarios (Scenario Min and Scenario Max, see Figure 4.6).

Fig. 4.6: Necessary semiconductor capacity to implement the climate goals per climate technology, based on 2 scenarios, as the required number of wafers in 200mm equivalent, in thousands

	2045 Scenario Min	2045 Scenario Max
PV systems	4,629	5,990
Wind	3,240	6,243
Battery storage	1,304	1,927
Heat pumps	333	461
Electrolysis	137	673
EVs	15,192	17,616
Charging points	951	1,356
Smart home	496	795
E-drives for industry	2,373	4,295
Control systems	0.8	1.3
Total	**28,837**	**39,356**

Source: Strategy& analysis

Before the results are discussed, we first explain the drivers of this demand in fuller detail. The biggest share of the demand for semiconductors falls to power semiconductors and other discrete components, which together account for over 80% of total demand. This result can be explained by the technologies mainly used, which enable the electrification of industry and everyday systems. In addition, the chip area for this group of semiconductors scales directly with the electrical power of the respective system. A large-scale heat pump, for example, needs a greater area of power semiconductors than a domestic heat pump, since higher currents and voltages need to be regulated.

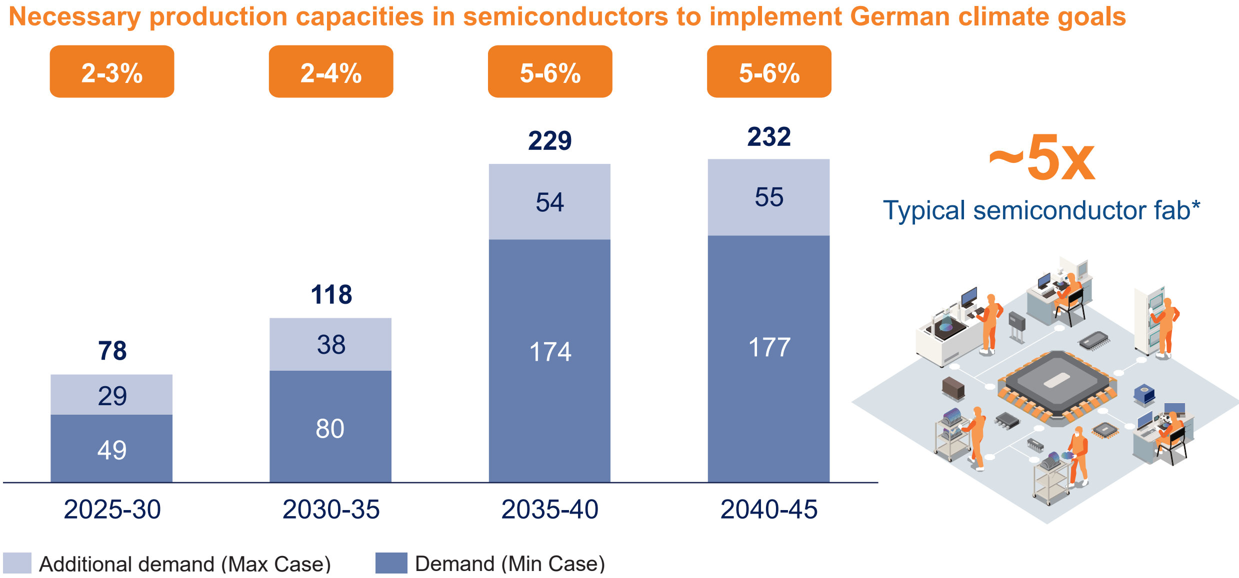
Other semiconductor categories, such as microcontrollers or communications semiconductors, are not dependent on the electrical power of the units, but only on the number of climate technology systems. One articular difference is evident for modular-construction technologies such as PV systems: even large PV plants comprise series-switched, autonomous PV units, each with its own logic, sensor and communications components.

The high demand for semiconductors in the mobility sector is particularly noteworthy, as it is more than three times that of the second-largest technology, PV systems. The reason for this lies in the combination of the number of vehicles and the necessary chip area, particularly for power electronics. Electric vehicles require a larger power semiconductor area than, say, smart home systems or smaller electric drives in manufacturing, even if these are found in comparable numbers of units.

On the other hand, the strong scaling of larger PV systems is clearly evident in the demand for semiconductors. Although the number of PV systems is only around one tenth of the necessary vehicles, the semiconductor surface area is almost one third as high. This is attributable above all to the large PV plants, which drive semiconductor demand in this category to a considerable degree. The pattern is similar for large wind turbines, which similarly require a considerable number of power semiconductors due to the high currents involved. Heat pumps reveal a comparable pattern, but here it is lower-output domestic heat pumps which dominate, thus reducing the demand for semiconductor surface area.

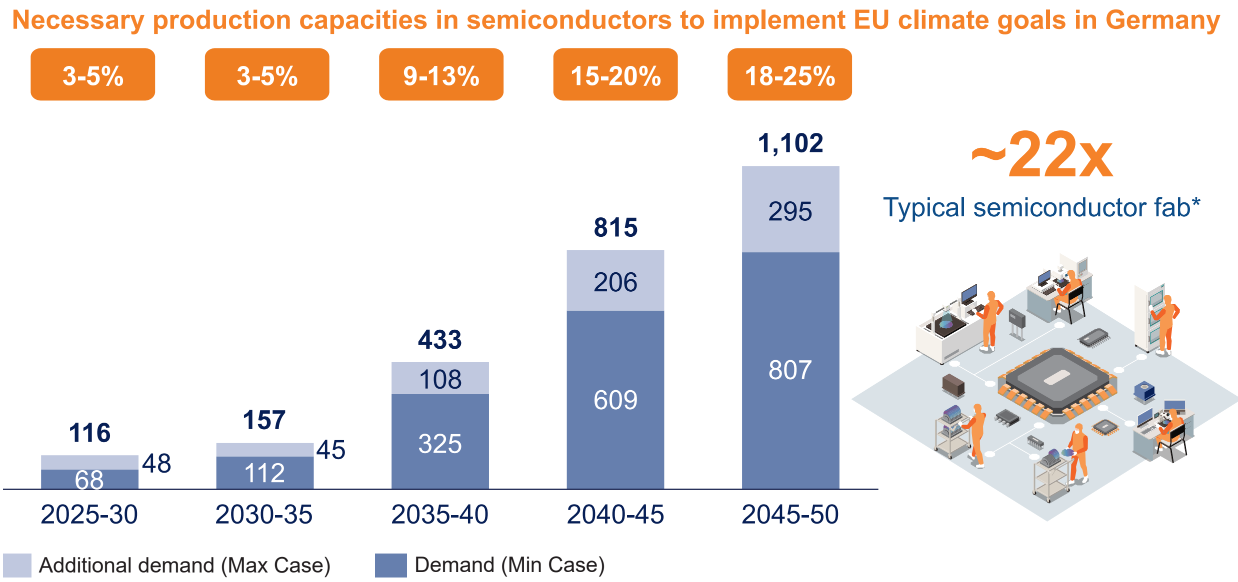
When these demands are considered over time, the extent of the necessary transformation becomes clear. To reach the German climate goals in the context of electrification alone, from 2025 production capacities of close on 80,000 wafer starts per month are needed.

Fig. 4.7: Necessary production capacities for semiconductors to implement the German climate goals, in thousands of wafer starts per month in 200mm equivalent, and the share of this demand in European production capacities (2025-2045)



*Typical reference fab with a capacity of 50,000 wafer starts per month[28]
Source: Strategy& analysis

Fig. 4.8: Necessary production capacities for semiconductors to implement the EU climate goals, in thousands of wafer starts per month in 200mm equivalent, and the share of this demand in European production capacities (2025-2050)



*Typical reference fab with a capacity of 50,000 wafer starts per month[28]
Source: Strategy& analysis

This figure is set to rise significantly in the next 15 years, since the introduction of more climate technologies – particularly in the second half of the next decade – will increase considerably. In the last five years of the period considered, demand will grow to up to 232,000 wafer starts per month. For comparison purposes, this is roughly the equivalent of the capacity of five larger fab modules.[31] In addition, this constitutes up to 6% of total European semiconductor production capacities in this period. The estimate is based on "Scenario 2 – Current funding programme" in the previous chapter.

If the transformation is considered at EU level, the scope becomes even clearer. In order to achieve the self-imposed goal of climate neutrality by 2050, it is possible that up to 25% of the anticipated European production capacities will be needed for electrification (see Figure 4.8). This is the equivalent of 22 typical semiconductor factories or large fab modules. And this takes no account of further applications such as autonomous systems, infotainment electronics in vehicles, consumer electronics or data centres. In view of the anticipated growth from AI applications and cloud-based solutions, it becomes apparent that the demand for the upcoming industrial and social transformation will be considerably bigger again.

In addition, it must be noted that European production capacities not only cover demand within Europe, but also contribute to a significant degree to supplying non-European markets. This underlines the point that ensuring supply in the long term will remain a key challenge. In this context, a considered balance between regional security of supply and the global competitiveness of the European semiconductor industry is important.

4.5 Framing conditions for sustainable production

Microelectronics ranks amongst the most energy- and resource-intensive industries, and as a result sustainability and efficiency are becoming increasingly important in production. Europe, particularly Germany, offers unique conditions for assuming a leading role in sustainable semiconductor production – whether due to the high share of renewable energies, stringent environmental regulations, or targeted investments in resource-saving technologies.

Energy supply and volatility

Modern semiconductor factories can consume up to 500 GWh of electricity annually,[32] corresponding to the energy requirements of around 150,000 homes. Europe has one of the highest shares of renewables in the world: in 2023, 45%[33] of electricity in the EU and as much as 56%[34] of electricity in Germany came from renewable sources. This offers ideal conditions for the energy-intensive semiconductor industry to reduce CO_2 emissions significantly. On the other hand, the volatility of renewable energies represents a further challenge for the semiconductor industry. The fluctuating availability of solar and wind energy, together with the price fluctuations conditioned by this, can have considerable effects on production costs. As electricity makes up a significant part of the operating costs of modern semiconductor factories (in some cases over 5%[35]), even moderate price increases or fluctuations can impair the competitiveness of European semiconductor companies. In addition, grid instabilities can cause power outages, leading to production downtimes and thus to disruptions in the supply chain.

To counter this volatility, it is necessary to push for expansion of the European power grids and for expansion of energy storage capacities, in order to improve integration of renewables and ensure steady supply.

Challenges due to PFAS regulations

The planned regulations on per- and polyfluoroalkyl substances (PFAS), often referred to as "forever chemicals", represent a further challenge. PFAS are used in semiconductor production in key processes such as lithography or etching, and due to their chemical stability they have been practically impossible to substitute to date. A unilateral ban by the EU could restrict the availability of these materials, leading to considerable cost increases and putting the production capacities of European semiconductor manufacturers at risk.

The development of alternatives to PFAS is already a focus for research activities, but the initial solutions will probably only be marketable in 10 to 20 years. To de-escalate the goal conflict between the environmental requirements and the EU chips strategy, close agreements between industry, politics and research is required, along with flexible transitional arrangements. An imbalanced approach could undermine European competitiveness and increase dependency on non-European manufacturers.

The circular economy in semiconductor production

The introduction of circular economic principles offers the semiconductor industry the opportunity to reduce its dependency on critical raw materials such as gallium, germanium and tantalum. These raw materials are essential for chip production, but their extraction is often associated with high environmental impacts and geopolitical risks.

A key approach for greater sustainability in the semiconductor industry is designing products with an optimised environmental footprint. Through more compact designs, which enable smaller volumes and weights, emissions can be reduced almost proportionately along the entire value chain: reducing the volume or weight by 50%, for instance, results in a corresponding reduction in emissions. In addition, integrating functions plays a key role. Highly-integrated designs reduce the demand for materials, whilst simultaneously improving the energy efficiency of end-products. Materials with a lower CO_2 footprint, such as copper instead of gold or nickel, offer additional savings potentials. Beyond that, there is a growing emphasis on the use of non-hazardous materials, in order to minimise both the burden on the environment and health risks along the production chain.

A further important aspect is the packaging: using recycled plastic to package semiconductor products contributes to lowering the consumption of resources and the volume of waste. These initiatives demonstrate how, through innovative design decisions, not only the environmental footprint, but also the sustainability of semiconductor production overall can be improved.

Europe’s potential as a trailblazer

Europe has the potential, through the combination of high environmental standards, a strong infrastructure and technological innovations, to become a global trailblazer in sustainable semiconductor production. Expanding renewable energies, developing alternative chemicals and supporting the circular economy are key steps in overcoming the sector’s environmental and economic challenges. Close collaboration between politics, industry and research will be necessary to shape this path successfully and to consolidate Europe’s position as a sustainable technology location. Only if the challenges are addressed jointly along the entire value chain can a sustainable solution for the whole ecosystem come about. This also includes companies in the end-industries and their requirements regarding the technological solutions and supply chains in the microelectronics industry.

5 Microelectronics as a core component of technological sovereignty

As the backbone of the digital and electric transformation, the microelectronics industry represents a fundamental building block for economic competitiveness, resilience and sustainability. Given this importance, microelectronics is developing into a hotspot of geopolitical tensions, amidst the changed global dynamics.

In this regard, export restrictions and local content requirements are increasingly influencing global supply chains. One example of this is the U.S.'s National Defense Authorization Act (NDAA)[36], imposing restrictions on the export of advanced technologies to certain countries, notably China. The technologies affected include advanced AI chips, and certain equipment for their manufacture. China is also acting similarly: here, strict regulations were recently introduced governing the export of certain critical materials such as gallium or germanium, required in semiconductor manufacturing.[37] These developments limit technology transfer and strengthen dependence on local supply chains. Global markets are changing as a result, and regionally-operating supply chains are steadily growing in importance. While some regions are consolidating a strong position, others see themselves confronted by the challenges that geopolitical realignments bring with them.

Technological independence, often called technological sovereignty, is the key to securing prosperity and self-determination. It means being able to understand, manufacture and further develop key technologies, and to play a part in shaping them on an international footing. The overarching aim is to exploit the potential of these technologies to create high-value jobs, whilst simultaneously ensuring social values such as security, reliability, data protection and sustainability.

Precisely in this challenging global competition, technological sovereignty is important in order to avoid becoming dependent and to preserve economic and political freedom of action.[38]

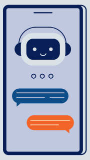
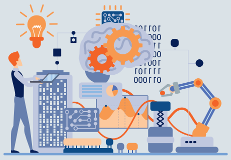
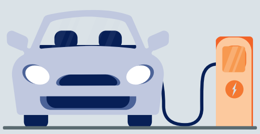
5.1 Technology trends as drivers of transformation

The world finds itself in the middle of far-reaching technological change. Digital technologies and green innovations are changing industry, social life and the global economy. The increasing digitalisation, the electrification of vehicles and machines, and the automation of production processes are just some of many drivers in this transformation. These developments, in turn, are marked by global trends in technology. Below, we look in greater detail at the most significant of these technology trends and at their importance for future economic development and social transformation (see also Figure 5.1).

Artificial intelligence	AI is changing the way data is analysed and decisions taken. From industrial manufacturing to autonomous vehicles to defence, AI is boosting efficiency and accuracy. As a result, new potentials are being created for the further development of these industries. Edge AI, in particular, which processes data locally on end-devices and thus enables fast, data protection-friendly and independent decisions, will play a fundamental role as a supplement to cloud-based high-performance computing. It is more energy-efficient, more secure, and through applications such as image and speech recognition along with data analysis, it makes it possible to react rapidly to changes and to optimise processes efficiently.
IoT and sensor systems	IoT and sensor systems contribute in a vital way to the comprehensive networking of machines, systems and devices. These technologies are of key importance notably in smart homes and smart cities, as they increase convenience in daily life and increase energy efficiency at the same time, leading to a reduction in energy consumption. In industry, they improve the monitoring and control of processes, and as a result Industry 4.0 applications and automated processes are being realised. Connected vehicles, communicating with each other and with their surroundings, are increasing road safety and bringing about new mobility solutions.

Data centres and decentralised computing	The integration of edge computing and cloud technologies into data centres, along with decentralised computing systems, are improving data processing and storage. Using these technologies, both industrial production and telecommunications are benefiting from more flexible and more efficient processes. Edge computing enables the analysis of large volumes of data directly at the point of creation, while cloud solutions help companies to scale their software-as-a-service (SaaS) applications.
Cybersecurity	With increasing connectivity, the subject of cybersecurity is constantly growing in importance, since protecting data and critical infrastructures lies at the heart of the digital transformation. Technologies such as firewall systems, encryption and authentication play a vital role in defending against cyber-attacks and ensuring security. In future, a particular focus will be placed on the further development and implementation of quantum encryption. The computing power of quantum computers represents a challenge which is not to be underestimated to current cryptography, and thus to the cybersecurity of all connected devices and infrastructures.
High-speed communication	The further development of high-speed communications technologies such as 5G and 6G and fibre-optic technology is opening up new possibilities for mobile devices, cloud-based services and machine-to-machine communication. The ever-increasing data rates and lower latency times enable real-time applications in industrial production and in connected mobility. These technologies form the backbone of the digital transformation, opening up new markets and business models.
Virtual and augmented reality (VR, AR)	AR and VR technologies offer new possibilities in areas such as education, entertainment and healthcare, for instance through reality-based training environments or interactive learning experiences. AR solutions are used in industry to make servicing and training easier by superimposing information visually, while VR is making immersive simulations for design and safety applications possible. They are based on high-performance logic semiconductors and sensors, enabling real-time data processing and high-resolution graphics.
Autonomous systems	Autonomous systems and robotics are similarly driving automation in many sectors. For instance, autonomous driving is revolutionising the automotive industry, while robots are increasing efficiency and productivity in production facilities and logistics centres. By automating complex tasks, these systems are contributing to lowering production costs and boosting quality. In addition, they enable greater precision and shorter production times.
Electrification for the energy transition	As already mentioned in the previous chapter, the electrification of vehicles, homes and industrial plants plays a decisive role in reducing CO_2 emissions. New semiconductor materials such as silicon carbide (SiC), gallium nitride (GaN) and graphene offer considerable advantages here in terms of power, efficiency and thermal conductivity, and are critical for the development of high-voltage electronic components.

Fig. 5.1: Relevant technology trends and illustrative applications for microelectronics

Technology trends		Applications (Examples)
	**AI**	• Image and speech recognition • Data analysis and simulations • Automation
	**IoT and sensor systems**	• Smart home: connected household devices • Smart cities and connected vehicles • Industry 4.0: automated production using connected machines and plants
	**Data centres and decentralised computing**	• Processing and analysis of large volumes of data (customer data, simulations, etc.) • Blockchain and cryptocurrencies • Software-as-a-Service
	**Cybersecurity**	• Firewall systems and network protection • Encryption and decryption • Authentication and authorisation
	**High-speed communication**	• 5G and 6G networks for mobile devices • Cloud-based services • Machine-to-machine communication
	**Virtual and augmented reality (VR, AR)**	• Gaming and entertainment • Education and training • E-commerce and retail
	**Autonomous systems**	• Autonomous driving • Robots and drones
	**Electrification for the energy transition**	• Electrical systems in transport, the home and renewable energies • Energy-efficient power semiconductors (SiC/GaN) and faster data processing using multi-purpose graphene wafers

Source: Strategy& analysis

5.2 The relevance of individual steps in value chains for trends in technology

The relevance of individual steps across the value chain and microelectronics technologies varies depending on national resilience and competitiveness. Thus in the first instance the fundamental question needs to be answered as to which areas of the value chain and which technologies need to be claimed in order to achieve the targeted degree of technological sovereignty. Accordingly, below we highlight the relevance of microelectronics technologies along the value chain for future technology trends.

5.2.1 Equipment and tools: small wavelengths for small components

The manufacture of microelectronics components requires a large number of highly-specialised process steps and manufacturing facilities. One of the most complex processes is photolithography – where light is used to generate fine pattern structures on a semiconductor wafer. These structures ultimately determine the functionality and properties of a semiconductor. In addition, photolithography plays a vital role in miniaturisation and in the precise manufacture of modern microelectronics. As described previously in Chapter 3, the structure width indicates how small the individual circuit elements on a chip are. With a small structure width, it is possible to accommodate several components on a chip of equal area, allowing the performance and energy efficiency of the chip to be increased many times over.

With photolithography, two main technologies are employed: Deep Ultraviolet (DUV) and Extreme Ultraviolet (EUV) – the difference between these technologies lies mainly in the wavelength of the light used. Hence DUV lithography uses light with wavelengths of 248 nm and 193 nm, enabling the manufacture of semiconductors with structure widths between 12 nm and over 180 nm (see Figure 5.2). DUV lithography has established itself as the more conventional technology, and it is used for many of the applications produced in Europe today at above 10 nm – for example, in power semiconductors, microcontrollers, battery management systems and sensors.

However, the degree of complexity and the performance of semiconductor components is not determined solely by the process node. Even components with nodes above 10 nm are being continuously further developed and are gaining in efficiency and performance. Particularly for power semiconductors, larger structures are necessary in order to be able to switch high currents and voltages and to dissipate heat effectively.

Production of the smallest semiconductors, with nodes from 12 nm to 3 nm, requires the use of EUV technology, since only extremely short-wave light enables the manufacture of such fine structures. This would not be possible with conventional light sources. EUV technology makes it possible to overcome considerable technical challenges, and it is essential for the production of semiconductors for AI and high-performance computing. Currently, high-NA EUV technology is being developed. This uses even shorter wavelengths and is reportedly able to achieve three times as many structures on the same area as the current generation of EUV lithography machines.

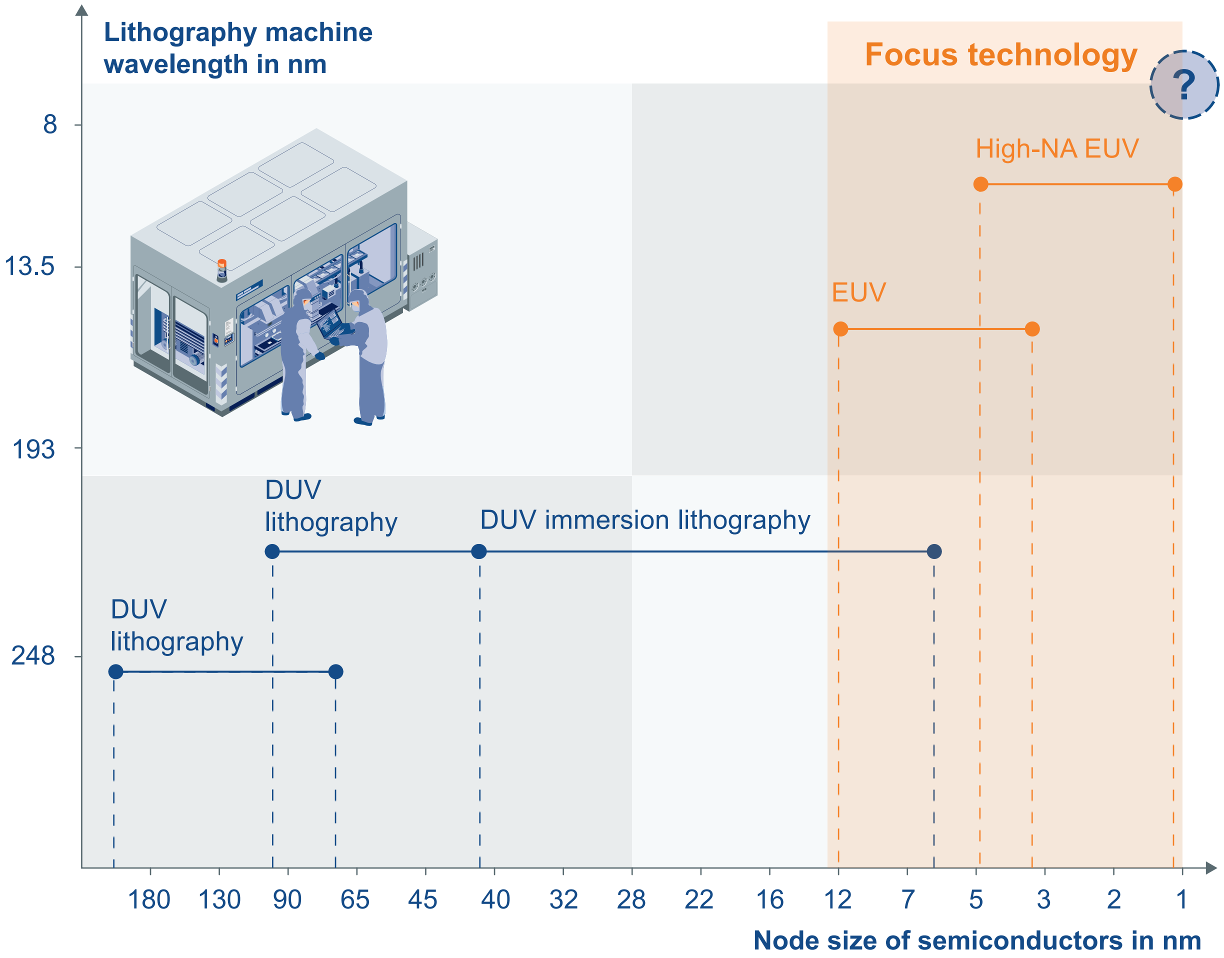
5.2.2 Materials: innovations from new semiconductor materials

At the level of materials, wide-bandgap (WBG) semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) are driving technological development: compared to conventional silicon, these materials offer higher energy efficiency, greater power density and the ability to work reliably even at high temperatures. Given these properties, SiC and GaN are ideal for high-voltage applications in areas such as industrial automation, telecommunications, aerospace, and energy technology.

SiC and GaN offer specific advantages which make them particularly suitable for different applications. SiC's strengths are particularly evident in high voltage (HV) applications, such as in power grids for inverters and DC-DC converters, in industrial automation and electromobility (see Figure 5.3). High dielectric strength and excellent thermal dissipation make SiC the material of choice for power electronics with high requirements regarding reliability and efficiency.

With the shift to larger 200 mm wafers for SiC, instead of the 150 mm wafers used previously, a further reduction in production costs is anticipated. It means that a higher number of chips can be manufactured per wafer, and thus the number of production steps and the quantity of materials can be reduced.

Fig. 5.2: Key technologies in the area of semiconductor equipment for tech sovereignty

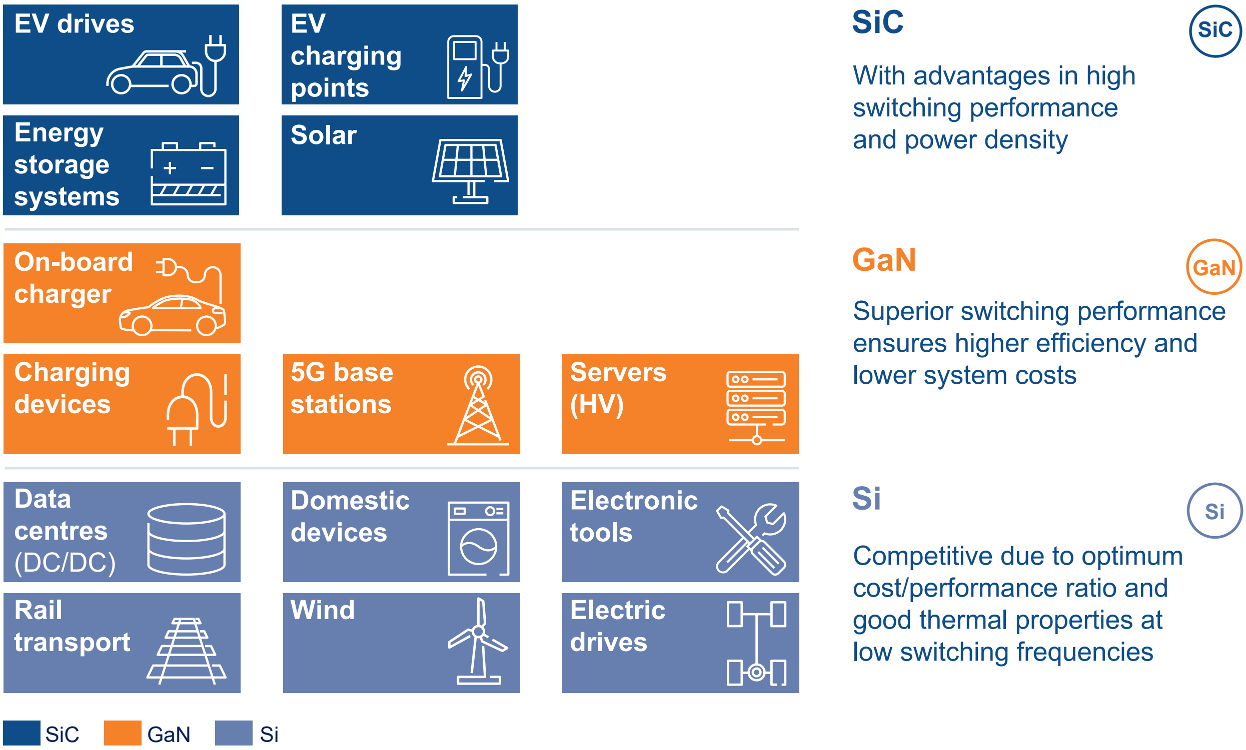


Source: Strategy& analysis

By contrast, GaN is particularly suitable for applications requiring high switching speeds and low power losses. It is used in high-frequency technologies such as 5G (and in future 6G), and it is also particularly attractive for power electronics in low and medium voltage ranges, such as in charging devices, power supply units or on-board chargers in the automotive sector (see Figure 5.3). Given the compatibility with 300 mm wafers, GaN can also be readily integrated into existing silicon infrastructures, which can bring scale effects and cost advantages in the long term. In future, GaN offers potential for use in high-voltage applications in the automotive sector (e.g. main converters), which will expand the range of uses of GaN.

Advances in the area of WBG semiconductors show that these innovative materials not only boost efficiency and performance in established sectors, but also create the foundation for the next generation of more energy-efficient applications in various industries. With the expansion in production capacities and the falling costs due to larger wafer sizes, SiC and GaN are developing into key components in modern high-performance technologies and are encouraging future innovation, sustainability and competitiveness.

Fig. 5.3: Areas of use for power semiconductors, by material



Source: Infineon Q4 2024

5.2.3 Semiconductor design and manufacture: at the heart of technology trends

All these global technology trends present opportunities and threats for competitiveness and strength of innovation for European key industries. If the semiconductor technologies needed for this are not developed and widely implemented at home, then Europe runs the risk of lagging behind in the global competition (see Figure 5.4).

In computing-intensive areas such as AI and cloud computing, both fast data processing using logic chips (high-performance AI chips, GPUs and CPUs) and data storage play a key role.

With IoT, autonomous systems, and for VR and AR, it is microcontrollers that play a vital role, since here real-time control with high reliability is essential. A further consideration is that technologies such as optoelectronics, sensor systems and communications are also essential for efficient connectivity and latency-free communication between systems and their surroundings.

With regard to the increasing transition to cloud, edge and decentralised computing, the demand for fast transfer of large volumes of data is continually growing. The expansion and further development of mobile phone networks, particularly 5G and 6G, is also becoming increasingly important.

Moreover, power semiconductors, power management semiconductors and discrete components are essential in realising many of these technologies, and thus vital to implementing the technology trends outlined. Power semiconductors, in particular, are critically important, since they offer massive potential to lower energy consumption further, especially in the area of high-voltage applications (such as in electric mobility, industrial motors, or in electricity supply). As such, they contribute decisively to the transformation towards a more sustainable and more resource-economical society.

Strong positioning within these technologies is a key catalyst for the necessary transformation of industries and of future economic growth.

Fig. 5.4: Relevance of semiconductor technologies for implementing technology trends

Technology trends	Technologies required	Memory	Microprocessors	Logic	Power management	Other analog	Communication	Optoelectronics	Non-opt. sensors	Other discrete	Power semiconductors
AI	• AI "accelerators", end-to-end AI chips	Very high	High	Very high	Moderate	Low	Very high	Moderate	Moderate	Moderate	Low
IoT and sensor systems	• Similar to technologies for AI • High-speed communications	Very high	Very high	High	High	High	Very high	Very high	Very high	High	Low
Edge, cloud, decentralised, computing	• High-performance computing and AI chips • High-speed communications	Very high	High	Very high	High	Moderate	Very high	Moderate	Moderate	Moderate	High
Cybersecurity	• Encryption, including post-quantum solutions • Digital identity	Very high	High	High	Low	Moderate	Moderate	Moderate	Low	Low	Low
Communi-cations	• Advanced telephony and optical communications technologies • High-performance computing	Low	Moderate	Moderate	Low	High	Very high	Low	Not applicable	Low	Moderate
AR and VR	• High-performance computing, next-gen displays • Advanced sensor systems, embedded and decentralised AI	High	Very high	High	Low	Moderate	High	Very high	Not applicable	Low	Low
Autonomous systems	• End-to-end AI, high-speed communications • Advanced sensor systems and actuators	Very high	High	Very high	High	High	Very high	Very high	High	High	Low
Energy production and storage	• Power electronics including high-voltage, energy production and storage • Embedded computing, communications technology	Low	Moderate	Low	Very high	High	Moderate	Low	Low	Very high	Very high

Relevance: Very high | High | Moderate | Low | Not applicable

Source: Strategy& analysis

5.2.4 Packaging: processes and methods for semiconductors

The situation is similarly diverse when it comes to semiconductor packaging (see Figure 5.5). The wire bonding process which has dominated to date is increasingly being supplemented by various advanced packaging methods, offering advantages with regard to miniaturisation, high degree of integration, energy efficiency and reliability. To ensure optimisation of the system as a whole, close collaboration with PCB engineering is necessary.

One advanced packaging method is flip-chip packaging, where the chip is flipped and soldered directly onto the carrier substrate, for example a circuit board. This method enables optimised electrical performance, and more efficient thermal dissipation. As such, this packaging process is particularly relevant for applications where fast current flow and high efficiency are needed – for instance, in electrification.

In addition, there are processes where the semiconductors are packaged while they are still on the wafer (wafer-level packaging, WLP). This enables more compact design, and thus significant miniaturisation. WLP is used particularly in small, high-performance devices such as smartphones or AR and VR glasses.

A further example of advanced packaging processes is 3D packaging. With this method, several semiconductor chips are stacked vertically and interconnected using direct connections. Performance is boosted, space saved, and the signal paths shortened, leading in turn to increased speed and energy efficiency. This is particularly advantageous for AI, IoT applications and distributed infrastructure applications, where fast and energy-efficient computing in limited space is required.

A further innovative packaging solution is the system-in-package (SiP), which is used in particular for heterogeneous integration. Thus this technology makes it possible to combine various semiconductors with different functions, such as memory chips or processors, in a single housing and thus create multifunctional packages. This offers particular advantages for technology trends where multiple functions are combined – such as AI, IoT, AR and VR, or advanced robotics and autonomous systems. This heterogeneous manner of integration can also be realised to a certain degree using 3D packaging.

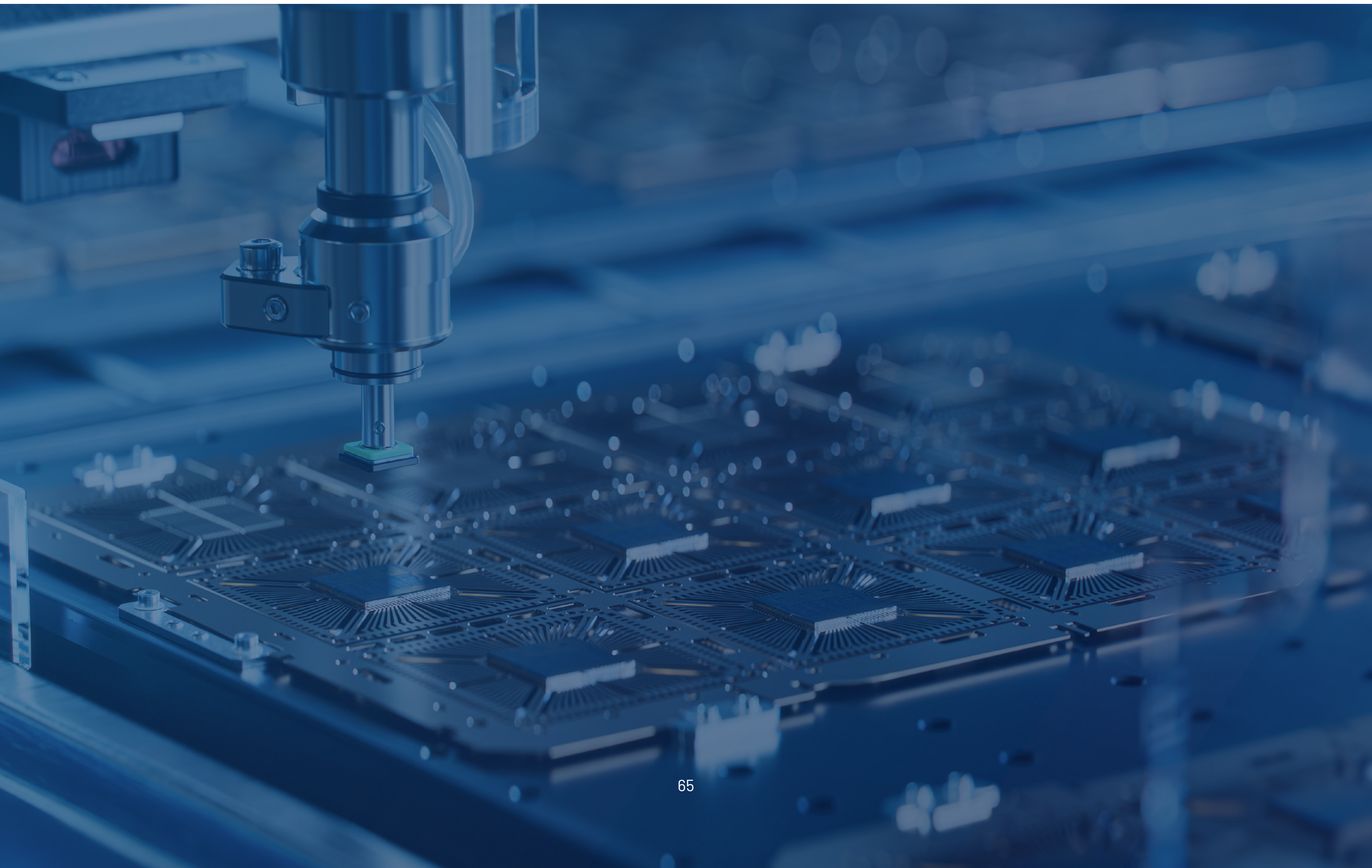


Fig. 5.5: Relevance of semiconductor packaging technologies for implementing technology trends

Technology trends	Technologies required	Wire-bonding	Flip-chip	Wafer-level packaging	3D packaging	System-in-package
AI	• High-performance computing and AI chips • AI "accelerators", end-to-end AI chips	Low	Moderate	Very high	Very high	High
IoT and sensor systems	• Similar to technologies for AI • High-speed communications	High	High	High	High	High
Edge, cloud, decentralised, computing	• High-performance computing and AI chips • High-speed communications	High	Low	Very high	Very high	Moderate
Cybersecurity	• Encryption, including post-quantum solutions • Digital identity	Very high	High	Moderate	Moderate	Low
Communi-cations	• Advanced telephony and optical communications technologies • High-performance computing	Very high	Moderate	Very high	Moderate	Moderate
AR and VR	• High-performance computing, next-gen displays • Advanced sensor systems, embedded and decentralised AI	High	High	Very high	Moderate	High
Autonomous systems	• End-to-end AI, high-speed communications • Advanced sensor systems and actuators	High	High	High	Very high	Very high
Energy production and storage	• Power electronics including high-voltage, energy production and storage • Embedded computing, communications technology	High	Very high	Low	Low	High

Relevance Very high · High · Moderate · Low · Not applicable

Source: Strategy& analysis

5.2.5 PCB and EMS: the backbone of microelectronics value added

The manufacture of PCBs and their assembly with semiconductors involves a complex network comprising various specialised part industries. To be able to assess the relevance of these process steps for technological sovereignty, we first offer an overview of the individual value added steps in these industries.

Procurement and design

Before the PCBs can be produced, the first value step starts with the procurement of raw materials such as copper, epoxy resin or glass fibres. The high quality of these materials serves to guarantee the electrical and mechanical properties of the circuit boards. Next comes the design of the PCBs, using specialised software to plan the electric circuits and mechanical configurations. This phase is significant for functionality and reliability.

Production

The next step is to produce the PCBs. This occurs in specialist factories, where the layouts are translated into physical boards. This process comprises applying layers of copper, etching the traces and creating the vias. Following manufacture, electronic components such as resistors and integrated circuits (ICs) are mounted on the boards and soldered in place. Automated machines ensure precision and efficiency here. After this, the fitted PCBs need to be tested, to ensure that they conform to the specifications and quality standards. The seamless collaboration of the various part industries is critical for smooth PCB production.

Relevant technologies and manufacturing methods

When it comes to manufacturing PCBs, innovative technologies are again used, and their relevance is set to grow further in future. Traditional subtractive methods to produce conventional boards are coming up against their limits, particularly in miniaturisation. This is also true of high-density interconnect (HDI) boards, which have a higher density of connections per area and are frequently used in smartphones.

To satisfy the increasing requirements of the electronics sector, more advanced processes are needed. Processes such as the semi-additive process (SAP) make it possible to achieve even finer traces and smaller gaps, using widths of up to 5 μm (see Figure 5.6). This process is relevant in particular for the production of complex electronic devices such as smartphones or wearables, which require high integration density and performance requirements. One more advanced method is embedded traces (ET) technology, where the traces are embedded directly into the PCB material. This not only allows for a higher packaging density, but also improves electrical performance and thermal dissipation. Using ET technologies, it is possible to realise very thin traces of up to 1 μm in width, meaning that using these technologies is particularly well-suited to demanding applications in miniaturisation.

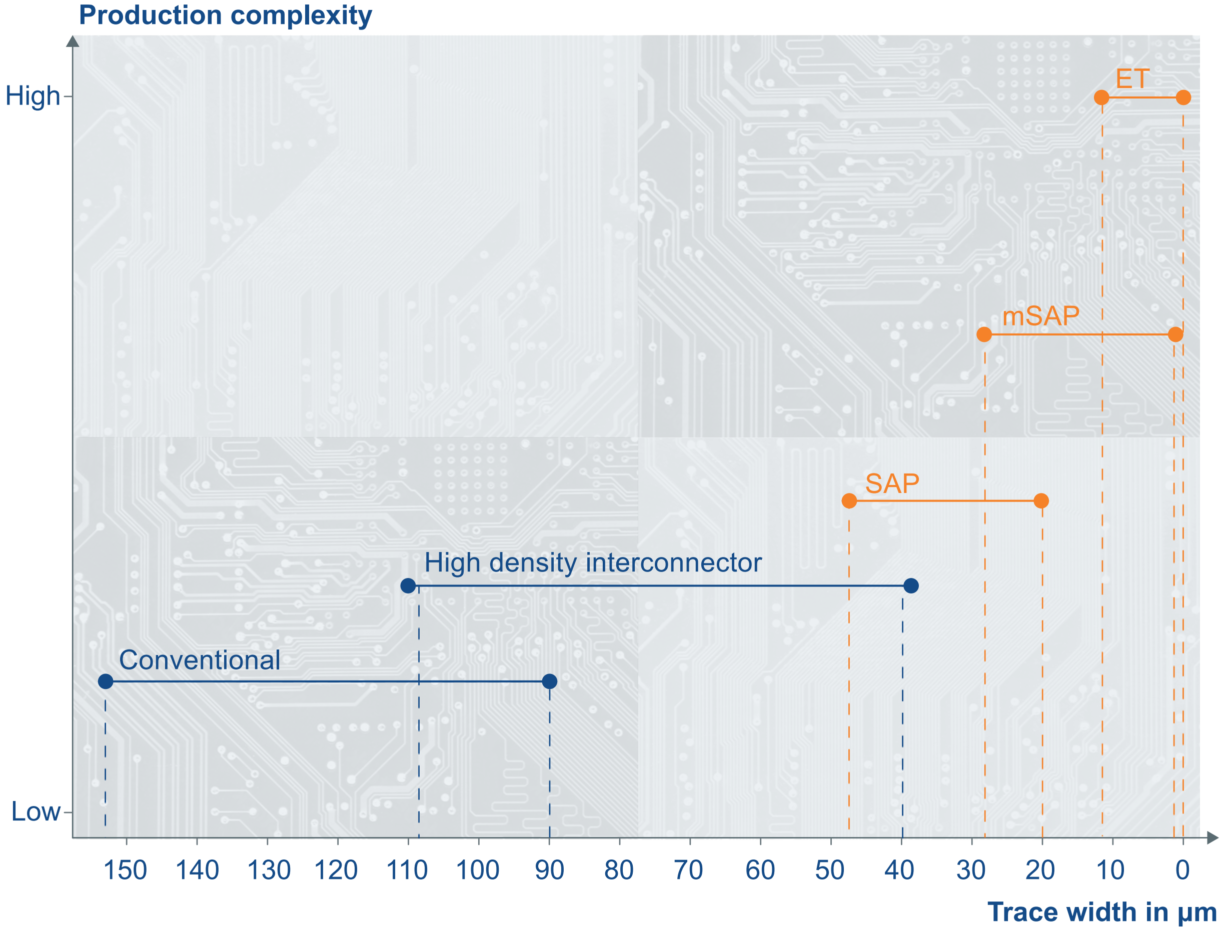
The assembly of the circuit boards

The subsequent assembly of the circuit boards with finished semiconductors is often handled by contract manufacturers. Known as electronic manufacturing services (EMS), these companies play a major role in the electronics value chain, handling tasks from development through to after-sales services. This phase begins with development, where EMS providers create customised solutions for clients – including circuit design, component selection and prototype development. Next comes industrialisation, where prototypes are optimised for mass production.

One key area of EMS is procurement, where EMS companies source the components needed from various suppliers and thereby coordinate global supply chains. The subsequent assembly is undertaken to a large extent using automation, and calls for advanced machines which mount and solder the electronic components with precision.

The next step involves to-order manufacturing, which encompasses the full assembly of end-products, often consisting of several fitted PCBs and additional mechanical components. EMS providers are therefore reliant on the most modern machines, in order to ensure maximum efficiency.

Fig. 5.6: Technologies for PCB manufacture



Source: Strategy& analysis

After-sales services

After manufacturing, EMS providers also offer after-sales services such as servicing or repair, to optimise product lifetimes. These services are crucial for high customer satisfaction and in maintaining long-term business relations. Overall, these various tasks demonstrate that EMS providers are a supporting pillar in the electronics industry, promoting efficiency, quality and innovation across the entire value chain.

5.3 The importance of technological sovereignty

Having technological sovereignty means avoiding being wholly dependent politically or economically on external actors and thus losing one's own scope for action. To be able to assess the relevance of the individual steps in the value chain for technological sovereignty, in what follows we draw on a methodology from John Lee & Jan-Peter Kleinhans.[39] In this methodology, the evaluation of sovereignty is undertaken using three strategic dimensions: competitiveness, resilience and national security (see Figure 5.7). Alongside this, it should be emphasised that collaboration with reliable partners and the use of free world trade remain essential. Diversified dependencies on several countries with stable structures reduce supply chain risks and can contribute positively to resilience and economic security, so long as they are incorporated within a stable global division of labour. At the same time, it remains important to maintain capacities for security-critical applications, such as in the arms industry, within the EU, in order to safeguard strategic interests.

Competitiveness describes how the market conditions in a production step influence the economic and technological strength of a country in a competition-oriented, international context. The criteria comprise:

Commercial opportunity	The financial returns generated through a dominant market position. The financial returns vary depending on the production step, with some being clearly more lucrative than others.
Barriers to market entry	The difficulty for new actors to establish themselves in a production step. High barriers to entry are particularly relevant if the market is dominated by a few actors, as these barriers make it more difficult to copy these capabilities.
Spillover effects	This effect describes the potential of capabilities in one production step leading to activities being implemented in other areas of the value chain or in other sectors.

Resilience relates to the entire semiconductor value chain. Since this is integrated worldwide, disruptions have negative impacts on national interests, irrespective of existing rivalries:

(Geo-) concentration	These weaknesses threaten business continuity in the global value chain – for instance, due to natural disasters, pandemics or political interventions.
Collateral damage	The risk that an interruption in a particular production step has impacts on other segments in the global value chain or other areas of industry. One example of this is the chip shortage, considered in Chapter 2.
Reconstruction	The expense of replicating a particular production step through state intervention in countries where that step is not concentrated.

National security concerns the importance of a production step as part of a zero-sum competition between nation-states. In this regard, there is also the potential for national governments to use production steps to harm the interests of other nations. The criteria comprise:

Risk of espionage	The possibility that manipulation of a production step is exploited in a deliberate way to gather information about rival nations or to sabotage their interests.
Military use	The importance for a nation's military capabilities (including the ability of a national economy or of an alliance) to develop complex military platforms, for instance fighter planes.
Control point	The risk that a dominant market position in a production step is used to put nations without particular capabilities under pressure strategically. An example of this is national and multilateral export controls, deliberately targeting particular nations.

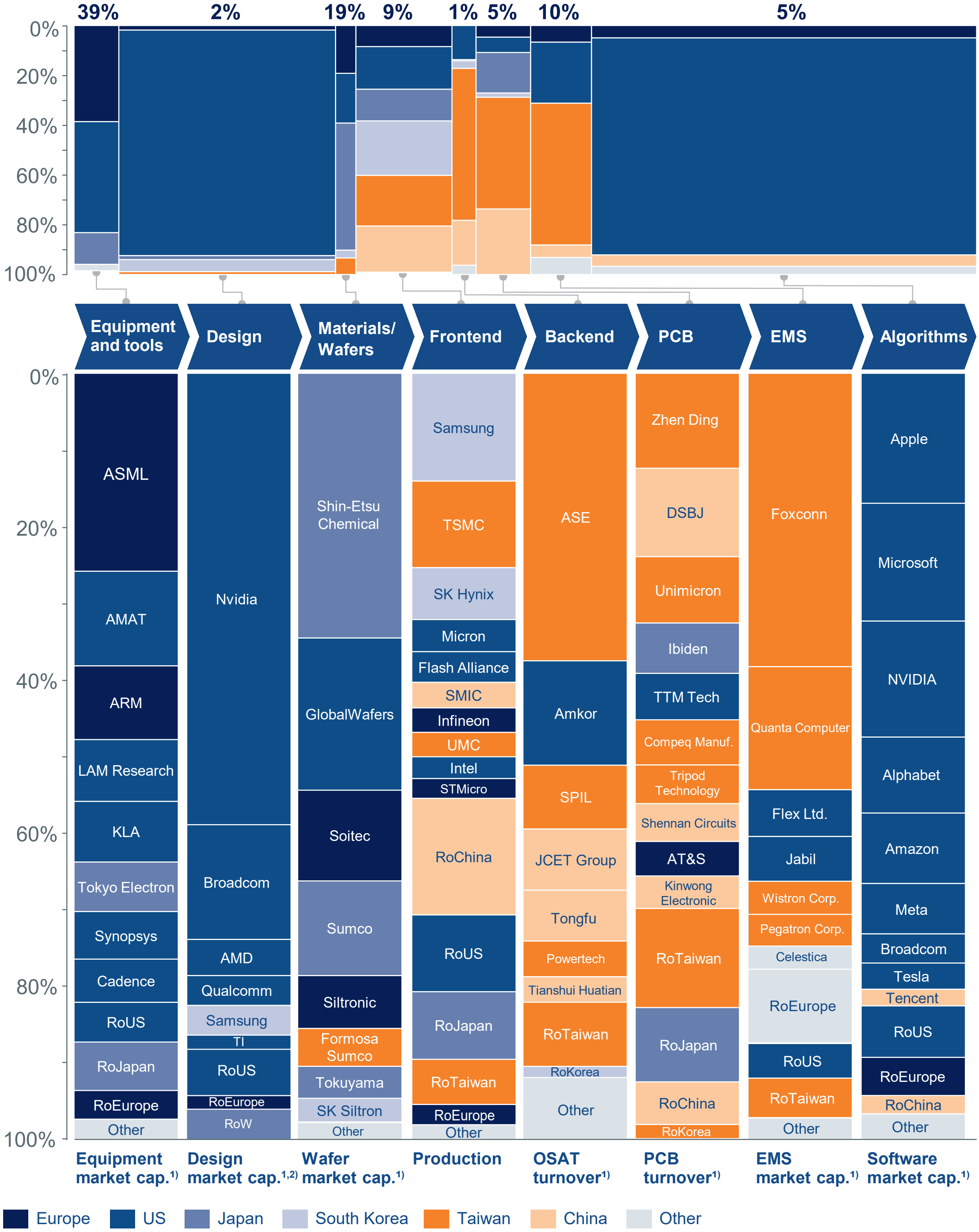
Fig. 5.7: Evaluation criteria for technological sovereignty

Evaluation criteria for technological sovereignty

Competitiveness Global competitiveness and effect on (national) economy	**Resilience** Resilience of production in view of various disruptions	**National security** Protection against data espionage and manipulation, and establishing "equal footing"
Business opportunity – Economic effect in the existing/future microelectronics industry	**(Geo-)concentration –** Concentration of microelectronics skills and production in one company or specific region	**Data protection –** Data protection, integrity, protection against manipulation and interruption of communication and data
Entry barriers – Barriers to entry in this area of microelectronics	**Collateral damage –** Economic effects in other industries in the event of an interruption to production	**Military use –** "Equality of arms" in using technology for planning, control and implementation of defence measures
Applications industries – Current/future economic effect beyond microelectronics	**Reconstruction –** Potential to replicate a given production step	**Control point –** Control of individual elements in microelectronics which are only available in one country/region

Source: Strategy& presentation, based on Lee, John and Kleinhans, Jan-Peter (2021)[2]

Fig. 5.8: Top: Shares for value chain steps and regions in overall microelectronics value added, based on the registered offices of companies; Below: Shares of major companies in the value added step, using their market capitalisation, turnover and production capacities



1) Only shares for the biggest companies;
2) Only one-half of the market capitalisation of IDMs is taken into account, in order to allow for other shares in value added;
Source: Strategy& analysis based on SEMI World Fab Forecast 3Q23 and SIA Report 2021

5.4 An analysis of European technological sovereignty

Before the individual value chain steps for Europe's technological sovereignty can be assessed, it is necessary to understand their contribution to value added in microelectronics and their regional distribution (see Figure 5.8).

In the upper part of the figure, the contribution of the individual value chain steps to the overall microelectronics industry is shown along the horizontal axis – starting with equipment and tools, and moving through to algorithms and software. From this, it is apparent that the area of algorithms and software makes up over 40% of value added. Within microelectronics, the biggest share falls to chip design, with around 24%, followed by manufacturing, which accounts for around half as much. However, this analysis represents an average value across all semiconductor technologies and end-products. High-volume segments such as consumer electronics or high-price areas such as AI chips are more prominent if considered from those perspectives. Nevertheless, the presentation provides a basic picture of the relative importance of the individual value chain steps, in a global comparison.

The vertical axis in the upper figure shows the regional distribution within a value chain step. Europe is particularly strong in the areas of equipment and tools (39%) and materials (19%). In manufacturing, European companies such as Infineon or STMicroelectronics sit at around 8 to 9% of global production capacities. Here again, depending on the specific technology, a differentiated picture can be seen; this is considered in greater detail later in the study. The bottom part of Figure 5.8 shows a more detailed distribution of the shares to actual companies. This specific assessment is again referred to later in the study.

This analysis forms a basis for assessing the relevance of the individual value chain steps for Europe's technological sovereignty, particularly with regard to competitiveness. Below, this assessment is supplemented by additional technological sovereignty criteria (see Figure 5.7), in order to derive a comprehensive assessment of the European situation. The summarised results of this analysis are shown in Figure 5.9. The following sections offer a focused discussion of the results, looking across the individual value chain steps. After this, the areas of PCBs and EMS are also examined in detail, including an analysis of their specific value chains.

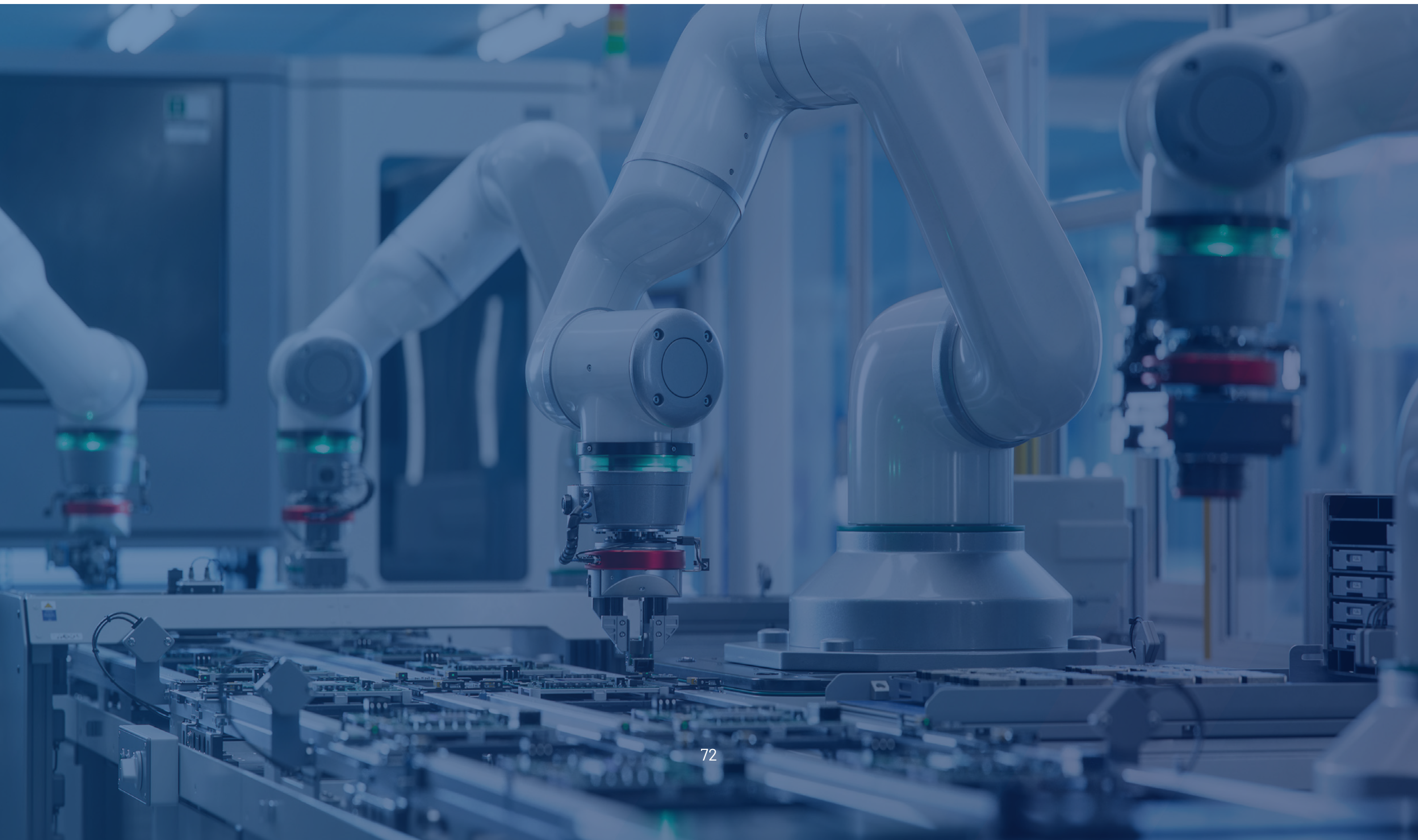
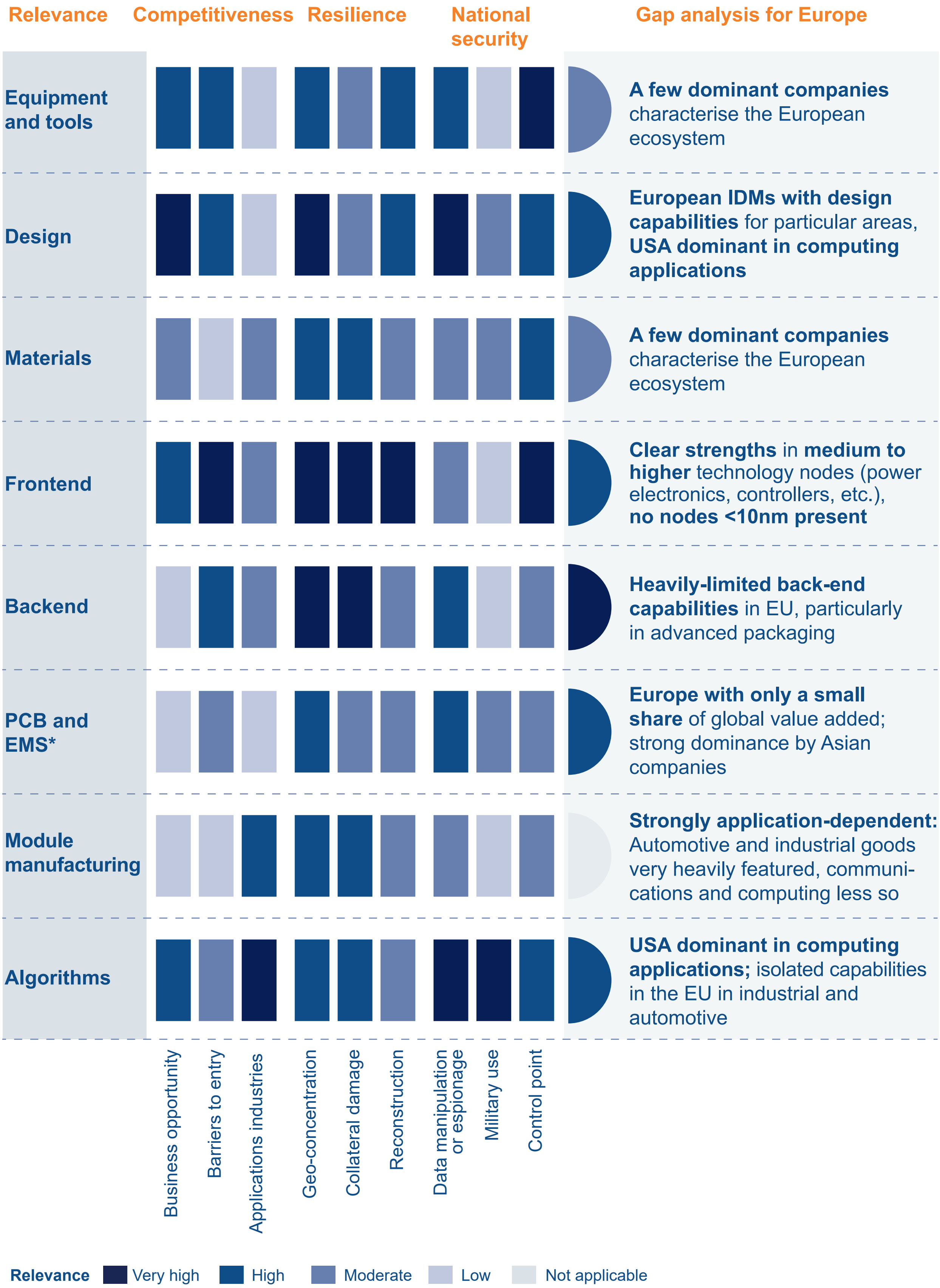


Fig. 5.9: Assessment of technological sovereignty along the microelectronics value chain



*PCB and EMS with own value chain (see Figure 5.12);
Source: Strategy& analysis

5.4.1 Equipment and tools: strategic control point in the EU

The manufacturing of equipment for semiconductor production is critical for competitiveness, as demand for smaller, faster and more efficient semiconductors is growing steadily. The barriers to market entry are high here: it requires extensive technological know-how and a specialised network of suppliers in order to develop the most advanced equipment – particularly for EUV technology. Moreover, lithography technology represents a critical control point: without the latest lithography machines, producing the smallest structure widths for high-performance computing and AI chips is not possible.

In this area, the EU is assuming a strong position, since in the company ASML it offers a global market leader which holds a key role, due to its almost monopolistic access to EUV lithography machines (see Figures 5.8 and 5.9). However, this position could come under pressure in future, since Chinese companies are being forced to develop their own solutions to produce high-complexity chips, due to export bans. If they are successful in the years ahead, then Europe's strong position could be weakened. It is therefore essential to invest continuously in researching and developing the next generations of the technology.

ARM architecture, too, plays an important role for the European semiconductor industry. Through the sale of licences for its ARM chip architecture, the company is making a key contribution to the global chip design supply chain. However, ARM's position could be challenged in future by developments such as the open RISC-V architecture (see the section on chip design below) and Chinese alternatives.

5.4.2 Materials: EU has strengths in wafers and process chemicals

The area of production materials and the area of process chemicals and gases are dominated by a few manufacturers. Particularly for wafers, there are only a handful of relevant companies worldwide who dominate the market. Any interruption in this part of the value chain can have considerable effects on semiconductor production, particularly for leading technologies. However, reconstruction is possible in this area at manageable expense. From the viewpoint of national security, process materials are less susceptible to manipulation or espionage, and even their direct military use is limited. Nevertheless, process materials can serve as a strategic lever to exercise pressure in geopolitical conflicts in the short to medium term.

In silicon wafers, it is primarily Japanese companies such as Shin-Etsu and Sumco who dominate the market. However, the EU also plays a significant role, with established companies such as Soitec and Siltronic (see Figure 5.8). In addition, some of the leading suppliers of process chemicals and gases are part of European companies, such as Merck or Air Liquide. Since it is difficult to determine the precise share of turnover of these companies in the microelectronics sector, this study has dispensed with any more detailed breakdown.

5.4.3 Semiconductor design and manufacture: EU has strengths and gaps

Chip design is a key competence for current and future competitiveness. It determines not only a key part of value added, but also forms the basis for the functionality and performance of electronic end-devices. The development of new chip technologies lowers system costs and enables innovations in end-industries. Only through efficient and high-performing semiconductors can new products be manufactured and sold at competitive cost. At the same time, chip design carries considerable risks, viewed from the perspective of national security, because it offers up potential for manipulation and espionage and represents an important geopolitical control point.

With regard to resilience, chip design is currently strongly concentrated in the U.S., particularly for smaller technology nodes and AI-based components. The barriers to entry vary depending on the technology: for advanced nodes, the development costs are often in the high three-figure millions range, with development time-frames of over three years.

Overall, chip design – which makes up the biggest share of value added in microelectronics – presents a mixed picture. American companies such as NVIDIA, Broadcom and AMD dominate the global market, particularly in areas such as AI, data centres and high-performance computing (see Figure 5.8).

On the other hand, the EU shows clear strengths in areas of technology such as energy management, sensor systems and microprocessor technologies (MCUs). European IDMs such as Infineon, NXP and STMicro-electronics have established themselves as market leaders in these areas (further details in the next section and Figure 5.10).

Even if this area is smaller, in terms of revenue, than that of the high-price AI chips from companies such as NVIDIA, these technologies play a key role for applications such as Edge AI, efficient energy management in mobility and industry, and in autonomous systems, including industrial automation. Europe's strong position in designing these components boost the region's technological competitiveness and simultaneously supports independence and strength of innovation along the entire value chain.

In the context of AI and high-performance computing, the open-source chip design model RISC-V is becoming increasingly important for Europe. RISC-V, an open and licence-free instruction set architecture, enables actors to develop and market their own processors. The use of this architecture not only promotes market diversification, but also strengthens Europe's strategic sovereignty by reducing dependence on external technology suppliers. Several European companies, including Bosch, Infineon and NXP, have founded Quintauris, which specialises in the development of RISC-V hardware architectures. The aim is to create and license open-source RISC-V reference architectures, which offer a basis for customised hardware solutions.

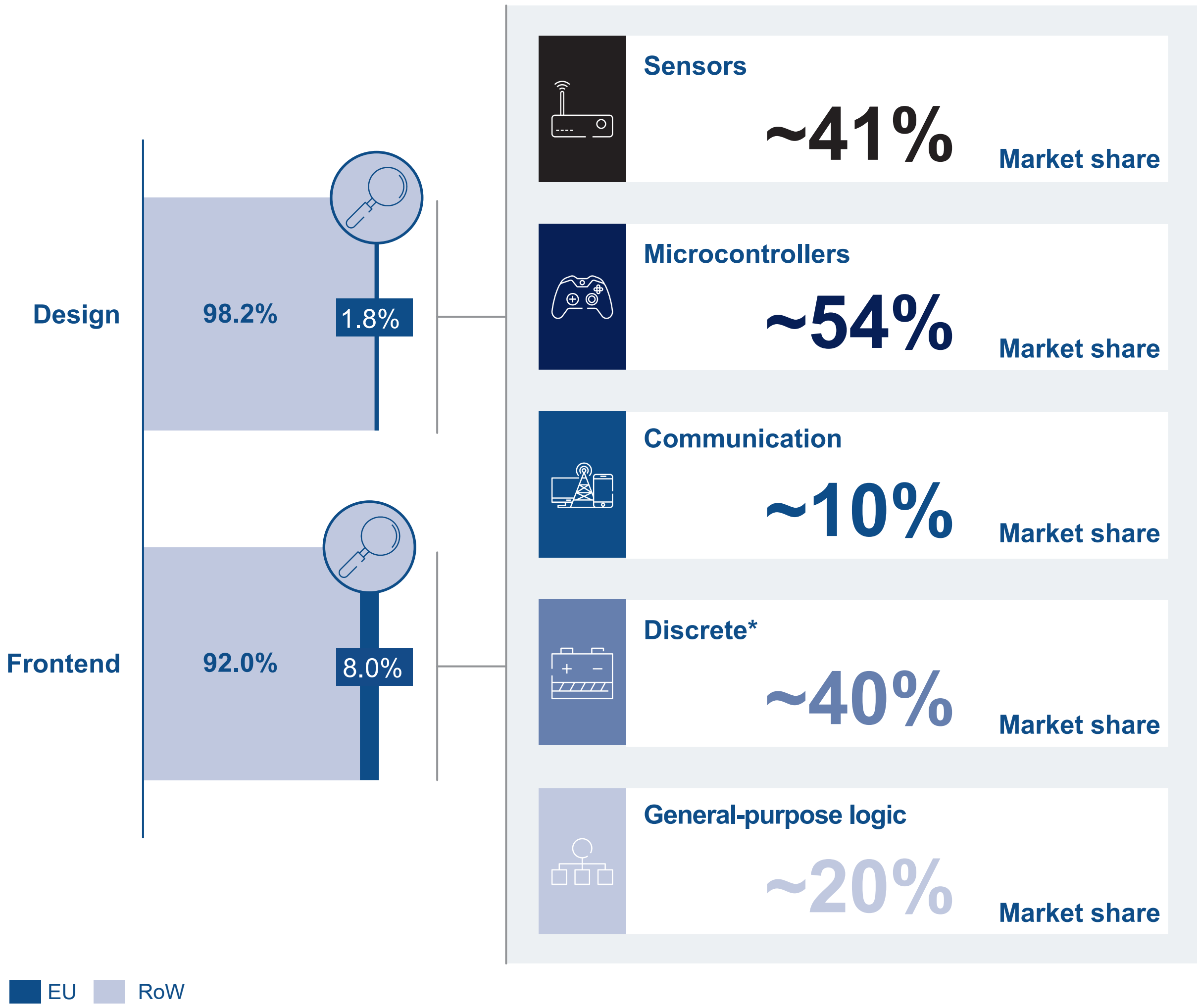
By building up an open-source ecosystem in chip design based on RISC-V, Europe could create an independent infrastructure for the semiconductor industry. This would benefit the whole European supply chain, and reduce market fragmentation and technological dependencies on non-EU countries. The potential to develop and share hardware architectures openly also lowers the barriers to entry for new market players, and in the long term opens up new opportunities for innovation and competitiveness.

In view of the growing importance of Edge AI and high-performance computing, it is vital for Europe to take on a role of its own in this area. Strategies such as supporting RISC-V architecture and developing European intellectual property in chip design are key elements in securing technological sovereignty and international competitiveness.

The production of semiconductors is the most technically challenging area of microelectronics, and forms a significant part of the value chain. This applies both for the smallest semiconductor structures, but also for medium nodes or "legacy nodes" with structures bigger than 20 nm. They are highly important both for competitiveness and also for resilience and national security. The barriers to market entry are high, since the investment costs for a semiconductor factory lie in the billions, and extensive know-how is required to master the highly specialised processes. This also applies in the case of any necessary reconstruction. Since semiconductors are a key component in practically all modern industries, larger disruptions in semi-conductor production would bring massive consequences. This became apparent during the chip shortage, the consequences of which caused considerable economic harm (cf. Chapter 2). Beyond this, it is noted that production capacities are distributed over only a few countries, in geographically concentrated regions and companies. Particularly for the most advanced nodes, there are only three companies worldwide with the ability to manufacture the latest node sizes, and accordingly a lot of know-how is bundled in these enterprises. Given this complexity and the massive importance for end-industries, semiconductor production is a key geopolitical control point.

Measured by the global share in production capacities of companies with head offices in Europe, the EU (with a little over 8 to 9%) is lagging behind the leading semiconductor nations of Taiwan, South Korea, U.S., China and Japan (see Figure 5.8). However, Europe does have major semiconductor manufacturers such as Infineon, STMicroelectronics and NXP, who are leading in the market and technologically in certain product categories. Along with the design value chain step, Europe has a strong market position in power electronics, controllers for digital and electrical signals, and sensor systems.

Fig. 5.10: Market shares of European companies in their semiconductor core industries

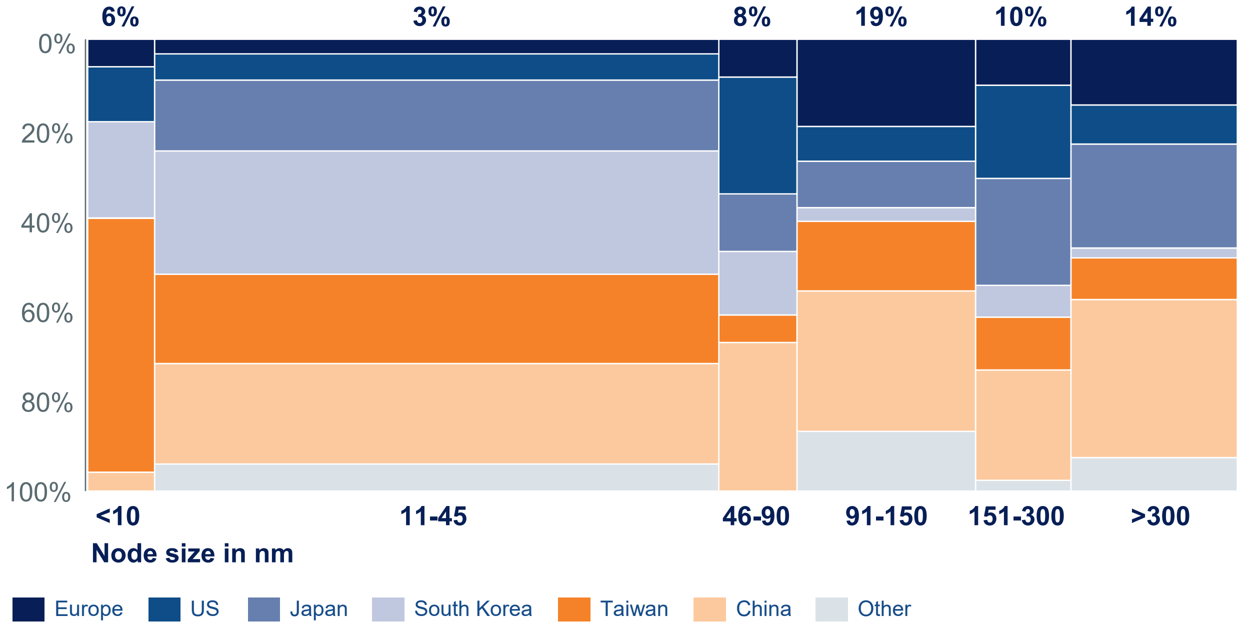


*Including power management;
Source: Omdia 2023; Strategy& analysis based on Gartner and publicly-available company figures

For example, European companies hold a market share of around 40–54% in microcontrollers and non-optical sensors (see Figure 5.10). When it comes to power electronics and power management, the EU is again leading, with a 25% market share. And for general-purpose logic too, such as field programmable gate arrays (FPGAs), the market share for European semiconductor companies is 20%. Lastly, the EU is internationally competitive in the area of communications, with a 10% market share. These existing strengths need to be built on further, in order to secure Europe's long-term competitiveness in these key areas. One critical factor in this is the strong interest from European applications industries, particularly the automotive sector, along with mechanical engineering and plant construction. This local demand is boosting the semiconductor industry, above all due to the close collaboration with regional customers.

Particularly in the value added step of semiconductor manufacturing, localisation of the production site plays a decisive role for supply chain resilience and in reducing regional dependencies. That said, semiconductor companies are fundamentally established on a global footing and operate production facilities worldwide, and even European companies such as Infineon and STMicroelectronics manufacture a significant part of their semiconductors outside Europe – either in their own plants or via contract manufacturers, particularly in South-East Asia. This foreign production brings with it risks for Europe's technological sovereignty, since geopolitical tensions could restrict access to these capacities, even if the parent company is based in the EU.

Fig. 5.11: Overview of manufacturing capacities by manufacturing facility region and node



Source: Strategy& analysis based on SEMI World Fab Forecast 3Q23

A detailed analysis of the distribution of manufacturing capacities by node shows that European capacities are particularly heavily concentrated in the range above 90 nm (see Figure 5.11). In this range, power electronics in particular plays a key role, confirming Europe's existing strengths. Conversely, for components with smaller structure widths, below 45 nm, Europe is heavily reliant on production capacities outside Europe and on contract manufacturers such as TSMC, Samsung or Intel. In these technologically leading areas, countries such as Taiwan, U.S. and South Korea are dominant. To strengthen Europe's technological sovereignty and to assume a greater role in future-relevant areas such as AI and high-performance computing, targeted investments in expanding the necessary skills – both in design and in manufacturing – are also likely to be needed. A successful catch-up process, however, can only succeed in close collaboration with user industries developed for that purpose, exploiting existing strengths. Future funding measures should always be geared to the existing pull effects within the European market.

5.4.4 Packaging: structural weaknesses in the semiconductor back-end

The semiconductor back-end is heavily concentrated in Asia, which represents significant risks for the resilience of global supply chains. Even if the barriers to entry and the complexity are generally lower by comparison with semiconductor production, when it comes to the details this is heavily dependent on the respective technology. Advanced packaging, in particular, is becoming ever more complex and is gaining in importance for the functionality and performance of electronic components. This is particularly relevant for key technologies such as AI, high-performance computing and autonomous systems. With this growing importance, its relevance for national security is also growing, since data manipulation and espionage are more easily possible. The advances in innovation in this part of the value chain present both opportunities and risks for future ambitions concerning technological sovereignty.

The back-end market, particularly in semiconductor packaging, is currently almost exclusively dominated by Asian companies. Taiwan and China have a particularly large market share in this area, but the U.S. also has a strong presence with Amkor, one of the world's biggest packaging companies. To date, the EU has played a negligible role in this market, and it possesses comparatively few packaging companies and capacities. Due to cost disadvantages, there are currently only few capabilities in this area in Europe. However, advanced packaging is becoming increasingly important, as it will play a key role in the future performance and functionality of semiconductors. Since an ever-bigger share of innovation and value added lies in these packaging processes, from the perspective of technological sovereignty it will be essential to assume a more active role in this area.

5.4.5 PCB and EMS: relevance for resilience and security

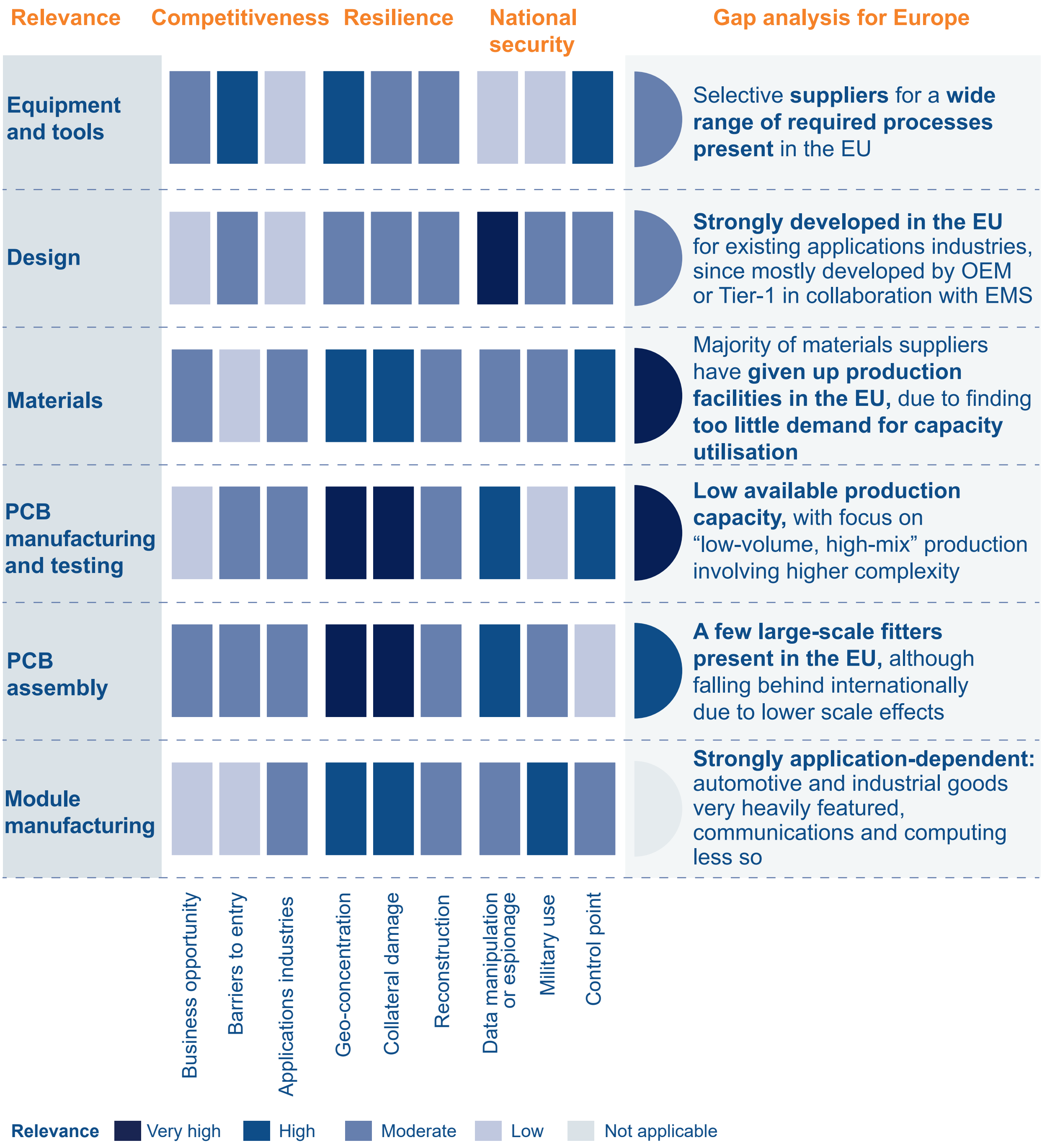
As previously described, the PCB industry has its own value chain, from equipment through to assembly (see Figure 5.12). The market for equipment for PCB production is smaller overall and less challenging than that for semiconductor production. However, the barriers to entry remain high, particularly for complex processes and smaller trace widths, in turn conditioned by the technological complexity. Market concentration is also high, although European manufacturers continue to be available for key processes. The collateral damage of a supply chain problem would be moderate, and reconstruction of production capacities is realistically feasible. However, the equipment represent an important control point, since without them neither PCBs nor electronic components can be manufactured.

The design and layout of circuit boards is frequently handled by EMS companies, as part of an integrated offer along with assembly. Alternatively, OEMs or module manufacturers develop the PCBs in-house as part of the electronic component. The development services are not centralised, as they often take place in the regions where the applications industries are based. Specific applications know-how puts up further barriers to entry. When reconstructing this know-how, it is particularly the shortage of specialists that presents a challenge, since there are no specialised training programmes for the sector and training new specialists can take a number of years. Layout is also important from the viewpoint of national security, since the risk of data manipulation and espionage is high, through targeted changes.

The production of PCBs requires materials such as laminates, glass fabric, resin, copper film and base chemicals. The relocation of a large part of production to South-East Asia means that many materials suppliers have migrated out of Europe. For European PCB manufacturers, this is leading to longer delivery times and higher costs, amplifying the region's cost disadvantages. In addition, the critical mass to purchase direct from the manufacturer is not being achieved, meaning that distributors often need to be involved as intermediaries. The effects of breakdowns on the materials supplier side are considerable. For instance, there have already been bottlenecks experienced in the European PCB chain when one hydrochloric acid supplier went under. With rising PCB production in the EU, however, it is conceivable that new materials suppliers could locate here. From the perspective of national security, the materials industry is a key control point, since a restriction on supplies of materials could considerably hamper the production of electronic components.

PCB manufacturing itself is a fiercely-contested market, characterised above all by high cost and efficiency pressures. Market entry is restricted primarily by the high investment costs for factories and equipment. To remain competitive, PCB manufacturers invest around 10% of turnover in manufacturing technologies. The complex production process comprises up to 300 part steps, and is heavily automated. Manufacturing is heavily concentrated in South-East Asia, with 85 to 90% of worldwide production volumes being covered in China and Taiwan. The effects of a loss of PCB production would be serious, since no electronic component operates without a circuit board. From the perspective of national security, PCB manufacturing is of major importance, both on account of the potential risk of data manipulation and as an essential control point. Loss of supply would considerably hamper the production of electronic components.

Fig. 5.12: Assessment of technological sovereignty along the PCB value chain



Source: Strategy& analysis

In summary, it can be stated that the PCB market is dominated primarily by leading nations such as Taiwan and China, who together control around three-quarters of the global market (see Figure 5.8). The biggest companies in the sector, including Zhen Ding, DSBJ and Unimicron, also come from this region. Asian PCB manufacturers have now also assumed technological leadership in miniaturisation and innovative production technologies. The EU's market share in the global PCB market has historically contracted heavily, and sits today at well under 5%. European suppliers are holding their own primarily in niche markets and for high-mix solutions.

PCB assembly is a market characterised by high volumes and low margins. The barriers to entry are moderate, and mainly defined by capital costs and deep application-specific expertise. Geographically, the market is heavily concentrated in South-East Asia, although there are also a few larger EMS companies in Europe. The effects of a loss of EMS companies would be slight, and the reconstruction of assembly capacities is possible at moderate expense. However, PCB assembly has a certain relevance for national security, since it guides the procurement of active and passive components and thus influences the content of an electronic component. Moreover, during assembly there is scope for manipulation, for instance by integrating remote controllers or manipulated components. Often, however, the module manufacturers and OEMs lack the specific expert knowledge to recognise and prevent such manipulations.

In the EMS sector, it is Taiwanese companies above all which are dominant, with a market share of around 60% (see Figure 5.8). Hon Hai Precision in particular, better known under the brand name Foxconn, dominates the EMS market as a component manufacturer, and it is deeply integrated through to semiconductor production. Together with Quanta Computer, the second-largest EMS supplier, these two companies account for over 50% of value added in the global EMS market. Outside Taiwan, the U.S. also has a significant market share, of 25%. By contrast, the EU has just a 10% share of the EMS market.

These market shares illustrate the existing gaps in the EU when it comes to PCBs and EMS (see Figure 5.12). Particularly when it comes to materials, the EU is heavily dependent on imports from South-East Asia, and as a result it has lost a key control point. In addition, there are only very limited PCB manufacturing capacities available in Europe. Given the high importance of these industries for resilience and national security, additional production capacities in the EU should be investigated. In the EMS segment too, building up further capacities in Europe could contribute to lowering risks such as data manipulation and cluster risks.

5.4.6 Hardware and software: a growing connection

The manufacture of electronic components and modules is heavily dependent on the respective end-consumer market (see Figure 5.12). The majority of module manufacturing occurs in Asian regions, leading to a stronger geographical concentration. Disruptions in this value chain step have direct effects on the applications industries and cause correspondingly high collateral damage. On the other hand, in many areas there are a large number of different suppliers, which leads to intense competition. Constant innovation and technological developments are also continuously changing the situation.

Even if this is not the focus of this study, the subject of algorithms should also be briefly highlighted. Algorithms and software are becoming increasingly important in many areas – both for competitiveness and for national security. With the progressive digitalisation of end-industries, on the one hand the risks with regard to data manipulation and espionage increase, while on the other new business models present themselves, like Software-as-a-Service (SaaS), which are applied across sectors. This is true in particular for European key industries such as the automotive sector, which in the course of the transformation to software-defined vehicles (SDVs) is increasingly focused on digital solutions. But other sectors too, such as industrial production, are also benefiting from advances in algorithms and software development, for instance via applications such as predictive maintenance or AI-assisted data analyses. In addition, hardware and software are becoming ever more closely connected, and even traditional component manufacturers are increasingly reliant on the capabilities that algorithms offer in order to secure their competitiveness along the entire supply chain.

In this area the U.S. is clearly dominant, with a market share of over 90%. Multinational tech giants such as Apple, Microsoft, NVIDIA and Alphabet are headquartered there, and they decisively shape the global market. By contrast, the EU has a share of only around 5%, with large industrial companies such as Siemens and Bosch active mainly in developing industrial applications.

This unequal distribution represents a considerable risk, both for national security and for the competitiveness of the EU. The relevance of algorithms and software is constantly increasing with progressive digitalisation, and extends over more and more key areas of the economy. Newly-arising fields such as SDVs, AI-based assistance systems, digital twins and the metaverse underline the growing importance of algorithms and their central role in future technologies. The U.S.'s dominance in these areas creates potential dependencies and vulnerabilities, which in the long term could threaten Europe's technological sovereignty.

This discussion demonstrates that the ecosystem approach plays a central role in establishing technological sovereignty. Economies that are able to manufacture "leading-edge" technologies along the entire value chain in relation to critical infrastructures and applications can secure prosperity, strengthen resilience and ensure national security. Amongst other things, this comes down to the various control points along the supply chain and to the risks of data manipulation and espionage within the value chain. Moreover, the individual steps in adding value are closely meshed with one another, meaning that strengthening the upstream supply chain is only possible by previously strengthening the downstream supply chain.

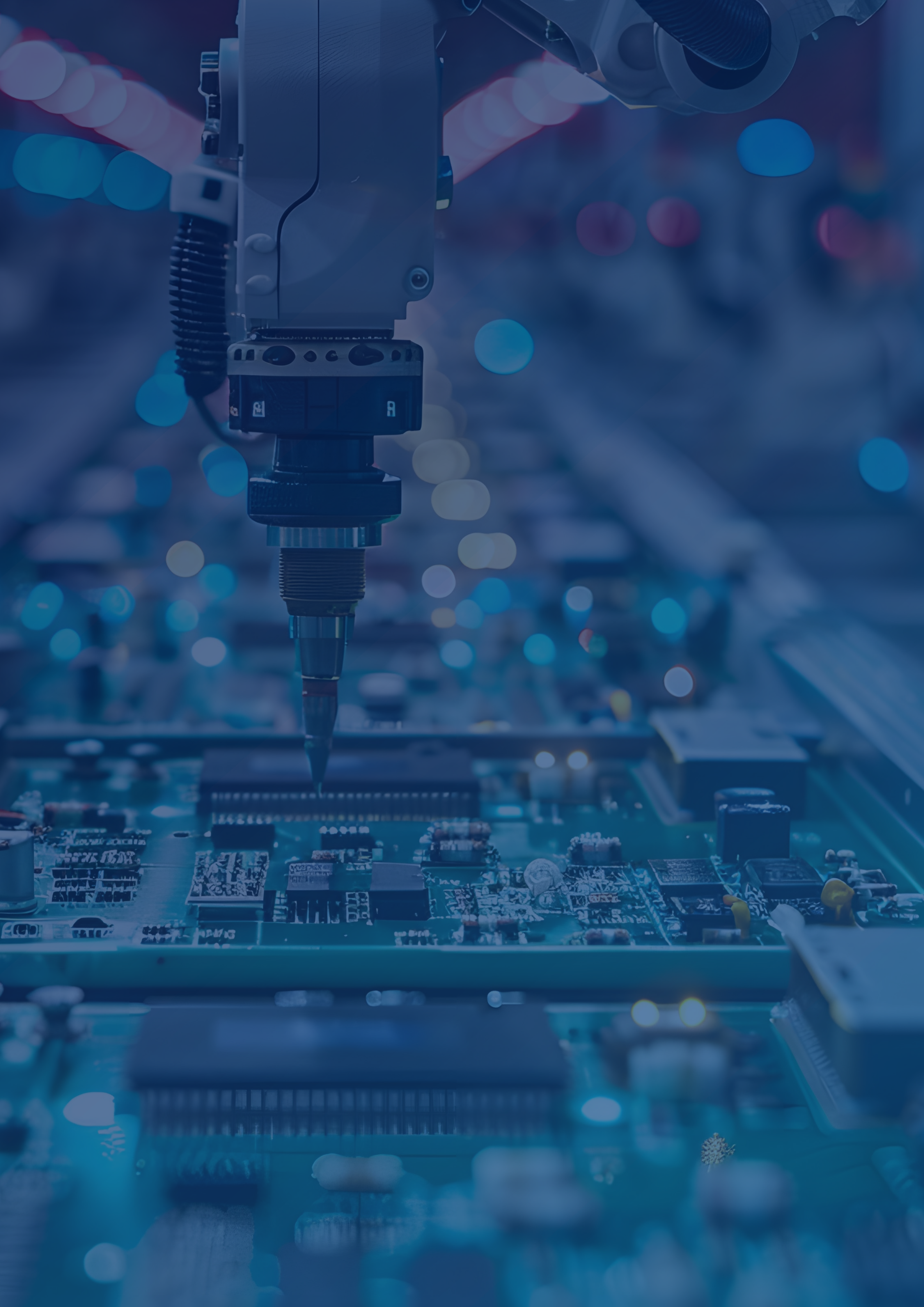
5.4.7 Intellectual property: the basis for economic competitiveness

Alongside the actual value added, the development and ownership of intellectual property (IP) plays a key role in the microelectronics industry. As part of Economic Sector 26.1 "Manufacture of electronic components", microelectronics ranks in 8th place for the European industry with the most patents, with roughly 15 to 16 patents per 1,000 employees.[40] In addition, it should be noted that a considerable part of the IP in this innovation-driven sector is deliberately not published, in order to prevent any opportunity of copying and thus a potential loss of competitive advantages.

Despite this, the number of patent applications provides an indication of economic growth and strength of innovation. Worldwide, patent applications rose by 189% between 1998 and 2018.[41] This underlines the increasing importance of IP in the global competition for technological leadership. Intellectual property rights not only create incentives for private investment in research where risk is attached, by ensuring market access for a given period, but also encourage knowledge transfer by making scientific insights accessible for further research.

The importance of IP for the European economy is shown in recent studies. According to the European Patent Office (EPO, 2022), IP-intensive industries are directly responsible for 29.7% of jobs and generate a further 9.7% indirectly. These industries thus secure a total of 39.4% of jobs, and on average they pay their employees 41% higher salaries than in other sectors. In addition, IP-intensive sectors contribute considerably (47.1%) to GDP in the EU. These numbers show how important intellectual property rights are to ensuring prosperity and competitiveness.

The facts set out here underline that the development and ownership of IP is a critical driver for economic growth and a society's prosperity. For that reason, it is vital to invest resources not only into production and maintaining existing capacities, but also long-term into future technologies. Particularly attractive in this regard are disruptive innovations which develop new technologies for the first time and make them fit for market. These technologies often represent significant advances in their respective areas, and have the potential to change industrial standards. Subsidy programmes like IPCEI play a key role here, since they support precisely such groundbreaking technologies.



6 Conclusions

The results of the study underline the central importance of microelectronics for the future capacity of Germany and the EU to innovate and compete. The analyses show that further measures are needed to avoid lagging behind in the international competition. With regard to future European competitiveness, sustainability and technological sovereignty, eight main areas for action can be identified:

1. Further investments needed	The study shows that supporting the microelectronics sector is an effective means to strengthen the European economy. However, additional investments will be needed to claim market shares in the global competition and to secure Europe's long-term competitiveness.
2. Boosting existing strengths	Europe has clear strengths in the value steps for materials and equipment, and in design and in the manufacture of power semiconductors, microcontrollers and sensor systems. These competencies need to be built up in a targeted manner in order to secure critical control points along the value chain.
3. Building up the combination of strengths with new technologies	Strategic gaps exist currently, notably in chip and software design and in advanced packaging. These areas require targeted measures to make good technological deficits and to exploit existing strengths in new areas of applications. In the long term, investments could be considered in the manufacture of semiconductors with small structure widths, essential for high-performance computing and AI applications, as long as these are oriented to the innovation road-maps and the demand situation in German and European user industries.
4. Boosting PCB and EMS	Major gaps in the areas of PCBs, EMS and algorithms are putting Europe's technological sovereignty at risk. Other regions have recognised the relevance of these value added steps and are investing in these areas. Europe needs to develop a long-term strategy for these critical value added steps.
5. Stronger growth via demand from applications industries	A strong microelectronics industry needs strong demand from applications industries. European core industries such as automotive and mechanical engineering, along with sectors that are currently under-represented such as AI applications and data centres, need to be strengthened in a targeted way to promote innovation and synergies along the entire value chain.
6. Overarching European microelectronics strategy	An overarching, European microelectronics strategy is needed. Stronger meshing of major projects within the EU, and closer alignment with the strategic aims for Europe as a location for microelectronics, are essential to maximise synergies between Member States.
7. Using sustainability as opportunity	Europe is well-placed to position itself as a global trailblazer for sustainable semiconductor production and to decisively shape the development of climate technologies. The high proportion of renewable energies, along with stringent environmental standards, are creating the ideal preconditions for this. To implement this, investments are needed in the energy infrastructure, together with close collaboration along the value chain.
8. Building up and bringing on specialists	The study has shown that the microelectronics sector contributes decisively to building up and retaining jobs, and encourages the development of innovative know-how in the EU. In view of the threatened shortage of specialists, intensified due to demographic change, targeted measures are needed in education, training and nurturing talent. These include adapted courses of study and apprenticeship routes, particularly in the areas of mechanical engineering and machine maintenance.

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Contact
Clemens Otte • Director Microelectronics & Cables
Phone: +49 30 306 960 10 • Mobile: +49 162 2664 930 • E-mail: Clemens.Otte@zvei.org

Imprint
ZVEI e. V. • German Electro and Digital Industry Association
Amelia-Mary-Earhart-Str. 12 • 60549 Frankfurt am Main
Lobbyregisternr.: R002101 • EU Transparency Register ID: 94770746469-09 • www.zvei.org

In co-operation with Strategy&
Tanjeff Schadt • Partner / Managing Director • Strategy&, Part of the PwC network
Phone: +49 89 54525521 • Mobile: +49 1516 7330436 • E-mail: t.schadt@pwc.com

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