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Competition, open innovation, and growth challenges in the semiconductor industry: the case of Europe's clusters

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Abstract

In recent years, public policymakers in Europe have become increasingly aware of the need to support Europe's failing semiconductor industry. This is an emerging policy area, and this paper examines the current state of the industry in Europe and assesses its potential future. It contends that the competitiveness of the industry will be related to its innovative capacity, especially its capability to engage in processes of open innovation. The industry in Europe is largely located in a number of discrete regional clusters, and the analysis focuses on data collected from a series of interviews with lead representatives of these clusters. The analysis indicates that the challenges facing the industry stem from the structure of the industry in Europe and the structure of the wider European technology industry. It is concluded that policies, such as the introduction of the European Chips Act, are likely to have a limited, or even negative, impact on the types of open innovation–led growth that will improve long-term competitiveness.

Key words: competition; open innovation; clusters; semiconductors; Europe.

1. Introduction

The production process of semiconductors, which are the hardware underpinning all information technology devices from smartphones and computers to automobiles and medical devices, is acknowledged to be one of the most complex and knowledge-intensive manufacturing processes in existence (Adams et al. 2013). Furthermore, the market for semiconductors is extremely valuable, being worth US$440 billion in 2020 and doubling in value over the preceding 20 years (US$204 billion in 2000), with a nearly ninefold increase over the past 30 years (US$50 billion in 1990) (Cerulus 2021; Semiconductor Industry Association 2021; Miller 2022a; Peters 2022; Yeung 2022a). Following the coronavirus disease (Covid-19) pandemic, there has been a significant interest in the complexities associated with semiconductor production and the realisation that this area of high technology is in many ways fundamental to the effective operation of contemporary society and its economy (European Commission 2021). This is particularly the case in Europe—which, in this case, we consider to be the European Union (EU) Member States and the now EU-exited UK—whereby shortages produced bottlenecks within many industries (Bloomberg 2021; Cerulus 2021).

At the same time, it has also become apparent that the European semiconductor industry has seen a significant relative decline for at least the last 30 years at the expense of the growth of the industry elsewhere, principally in North America and Asia (Macher et al. 2002; Walsh et al. 2005; Bonaccorsi 2011; Epicoco 2013; Deloitte 2020). Against this backdrop, national governments in Europe have started to reconsider the strategic importance of the semiconductor industry and the sovereignty of its assets, both tangible and intangible. At the higher policy level, the EU has pledged to make significant funding available to the industry via the EU's 'Chips Act' (European Commission 2022). The Chips Act sets out the scope of EU legislation to boost its share of production in semiconductors from ∼10 to 20 per cent of the world's total share by 2030. It aims to promote 'digital sovereignty' (i.e. self-sufficiency in semiconductor production) by supporting the development of new production facilities, supporting start-ups, developing skills, and building partnerships. In total, the Act will result in €43 billion being invested in the sector although a significant amount of the investment (∼€28 billion) was already committed to existing programmes at the EU and Member State level (European Commission 2022).

The Act set out a range of measures to boost European production by pooling different countries' resources to complement their individual research strengths and to support the development of new production facilities. On the face of it, the Act would appear to be an intervention that could improve the competitiveness and growth rates of the semiconductor industry in Europe, but some have criticised its formulation and considere that digital sovereignty is not a viable or desired route for Europe (Meyers 2022; Miller 2022b). Instead, it is argued that such is the global networked interdependency across the areas within which the European semiconductor industry operates international connectivity remains vital.

Given these policy developments, the aims of this paper are to examine the current state of Europe's semiconductor industry and to assess its potential future. Through the lens of the Schumpeterian growth model (Aghion et al. 2015), it focuses on competition and the nature of innovation within such competition. While growth and competition could be viewed through the lens of cost reduction growth models or trade growth models, the innateness of innovation within the semiconductor industry makes Schumpeterian growth models particularly applicable for examining the industry (Yeung 2022a,b). Innovation across high technology is increasingly considered to be 'open', whereby innovation occurs via connectivity and collaboration across firms and other organisations such as universities (Chesbrough 2020). This environment of open innovation is particularly relevant given that the semiconductor industry can be characterised as being in a constant state of flux and change, driven by dynamic research and development (R&D) firms that focus on continuously improving their output, especially through their supply and value chains (Adams et al. 2013; Miller 2022a; Yeung 2022a,b).

Clearly, the semiconductor industry is an important global sector, providing inputs that enable electronic devices to function and underpin technologies and digital transformations that power Industry 4.0 (Nambisan et al. 2019). Therefore, the key question the paper seeks to address is how fit for purpose is the structure of Europe's semiconductor industry to compete globally.

To address this question, the analysis, which is structured as a single case study of Europe's semiconductor industry, questions the industry's nature and engagement with innovation, the investment available for such innovation, and the demand for innovative products from major customers. Based on this analysis, the paper seeks to contribute to contemporary thinking on the nature of future public policy interventions to support Europe's semiconductor industry. From a more theoretical perspective, it seeks to begin to explore how innovation studies can further integrate innovation-based models of economic growth, such as Schumpeterian models, with the parallel discourse in management studies that have highlighted the perceived role of open innovation strategic management models as drivers of business growth.

As this paper illustrates, the structure of the industry in Europe is characterised by clusters of activity around a number of key locations. Accordingly, the core of the analysis stems from data gathered by a series of interviews across five of Europe's leading clusters, namely those located in Leuven (Belgium), Dresden (Germany), Eindhoven (Netherlands), Grenoble (France), and Cardiff (UK). The data from the interviews are coupled with an analysis of data from a range of relevant secondary sources. The paper begins by outlining an appropriate conceptual framework for analysing the semiconductor industry, especially in the context of the European industry. It then moves on to a discussion of the methodological and contextual issues underlying the empirical analysis. Following the empirical analysis, the public policy and concluding sections reflect on the key findings and outline the policy issues in relation to the key challenges found, with a view to giving consideration to rebuilding Europe's semiconductor industry.

2. Innovation, Schumpeterian growth, and semiconductors

This section outlines the nature of Schumpeterian growth and the contemporary emphasis on open innovation practices as a means of promoting this growth. It is argued that this growth model is particularly applicable to understanding the functioning of the semiconductor industry. It is then shown that different geographic segments of the industry have evolved along different trajectories, with the European industry slipping into a period of decline, especially compared with the growth of the industry in North America and Asia.

2.1 Innovation and the Schumpeterian growth model

The notion of the Schumpeterian growth model is based on three main ideas: (1) innovations lead to long-run growth, (2) entrepreneurial investments are motivated by prospects of monopoly rents, and (3) new innovations replace old technologies (Malerba and Orsenigo 1996; Aghion et al. 2015; Mathews 2020). In particular, within a Schumpeterian growth model, competition and productivity growth in an industry display an inverted-U relationship. Competition stimulates innovation and growth at lower levels of competition but less positively or even negatively affects innovation and productivity growth at high levels of competition (Aghion et al. 2015).

The semiconductor industry displays clear signs of being driven by Schumpeterian growth in that it is innovation focused, incumbent firms tend to be large producers, and these firms catalyse the growth of the sector (Adams et al. 2013; Aghion et al. 2015). Indeed, throughout its entire history, the industry has been regarded as being cyclical in nature and characterised as being continuously innovative and evolutionary as new ideas emerge, with new applications requiring new solutions to be developed (Walsh et al. 2005; Kapoor and McGrath 2014). This turbulence results in a high rate of firm entry and exit within the industry, with surviving firms possessing the competencies to develop improved semiconductor technologies and expertise (Walsh et al. 2005).

Of particular relevance to the contemporary evolution of the semiconductor industry is the emergence of evidence positing that the innovation process underpinning Schumpeterian growth has become more systemic and open in its nature (Dahlander and Gann 2010; Huizingh 2011; West and Bogers 2014; Roper and Hewitt-Dundas 2015; Chesbrough 2017; Yun et al. 2018), whereby 'new ideas may come from inside or outside the company' (Chesbrough 2003: 43). Open innovation can be defined as 'the use of purposive inflows and outflows of knowledge to accelerate the internal innovation, and to expand the markets for external use of innovation, respectively' (Simard and West 2006). Consequently, a key feature of open innovation is the knowledge-based network that facilitates the interactions necessary to access new knowledge, expertise, technology, and skills (Ahuja 2000; Chesbrough 2020). Accordingly, successful innovation is driven by networking that facilitates access to organisational partners possessing complementary knowledge, which is particularly the case in the semiconductor industry (Gassmann 2006; Dittrich and Duysters 2007; DiBiaggio et al. 2014).

Simard and West (2006) portray open innovation as a calculative process, whereby actors seek specific knowledge resources to augment their current stock. This deliberate construction of networks focuses on useful relations, which suggests that network capital is an important resource within the firm (Huggins and Johnston 2010; Huggins et al. 2012). As a result, firms pursuing a more open approach to innovation tend to outperform those that do not (Laursen and Salter 2006; Fu 2012). Open innovation, however, is not a risk-free process (Di Benedetto 2010). Potential negative externalities may exist, including the loss of knowledge when an organisation shares its knowledge, but the partner does not reciprocate (Lichtenthaler 2005). In addition, open innovation is far from costless as resources are required to identify a potential partner and maintain relationships (Sieg et al. 2010). Finally, firms must ensure that they work with an appropriate partner (Park and Ungson 2001), balancing the heterogeneity of organisations and their knowledge bases while ensuring that a degree of complementarity exists in order for the collaboration to be effective.

In general, the open innovation paradigm covers the forms of connectivity, collaboration, and cooperation we seek to explore in this paper. As the semiconductor industry is in a state of continuous innovation, these forms of networks relate to innovation and the systems through which it is generated (Kapoor and McGrath 2014; Chesbrough 2020). Therefore, our key research questions are formulated around the principles of the Schumpeterian growth model but adopted to account for the relevance of open innovation processes. These research questions are explicated and presented in the following subsections.

2.2 Growth and open innovation in the semiconductor industry

When addressing the evolution of the semiconductor industry, it is important to acknowledge that during its early years the fast pace of change meant that the design process for semiconductors was tightly controlled, promoting the internalisation of production as a means of minimising transaction costs (DiBiaggio 2007). However, the vertical integration and economies of scale generated by internalisation represented a significant barrier to entry into the industry (Macher and Mowery 2004). Consequently, in the early years of the development of the industry, R&D activities tended to occur within the laboratories of large corporations (Logar et al. 2014). This pattern was, however, relatively short-lived as two key changes promoted the rise of a more open approach to innovation in the sector.

First, the emergence of Asian semiconductor firms challenged the dominance of US firms and significantly increased production capacity while driving down costs (Walsh et al. 2005; Yeung 2022a,b). Second, increased production facilities promoted the rise of the so-called fabless firms (Nenni and McLellan 2014), i.e. those involved in the design of chips but with no fabrication capacity themselves instead contract the manufacturing to others, challenging the vertically-integrated model (Balconi and Fontana 2011).

Utilising the 'fabless' model enabled new entrants to circumvent the significant barriers to entry that existed in the semiconductor industry, avoiding the need to invest heavily in expensive new plants and equipment to realise economies of scale in production and catch up with existing entrants (Grimes and Du 2022). Furthermore, the rise of fabless firms has entrenched open innovation activities within the industry as its structure has changed, with fabless firms indirectly benefitting from the R&D of their client firms (Shin et al. 2017). Consequently, fabless firms have been shown to outperform others in terms of return on investment, gross margins, and net margins as they benefit from increased R&D ratios (Shin et al. 2017).

Although the emergence of fabless firms did not lead to the offshoring of R&D activities, with these typically remaining within the 'home' region, it has led to significant spillovers of knowledge through the industry (Macher et al. 2002, 2007). Open innovation activities typically focus on new manufacturing techniques, the use of new materials, or new applications and uses of the technology (Lim 2004). Importantly, open innovation is both encouraged and constrained by the fact that changes to any form of semiconductor must be 'controlled and coordinated' due to the high level of outsourcing within the industry, as well as the effects of changes on complementary technologies (DiBiaggio 2007; Sydow et al. 2012; Sydow and Muller-Seitz 2020).

Attempts to coordinate open innovation activities are often undertaken through road-mapping exercises, whereby plans are made to forecast future trends and developments in the industry (Spinardi 2012; Sydow and Muller-Seitz 2020). One example is the International Technology Roadmap for Semiconductors, which is designed to predict the future path for semiconductors to manage uncertainty, pool knowledge resources, and reduce R&D costs (Sydow and Muller-Seitz 2020). However, road mapping cannot always capture new developments as they are not necessarily predictable nor can new applications for the components always be foreseen (Spinardi 2012). Indeed, road mapping is largely regarded as a success for the existing technological regime, built around what is referred to as complementary metal–oxide–semiconductor (CMOS) technology, but has not yet been able to capture the next steps 'beyond CMOS' and define the next technological regime (Sydow and Muller-Seitz 2020). This lack of successful road mapping for future technologies hinges around three sets of uncertainties: (1) uncertainties regarding the new configurations for semiconductors, (2) partner uncertainty based on who are the collaborators, and (3) procedural uncertainty surrounding whether or not the new technology will work in the future (Sydow and Muller-Seitz 2020).

Consequently, open innovation activities in the semiconductor industry may focus on 'path extension', based on existing networks, proven solutions, and established routines, rather than 'new path creation' that seeks to develop new network partners and new ideas/technologies (Sydow et al. 2012). Nevertheless, the nature of open innovation activities in the semiconductor industry has evolved over time (West 2002); for example, different sets of ties between firms have been observed at different times (Wang et al. 2017), suggesting that alliances may be flexible and changeable based on the current configuration of the industry.

It must also be acknowledged that constraints to open innovation may exist. Significantly, the process relies on establishing network connections and their smooth function (Huggins and Johnston 2010; Chesbrough 2017). In the absence of these, open innovation may be less effective (Randhawa et al. 2016; West and Bogers 2014). Indeed, the semiconductor industry has been characterised as asymmetric and interdependent, with relationships facilitated by the existence of a global value chain whereby the design is concentrated in the USA and manufacturing in China (Grimes and Du 2022).

Given this, it may appear that open innovation across space is a straightforward undertaking. However, the existence of geopolitical tensions results in a complex innovation ecosystem (Peters 2022). Consequently, the 'openness' of the system may be subject to change as political issues take precedence over economic cooperation. Furthermore, coordination within the sector can be negatively influenced by uneven development paths, evolutionary trajectories, or innovation activities (Linden and Somaya 2003). This means that the effectiveness of open innovation is dependent upon cooperation among firms with comparable levels of development or following similar paths or trajectories. Given the above issues, the first research question the paper seeks to address is the following:

> Research Question 1: To what extent does the European semiconductor industry engage in open innovation and collaboration?

2.3 The key geographic segments of the global semiconductor industry

In terms of examining the semiconductor industry, it is important to consider the four general steps that are involved: R&D; design; manufacturing; and assembly, test, and package (VerWey 2019). An integrated device manufacturer (IDM) conducts all four steps, which are undertaken by large players such as Intel or Samsung. As indicated earlier, firms that specialise in design only are called 'fabless', which is an increasing feature of the industry. Firms that carry out manufacturing without any of the other four steps are known as foundries. There are also other types of semiconductor firms with further specialisations in the value chain, including semiconductor manufacturing equipment, outsourced semiconductor assembly and test (OSAT), electronic design automation, and intellectual property (IP) blocks.

Increasingly, specialised business models have resulted in unique and geographically disparate value chains, in which, for example, a chip may be designed in the USA, manufactured in Taiwan, and tested and assembled in China (USITC 2017). In 2018, Samsung (South Korea) and Intel (USA) accounted for 15.4 and 14.4 per cent, respectively, of global revenues in the IDM market, with Broadcom (USA) (18 per cent) and Qualcomm (USA) (17 per cent) leading the way in terms of global revenues by fabless firms, and Yeung's (2022a,b) detailed analysis of the evolution of the industry as a whole highlights the growing role played by East Asian firms, particularly for manufacturing. It is difficult to estimate the total size of the industry in terms of the number of firms across the semiconductor industry at either a global or European level as many businesses operate across a number of areas within the broader electronics industry. However, within Europe, it is estimated that there are at least 2,000 active firms related to semiconductor processes, development, and production (Silicon Europe 2022).

In general, the semiconductor industry has become increasingly mature and consolidated, with a small number of large firms from Europe, the USA, and East Asia dominating most of the segments on the value chain (see Table 1). This is further consolidated by the semiconductor industry's high barriers, including high fixed capital expenditure as the most important factor, as well as first-mover advantages, economies of scale, brand recognition, stickiness and customer loyalty, and IP (King 2003).

The cost of establishing a leading-edge semiconductor manufacturing facility has largely become prohibitive except for the few very large firms, especially as the industry approaches the limits of Moore's law (VerWey 2019). The costs related to such development have forced the global semiconductor value chain to become further consolidated, and most companies choose to focus on their legacy, outsourcing other segments to subsidiaries or other firms for R&D, design, and manufacturing that is not undertaken in-house (Yeung 2022a). This model has further reduced the number of firms that are able to fabricate cutting-edge chips or alter the prevalent model to a new one in the industry (Miller 2022a).

In 2021, European firms accounted for 9.6 per cent of the global semiconductor manufacturing capacity, generating US$37.5 billion in revenue (Semiconductor Industry Association 2021). However, recent trends highlight Europe's decline as a centre of production. In 1990, 44 per cent of the global chip manufacturing market was located in Europe mainly due to the early mobile phone market success of firms such as Ericsson, Nokia, and Siemens (Gooding 2021). This decline was initially precipitated by the availability of lower labour costs in Asia that attracted manufacturers out of Europe. It was reinforced by the changing nature of the mobile phone market, namely the emergence of smartphones, which fundamentally transformed the nature of demand for semiconductors (Gooding 2021).

As a result of these changes, the focus of European firms has been on building competencies in the automotive, power electronics and microelectromechanical sectors. For example, European chip designers, such as NXP Semiconductors and Infineon Technologies, outsource production to foundries such as the Taiwan Semiconductor Manufacturing Company (TSMC) (Bloomberg 2021). As such, this follows the pattern of the wider semiconductor sector, whereby R&D is typically conducted in headquarter locations and manufacturing bases concentrated in East Asia (Yeung 2022a), with European investment lagging significantly behind the USA and China (Dealroom and Sifted 2021; MGI 2022). Given the above issues, a key research question the paper seeks to address is the following:

> Research Question 2: Does the European semiconductor industry have access to the required levels and types of investment in order to allow it to innovate effectively and grow at a rate that matches competitors?

2.4 Growth challenges facing the European semiconductor industry

As shown in Table 2, only four of the top global semiconductor companies by revenue are based in Europe. The Dutch company ASML is the only supplier of photolithography equipment used in chip making, and none of the largest European semiconductor firms manufacture semiconductors themselves (Dornbusch 2018; VerWey 2019). Legal frameworks in the EU potentially pose a disadvantage for European firms compared to their Asian and US counterparts (Danish Technological Institute 2012). Importantly, some European countries exhibit a strong focus on microelectronics export activities but have comparatively low innovation activities in microelectronics.

Table 1. European, North American, and Asian semiconductor industries.

Semiconductor industries	European	North American	Asian
Size in 2019	10% of global production	The USA accounts for 48% of the global supply, and 12% is produced onshore	World's biggest consumption market for semiconductors, accounting for 60% of global semiconductor sales
Main organisations or regions/countries	Silicon Saxony (Germany) High Tech NL (Netherlands) Minalogic (France) DSP Valley (Belgium)	Silicon Valley Texas	South Korea Japan China Taiwan Singapore
Main areas of activity	Embedded systems in automotive, battery technology, environment, robotics, energy efficiency, internet developments, security, aerospace, and health care	R&D and intellectual property in semiconductors, chip and electronic design, software, and automation	Around two-thirds of the global fabless market, advanced IC design and manufacturing, semiconductor equipment and upstream semiconductor materials, competitive in chip manufacturing, and OSAT
Key companies	ASML Holding STMicroelectronics Infineon Technologies NXP Semiconductors ARM	Intel Micron Applied Materials (AMAT) Broadcom Qualcomm Texas Instruments Nvidia Lam Research Western Digital AMD	Samsung Electronics TSMC SK Hynix ASE Technology Holding Tokyo Electron (TEL) Sony Kioxia Holdings MediaTek HiSilicon Renesas Electronics

Source: Dornbusch 2018; Deloitte 2020; Semiconductor Industry Association 2021; Cerulus 2021; and interviews by the authors.

Table 2. Top 20 global semiconductor companies by revenue in 2019.

	Company	Country	Business model	Revenue in 2019 (billion)
1	Intel	USA	IDM	US$65.8
2	Samsung Electronics	South Korea	IDM	US$52.2
3	TSMC	Taiwan	Contract foundry	US$35.8
4	SK Hynix	South Korea	IDM	US$22.4
5	Micron	USA	IDM	US$20.0
6	AMAT	USA	SME	US$17.2
7	Broadcom	USA	Fabless	US$15.3
8	ASE Technology Holding	Taiwan	OSAT	US$13.8
9	Qualcomm	USA	Fabless	US$13.5
10	Texas Instruments	USA	IDM	US$13.2
11	ASML Holding	Netherlands	SME	US$13.2
12	Nvidia	USA	Fabless	US$10.9
13	TEL	Japan	SME	US$10.4
14	Lam Research	USA	SME	US$10.0
15	Sony	Japan	IDM	US$9.8
16	STMicroelectronics	France and Italy	IDM	US$9.0
17	Infineon Technologies	Germany	IDM	US$8.9
18	Kioxia Holdings	Japan	IDM	US$8.8
19	NXP Semiconductors	Netherlands	IDM	US$8.7
20	MediaTek	Taiwan	Fabless	US$8.2

Source: Institut Montaigne, Gartner (Cerulus 2021).

Taking patents as an indicator of performance in the production of new technological knowledge (Engel 2014), Europe's share has declined markedly and has been forced to focus on market niches that firms in other locations are less interested in (Dornbusch 2018). The vulnerability of global supply chains and semiconductor shortages, highlighted by the Covid-19 pandemic, has suggested the strategic need to reverse the offshoring trend and encourage more manufacturing in Europe (Clark 2020). According to the Semiconductor Industry Association (2021), demand for chips reached record levels in 2021 (with over 1 trillion sold). Accordingly, European policymakers are increasingly concerned about potential shortages caused by an overreliance on external manufacturers. However, little is known about the potential nature of demand, particularly in terms of the types and sophistication that European customers are likely to require. Therefore, a third research question is the following:

> Research Question 3: What is the nature of the demand for semiconductors across European customers?

As indicated earlier, Europe's relative decline as a semiconductor manufacturing centre has been increasingly recognised by European policymakers. In 2018, the EU Commissioner for Digital Economy and Society commissioned a study on 'Boosting Electronics Value Chains in Europe' (European Commission 2018). This set out the broad steps required to reverse this decline. This action plan identified the following areas for development: promoting collaboration and partnerships, encouraging investment, promoting strategic sovereignty, facilitating innovation from IP creation to product development, pursuing strategic design initiatives, creating design tools for electronic value chains, enhancing electronic education and skills, and developing a pan-European research infrastructure for advanced computing technologies.

As such, the aim of EU policymakers is to increase the self-sufficiency of Europe in terms of semiconductor production by promoting R&D and investing in new facilities to produce innovative new chips. However, these facilities are expensive and costs are increasing. The estimated cost of new fabs ranges from around US$13 billion to US$20 billion depending on the types of semiconductors to be produced. Therefore, these facilities require significant investments. Importantly, it has also been recognised that inter-cluster cooperation is a key enabler of technological progress in this sector (Silicon Europe 2022). Partly as a response to the decline, the EU aims to produce the next-generation of leading-edge chips (2 nm) by 2030. This is a rather ambitious goal and has not yet been reached by the globe's leading manufacturer, TSMC (Peters 2022). In 2014, Europe's capacity in 300-mm wafer chip (which is one of the larger chips) manufacturing was 2 per cent, and only half of this was manufactured onshore in Europe (Clark 2020). The situation has deteriorated over the following years, and as already indicated, the vulnerability of global supply chains and semiconductor shortages has been highlighted by the Covid-19 pandemic (Clark 2020).

In summary, there are serious long-term concerns. Closing production sites due to the lack of relevant investment will further result in a loss of human resources, know-how, and equipment, which is very difficult to regain. Consequently, the loss of production and employment may deepen existing fractures and cause further missing links to the global microelectronics-related value chain (Dornbusch 2018).

Other European Commission initiatives, such as the 'Important Project of Common European Interest on Microelectronics', have sought to facilitate transnational cooperation projects in microelectronics across four European nations: France, Germany, Italy, and the UK. Significantly, this programme permits the use of state aid for microelectronics industrial competitiveness to encourage R&D investment and activity. Furthermore, an emerging positive development is that a European initiative on processors and semiconductor technologies declaration was signed in 2020 (European Commission 2021).

The Member State signatories agreed to cooperate and co-invest in semiconductor technologies across the full value chain. They also agreed to work together to strengthen Europe's capabilities to design and eventually fabricate the next generation of trusted, low-power processors for applications in high-speed connectivity, automated vehicles, aerospace and defence, health and agri-food, artificial intelligence, data centres, integrated photonics, supercomputing, and quantum computing among other initiatives to bolster the whole electronics and embedded systems value chain (European Commission 2021). This declaration aims to create synergies among national research and investment initiatives and ensure a coherent European approach to achieving sufficient scale. It seeks to build on and expand collective efforts and will require investments from the EU budget, national budgets, and the private sector (Archibugi et al. 2020; European Commission 2021).

These policy developments were broadly brought together and packaged within the formalised European Chips Act, announced in 2022, which puts in place the legislative infrastructure to realise these ambitions (European Commission 2022). The concept of the European Chips Act is a response to the introduction of the CHIPS and Science Act in the USA, which is based on the ethos of improving the sovereignty of semiconductor production within the USA (US Department of State 2022). The US Chips (short for 'Creating Helpful Incentives to Produce Semiconductors') for the America Act seeks to establish investments and incentives to support US semiconductor manufacturing, R&D, and supply chain security. The Act partly came about as a result of ongoing geopolitical tensions between the USA and China, with the USA attempting to decouple some of its trade relationships with China, most prominently across the semiconductor industry (Miller 2022a). Following bipartisan support, the US Chips Act bill became established legislation to provide a set of semiconductor incentives together with appropriations for wireless supply chain innovation and advanced manufacturing investment credit. It authorises US$50.3 billion over 5 years, with a further US$550 million per year between 2023 and 2027 for science lab infrastructure (Peters 2022).

In comparison, the European Chips Act has a proposed budget of €43 billion, but a breakdown of the sources of funding indicates that a significant amount of this investment was already committed through existing programmes (Meyers 2022). A key feature of the Act is to establish a 'Chips Fund' that is underpinned by the allocation of public R&D support to firms. This is aimed at facilitating access to debt financing and equity in the semiconductor value chain and supporting the development of a dynamic and resilient semiconductor ecosystem. It is stated that this will provide opportunities for the increased availability of funds to support the growth of start-ups, scale-ups, and small and medium sized enterprises (SMEs), as well as investments across the value chain. Other dedicated resources proposed by the European Innovation Council will provide further support through grants and equity investments to high risk, market creating innovators (European Commission 2022). These funds will form part of the Act's 'Chips for Europe' initiative, which will be formulated via a platform aimed at improving capabilities in designing chips and developing 'pilot lines' to take chip designs from a lab environment and into pre-commercial manufacturing, especially funding for developing quantum chips, and centres to improve chip-related skills (European Commission 2022).

The 'Chips for Europe' initiative represents a positive step forward in promoting innovation across Europe's semiconductor industry, but in reality new funding is relatively limited. Despite an announced budget of €11 billion, only €5.8 billion will be direct EU funding (the rest made of money from existing programmes such as Horizon Europe and funding from Member States or the private sector (Meyers 2022)). The potential impact of the European Chips Act on semiconductor innovation is likely to be considerably less than that of the US Chips Act, which has allocated more than US$13 billion of new funds to R&D and upskilling (Meyers 2022). Therefore, despite the introduction of the European Chips Act its ability to improve the competitiveness of the European semiconductor industry remains highly contested due to a range of structural issues that may limit the growth and innovation capacity of the industry (Meyers 2022; Miller 2022b). These are the issues that are more empirically analysed in the sections to follow, especially in terms of addressing the following research question:

> Research Question 4: How fit for purpose is the structure of Europe's semiconductor industry to achieve the required rate and forms of innovation to compete globally?

3. Methodology and context

This section first outlines the methodological approach adopted for the empirical analysis and, second, the context concerning the nature of the European semiconductor industry.

3.1 Methodological approach

The methodological approach adopted is to take the European semiconductor industry as a case study to examine the challenges it is facing in terms of growth within a highly innovation-driven sector. Given that the majority of economic activity across the sector is focused on a small concentration of clusters, it is logical to concentrate on these clusters. In total, five key clusters were chosen given their focus on silicon technologies, namely (1) DSP Valley, which is largely located in Leuven (Belgium); (2) Silicon Saxony, which is largely located in Dresden (Germany); (3) High Tech NL, which is largely located in Eindhoven (Netherlands); (4) Minalogic, which is largely located in Grenoble (France); and (5) CSconnected, which is largely located in Cardiff (UK). These clusters were selected as they represent both the critical mass of activity of the semiconductor industry in Europe and some of the emerging trends across the industry. Leuven, Dresden Eindhoven, and Grenoble are the acknowledged hotbeds and the largest concentrations of semiconductor activity across Europe (European Commission 2013; Dornbusch 2018).

These clusters previously formed part of a major European Commission (2013) international comparative study of semiconductor clusters and were chosen because they each have: a clear specialisation in integrated circuit (IC) technologies; a relatively high density of firms working with these technologies; a significant number of larger firms and share of employment, and more generally have historical strength in the industry. Cardiff was not included in the 2013 study, but it has since become an emergent cluster that operates within the industry's research-intensive and innovative area of compound semiconductor production. Given this, these five clusters can be considered to provide a valid and reliable data source for addressing the research questions developed earlier in the context of a European-wide case study (Denzin and Lincoln 2011).

Building the case study data involved two elements: (1) desk-based research to establish the key information on the industry from a range of sources such as policy documents, industry reports, strategy documents from cluster organisations, and databases of semiconductor firms and (2) a series of interviews with key informants within the European semiconductor industry. Interviews were undertaken online (using Zoom software) for both the practical realities that data were collected in the second part of 2021 when Covid-19 restrictions were in place across much of Europe and also due to the fact that online interviews provide an environment to collect data of the same quality to that administered in-person but have the advantage of securing access to interviewees from across a wide geographical research (Salmons 2015). In-depth interviews were undertaken with leading representatives of each cluster, covering the Chief Executive Officer/managing director of the formal cluster organisation as well as another individual representing a prominent cluster member. These interviewees were identified through web searches and subsequently contact names provided by initial respondents.

All the interviews were undertaken in 2021 and lasted on average approximately 1 h and were recorded and fully transcribed, with eleven interviewees providing relevant information across the five cluster locations. As the respondents were able to provide a strategic overview of the cluster and industry, its complexity, nuances, current state, and future directions, the data generated significant insights into the industry, the clusters, and the firms. A standard interview pro forma was utilised, which covered the following issues: (1) the recent evolution of each cluster, (2) the innovation capacity and capability of each cluster and the European semiconductor industry as a whole, (3) the functioning and operation of the European semiconductor value chain, (4) the strengths and weaknesses of the European semiconductor value chain, and (5) the role for future public policy and investment. However, the interview pro forma was designed to be a relatively 'loose script' (Johansson 2004), allowing the respondents to outline significant issues and experiences in their own words, rather than responding to a predefined set of factors (Bauer 1996; Clandinin and Connelly 2000).

A thematic analysis involving a two-stage process was undertaken. The first stage coded the transcripts according to the conceptual framework, utilising the following top-level codes to organise the data as follows: (1) innovation and commercialisation, (2) openness and connectivity, (3) knowledge and resources, and (4) the value chain. Subsequently, the second stage involved an analysis of the data under each theme to identify the salient factors underpinning each of them (Fereday and Muir-Cochrane 2006). As such, theoretical constructs were defined according to the extant literature, providing a theoretical justification for the coding frame (Eisenhardt 1989), and the analysis draws on the process of 'systematic combining' outlined by Dubois and Gadde (2002), whereby the theoretical is confronted with the empirical in order to juxtapose actual events with theoretical explanations.

3.2 Context

This section briefly introduces the five clusters that were the observations for the case study, and the key characteristics of each cluster are summarised in Table 3. Each of these regions has developed different specialisations and comparative advantages in certain technological and sectoral niches. For example, High Tech NL specialises in robotics and life sciences, while Minalogic focuses on microelectronics. In addition to these clusters, an emergent cluster based in the UK (CSconnected, Cardiff) has developed, with a specialism

Table 3. Key characteristics of the European semiconductor clusters.

Cluster location	Member firms	Key characteristics
Minalogic (Grenoble/Lyon/St-Etienne, Auvergne-Rhône-Alpes region, France)	~500	Comprised start-ups, SMEs, and large firms: the cluster is anchored by the Alternative Energies and Atomic Energy Commission, nineteen expert academic laboratories linked to microelectronics, and local universities. The cluster has specialisms in microelectronics, the ECHO system, photonics, infrared image sensor software, artificial intelligence video, virtual reality animation, and video gaming. Member firms are involved in the design and manufacturing of chips and systems (STMicroelectronics and E2V Semiconductors), as well as applications (Schneider Electric). The Minalogic mission is focused on supporting members with European funding opportunities, identifying potential projects and partners, and supporting members with project development. In addition, they are focused on transferring technology to the region's key high-tech industries such as energy, chemicals and envirotech, health care, and agri-food.
Silicon Saxony (Dresden, Germany)	350	This cluster hosts four major semiconductor manufacturers: Infineon, GlobalFoundries, X-FAB, and Bosch fab. Consequently, the cluster possesses significant competences for high-volume chip production and hosts a fab for 300-mm wafer production, which can be considered as the current state-of-the-art, and is currently planning to double its production capacities. Additionally, several research institutions, including the Technical University Dresden, Max Plank Society, Fraunhofer Institute, and Hemlhotz Association, are located in Dresden. The cluster association is involved in the promotion of networking by organising industry events to ensure the transfer of know-how and close economic relations among the members. In addition, the association engages in targeted lobbying activities across Europe.
High Tech NL (Eindhoven, Netherlands)	150	Comprised SMEs, original equipment manufacturers, and knowledge institutes (e.g. University of Technology Eindhoven (TU Eindhoven)): the cluster is anchored by ASML, NXP, and Phillips. It specialises in semiconductors, robotics, and life sciences. The cluster association focuses on promoting long-term innovation and international collaborations by encouraging members to share knowledge, cooperate, and harness networks.
DSP Valley (Leuven, Belgium)	125	The DSP Valley cluster is based around Leuven and focuses on semiconductors and their application in the smart health, smart cities, smart vehicles, and smart industry sectors. The micro- and nanoelectronics lab IMEC is a significant member. Important knowledge is generated in microelectronics and embedded system design and development, but this is not fully exploited by the application end of the value chain. The DSP Valley cluster association provides members with a networking platform to explore one another's expertise and identify and exploit complementarities. The activities of the DSP Valley include regional and international business-to-buisness (B2B) forums, promoting university–industry links, custom matchmaking events, technical seminars, and brokerage services for participation in European ICT programmes.
CSconnected (South Wales, UK)	15	The cluster emerged out of the CSC, a joint venture between IQE plc and Cardiff University set up to develop and prototype compound semiconductor materials. This was followed by further public investments to develop a compound semiconductor hub and catapult centre in the region. In addition, the cluster intends to develop a state-of-the-art foundry. The aim of the cluster is to facilitate the development of new semiconductor technologies by uniting firms involved in the design of compound semiconductors with those developing related technologies that are enabled by compound semiconductors such as next-generation optical communications and sensing, large-scale GaAs-based wafer manufacturing, novel and efficient Compound Semiconductor Wafer Fabrication Tools, and advanced processes for 5G and EAV systems.

concentrated on compound semiconductors. The main focus of this cluster is R&D activities that examine the use of new materials for manufacturing semiconductors. Consequently, this cluster is still at an early stage of development and is yet to attract a critical mass of manufacturers.

In terms of DSP Valley, the city of Leuven is relatively small (population: ~100,000), but it has a large international university and highly-developed knowledge institutions and knowledge enterprises. In addition to being a renowned knowledge centre, the region has also become known for its active policy with regard to entrepreneurship and knowledge transfer. Four major technology domains—covering life sciences, nanotechnology, mechatronics and smart systems, and cleantech—have gradually emerged in the Leuven Technology Corridor, which has created dynamic clusters in which innovative companies and knowledge centres interact closely. Research in the field of microelectronics and nanotechnology is concentrated at the Catholic University of Louvain (KU Leuven) and the Interuniversity Centre of Micro-Electronics (IMEC), which have strong links across each other.

Dresden (population: ~550,000) is the main location for Silicon Saxony, which is the capital city of the Free State of Saxony in Germany. Over the last few decades, it has evolved into an attractive location for enterprises and jobs, especially in the semiconductor industry. A range of semiconductor, electronic, and microelectronics industries are now clustered in the region, with it gaining its reputation as 'Silicon Saxony'. Under the support of local and regional governments, Dresden is home to Europe's largest trade association for the microelectronics sector. Silicon Saxony e.V. was founded in 2000, and the association now has approximately 250 members and connects manufacturers, suppliers, service providers, and research institutes in Saxony. The network includes large corporations such as AMD (GlobalFoundries), Infineon, Siltronic, Zentrum Mikroelektronik Dresden, and Advanced Mask Technology Centre Verwaltungs GmbH.

High Tech NL is principally located in Eindhoven (population: ∼230,000) in the south-east of the Netherlands. It is a leading technology centre and is often referred to as the Technopolis of the country. The Eindhoven region accounts for nearly 25 per cent of the total Dutch R&D expenditure and 45 per cent of the R&D expenditure of Dutch-based firms (Statistics Netherlands 2020). Companies in the region are not only more R&D intensive but also more likely to focus on high technologies than those located elsewhere in the country. Eindhoven increased its average added value by more than 25 per cent in the years after 2008 and is the top Dutch region in terms of the number of innovation projects per thousand companies, which to some extent is dominated by three large high-tech companies (NXP, Philips, and ASML) and two higher education institutes (Eindhoven University of Technology and Fontys) (Romme 2022).

Grenoble (population: ∼155,000), the home of the Minalogic cluster, is a city in southeastern France situated at the foot of the French Alps and is known as the 'Capital of the Alps'. The Rhône-Alpes region as a whole is economically competitive and productive. It boasts France's second largest regional economy (after Paris-Ile-de-France) with per capita gross domestic product 6 per cent above the EU average. The economy of Grenoble has grown strongly, driven by 'an internationally competitive cluster of activities involved in research, development and product design for microelectronics, nanotechnologies and related software' (Baglieri et al. 2012). The Grenoble nanotech cluster is branded by the French government as one of the nation's eighteen 'global competitiveness clusters', or 'pôle de compétitivité', which aims to bring together firms, research laboratories, and educational establishments in a specific region to develop synergies and cooperative efforts (Assimakopoulos et al. 2022).

The newest cluster, CSconnected in Cardiff (population: ∼370,000), originally stemmed from a joint venture agreement between Cardiff University and IQE, which is a leading global supplier of advanced compound semiconductor wafer products covering a diverse range of applications. This joint venture led to the formulation of the Compound Semiconductor Centre (CSC) in 2015, which is beginning to position itself as a new European location for product, services, and skills development in compound semiconductor technologies. The CSC is building on research undertaken at Cardiff University's Institute for Compound Semiconductors in order to develop innovative new materials technologies that will enable a wide range of emerging applications. Since 2015, the cluster has expanded to form a nascent regional ecosystem with significant interdependencies across a range of organisations such as the private sector, public sector, and academic and research organisations.

4. The European semiconductor industry: a view from the clusters

This part of the paper examines the nature of and challenges in the European semiconductor industry in terms of Schumpeterian-based growth. From the perspective of generating long-run growth from innovations, it examines the innovative and competitive capacity and capability of the European semiconductor industry. In particular, it explores the industry's engagement in open innovation and collaborative practices and the extent to which these practices impact the innovative prowess and competitiveness of the industry and its clusters. The analysis draws on evidence from the interviews across the five European clusters. In general, the majority of the European semiconductor industry clusters are long established, with the critical mass tending to centre on an anchor such as a major vertically-integrated manufacturing company or a large government-funded research agency, for example, Leti and STMicroelectronics in Grenoble, Philips in Eindhoven, IMEC in Leuven, Infineon, Bosch, and Siemens in Dresden.

4.1 The nature of the innovation model: a need for more focus on commercialisation

The semiconductor industry is typically characterised by the need for high levels of upfront capital investment, and first-mover advantage can be significant (Peters 2022). It can then be difficult for competitors to catch up once certain firms acquire monopoly power or at least significant market share and scale advantages (Miller 2022a). Moreover, scale advantages can give incumbent firms further advantages in additional technological rounds (Yeung 2022a). Interviewees from the clusters in Europe indicated that self-imposed restrictions and competition regulations mean that many firms in the European industry face major disadvantages to their competitiveness. They indicate that Europe tends to invest significantly more funding in science and technology rather than the further development and commercialisation of this technology compared to other parts of the world, especially North America and Asia.

Indeed, there is little doubt that EU policy is strongly focused on research rather than commercialisation (Radicic and Pugh 2017). As a result, leading industrial clusters tend to receive little explicit public financial assistance. Some exceptions occur with industry engagement in EU-wide programmes such as Horizon 2020 and Digital Europe. According to interviewees, the research outcomes from such projects are often more scholarly than commercial and rarely link to the successful upscaling of industrial partners. A corollary of this process is the view that Europe has successfully developed a cadre of leading researchers, high-quality research infrastructure, and university testing facilities. However, interviewees consider that Europe's lack of commercialisation prowess has limited the transformation of research capability and infrastructure into innovative new businesses. For example, interviewees noted that:

> Europe is tech-savvy. We have top-notch researchers, top-notch research infrastructures, and great universities. The problem is transforming that capability into business, and for the last three decades, when digital really started as an activity, I guess Europe has missed two major waves. (Interviewee 4)

> The strengths of the European industry lie in research rather than commercialisation…. manufacturing, distribution, commercialisation are not the strengths of Europe. (Interviewee 6)

> We have plenty of good ideas. We can innovate in many fields, and we are always working on innovation for our customers today. But we do not have the power or the common will at the national or local level to help that innovation to become a product. (Interviewee 8)

Interviewees were unified in stressing that Europe largely missed the major technology change stemming from personal computing and the success of Intel, Microsoft, Apple, and others in the USA. Similarly, the second wave based on mobile telecommunications technology came to be dominated by Samsung and Apple. Europe's Nokia was clearly in the pack for a number of years but for various reasons lacked the innovative prowess to maintain its position (Gooding 2021). Interviewees argued that the innovation and technological gap among Europe, North America, and Asia can only be closed either by supporting large inward investors to locate in Europe or by enabling European companies to have more independence to grow:

> Europe is pushing far too much money into research programmes and far too little into business development programmes. And to some extent, the excuse for that always seems to be that you cannot state-fund technologies or innovations that are too close to market, because that would be disturbing the market. (Interviewee 4)

> The gap to real leading-edge technology should be closed, either by supporting companies like Intel to come here or by enabling European companies to have more autonomy. Not full autonomy but more autonomy in terms of the value chain. (Interviewee 5)

> In the past, companies like General Electric manufactured just about everything you needed, with their own machines, their own buildings, and their own finance companies. Well, those companies disappeared but maybe they are returning now. Look at what Amazon is doing. Look at what Google is doing, Volkswagen, Apple, Samsung. It looks like [growth] though vertical integration. (Interviewee 7)

In general, interviewees indicated that the European Commission needs to envisage the entire semiconductor value chain in terms of technological sovereignty, geopolitical risks, and ecological reasons. At present, they consider that local networks do not possess the requisite competency in terms of their technological compatibility across clusters. In particular, physical distance in the value chain is perceived to be an issue, which can lead to ineffective collaboration, cooperation, and clustering.

4.2 The openness of the innovation process: the requirement for increased connectivity

According to interviewees, there is growing connectivity across European clusters, partly due to the Silicon Europe Alliance, which was established by the main clusters in Dresden, Grenoble, and Leuven, as well as secondary locations in Graz and Torino. In particular, there are connections among university engineering schools, research institutes, and companies mainly based on European-funded projects. Although there is some industry involvement in these projects, interviewees indicated a requirement to ensure better connectivity across the industry at both European and global levels. A lack of connectivity between elements of the European industry and also their counterparts in the USA and Asia is very apparent according to interviewees and is considered to relate to differing innovation capacities and capabilities, especially in terms of differences in the capability to produce ultrathin chips. A general view is that better connectivity across clusters would improve innovation capabilities and competitiveness:

> There are elements of knowledge and technology sharing, but I would hope that we could build better relationships across clusters to better exploit research programmes that are underway and mainly as a route to scaling up. (Interviewee 2)

> Some of the companies at the bottom of that value chain, especially design tool companies, cannot even have a meaningful conversation among themselves. (Interviewee 4)

> Critical mass that can be achieved by cooperation is crucial for global competitiveness. I always insist that we can only survive globally if we cooperate on a European level. (Interviewee 5)

> The next step will need to be more cooperation between research institutes and companies on a European scale, to get the size that is necessary to make an impact. (Interviewee 6)

Overall, interviewees suggest that there is significant scope for additional collaboration across clusters in terms of knowledge and technology sharing, but given weaknesses in commercialisation, relationships focused on establishing innovation exploitation routes should be further promoted. Alliances are considered to potentially have a strong role to play in terms of stimulating the open innovation and collaboration that produces economies of scale:

> The clusters are mediocre at best. I don't see any really great clusters in Europe with extremely competent people, the top of the crop in terms of technology and business…. We'd like to use Silicon Europe as a platform for the internationalisation of our companies. It's much easier for us to organise something in the USA or in Taiwan or in Japan if we do it together. (Interviewee 4)

> The role of initiatives such as Silicon Europe is to help the SMEs….we can really act as a European ecosystem, which is necessary, because otherwise we are too small. Each of the existing European single ecosystems is too small to be competitive on a global scale. We need the European cooperation. (Interviewee 5)

A number of SMEs have already seen positive outcomes from Silicon Europe, with interviewees indicating that some have forged new innovative partnerships both within and outside of Europe. However, a clear message is that each semiconductor cluster in Europe is too small to compete at the global scale, and if they are to compete globally they need to be better connected. Cooperation and open innovation are considered to be vital for Europe's industry, and having critical mass will be reliant on this cooperation. Interviewees provided examples whereby European clusters are already cooperating and working together at some level, such as in the context of sharing information and intelligence. However, except specific publically-funded projects, there is a lack of large-scale pan-European cooperation that will compete with existing industry groups in the USA and Asia.

As already indicated, scale is clearly a key determinant of success in the industry, and interviewees consider that the approach for Europe is to develop more distributed and networked systems connecting SMEs that can aggregate and consolidate their resources. In general, North America is strong in designing chips and is keen to increase its fab capacity to produce small-density semiconductors (Miller 2022a), while Asia's strength lies in its large-scale manufacturing (Yeung 2022b). Interviewees consider Europe to be a diluted mixture of both and stress that its problems can only be addressed through global partnerships:

> If we need to have a 5-nm industry, I think we need to partner with those who are able to do it. That's my perception, so it's not necessary to recreate something that exists today. So I think we need to keep developing partnerships with the USA and Asia. (Interviewee 3)

Interviewees also argued that EU competition law constrains the European industry in the world market by prohibiting and regulating competition. State aid regulations are viewed as being outdated, with some regulations being adopted at least 30 years ago when the competition across the industry was not so global in its scope. Some interviewees argued that Europe needs to increase manufacturing capacity through the establishment of new foundries and fabs to balance trade and sovereignty. Open access foundries are considered to be an opportunity and an advantage compared with more vertically-integrated and consolidated organisations. To achieve this, however, there is a requirement for greater cross-skilling and more highly-trained mechanical engineers, assembly engineers, and technicians.

4.3 Investment and the protection of knowledge: a lack of capital

This section examines the role and extent of investment, both entrepreneurial and state, in terms of allowing the European semiconductor industry to have access to the required levels and types of investment in order to innovate effectively. Furthermore, issues of scale, the sovereignty of investments, and the nature of investments are considered. An overriding concern of interviewees relates to the lack of sophisticated investors and long-term patient investment in Europe. In particular, there are seen to be very few private equity companies that invest in semiconductor technology as it generally requires heavy and long-term commitments:

> It takes an entrepreneurial spark, which we don't have yet, and it takes links with venture capitalists, which we don't have yet…. [and] the infrastructure for spin-outs with early-stage capital, and we don't have that. (Interviewee 1)

> Clusters are under-financed. Europe is not financing its clusters…. We don't have a lot of capital that is savvy, that is knowledgeable about digital industry, digital economy and that wants to invest in things like deep tech….we have very few private equity companies that actually invest in deep tech. I mean, if you run a fund of €150 million, how on earth can you invest €100 million in a single company? (Interviewee 4)

> We do not have the amount of private risk capital in Europe compared with that available in the USA, and we are not able to invest the level of state capital that is being used in Taiwan or China. (Interviewee 5)

> A major issue is the way to finance innovation. We are seeing many companies with great ideas, but they do not have the means to move forward up to the product level, or they are receiving money from outside Europe. This means the value does not remain in Europe. So when a US-based company or Asian-based company puts the money in, the value is going there…. It's the way you finance the steps between the idea and the product. (Interviewee 8)

As interviewees indicate, investment is very much geared towards research at universities and institutes such as IMEC, with there being a migration of good firms to locations outside of Europe due to a lack of local investment. As indicated earlier, there is also a clear view of the need to invest in the improved commercialisation of innovation, and enhanced collaboration can play a key role in this respect. SMEs in the European industry are not always investment ready (MGI 2022), and interviewees argue that they often tend to be less aggressive in this sense and to be smarter and more eager to undertake high-end innovation.

An allied feature of the investment challenge is the low share of proprietary IP in Europe compared to Asia and the USA (Dornbusch 2018). This is coupled with a lack of high-technology focus in manufacturing more generally and the relative inability to turn strong R&D capability and applied technologies into marketable products (MGI 2022). Interviewees suggest that solutions to addressing these issues lie in the formation of new markets, but they consider that prevalent European state aid regulation limits the capability to establish the incentives for such developments. Interestingly, while the UK has a significant density of semiconductor design firms, even in a post-Brexit world it may need to align itself closely with the EU in order to keep control of its own technological sovereignty, not just in semiconductors but also in areas such as 5G (Moris 2021).

More positively, there is some evidence of growing manufacturing capability such as Bosch's new facility in Silicon Saxony (Ford 2021). However, some interviewees suggest that investing in large foundries would be a knee-jerk reaction to changing geopolitics. Instead, they argue that large-scale EU investment should be focused on designing applications for the industries and products of the future, including microfluidics, photonics, and flexible electronics. These are all new platforms that are emerging in the context of progressing the digital society. An issue with increasing the size of fabs is that high sunk costs make the industry vulnerable to technological shocks (Spinardi 2012). Furthermore, while the industry is often viewed as being locked into the continuing Moore paradigm (see Miller (2022a) for a comprehensive discussion of the evolution of the industry), some interviewees suggest the possibility of a future technological paradigm change:

> There is one school which is saying that we need to continue to invest in technologies that Europe is developing today, and continue to increase capacity. And there is another school that is stating that Europe needs to develop very leading-edge technologies and to develop a value chain for these technologies. (Interviewee 3)

> Quantum is still quite niche at the moment but more funding is being made over time. Collaborative R&D with universities will be very important in this respect especially for experimenting and taking risk. (Interviewee 9)

4.4 Innovation, demand, and the value chain: a lack of sophisticated customers

In this section, consideration is given to issues concerning the manner in which new innovations replace old technologies, especially from the perspective of the nature of demand for semiconductors across European customers. This is mainly because of the lack of significant customers in Europe. Furthermore, while the European Commission has realised the strategic weakness of not having advanced chip manufacturing capabilities, neither does it have the political power of the USA to push TSMC or Samsung to build a new foundry in Europe. The Digital Compass plan, therefore, was developed without perhaps realising the real costs of trying to sustain it.

A general view held by interviewees is that a challenge for Europe is the lack of local demand for leading-edge chips, e.g. from a recognisable European mobile phone or computer producer. The leading companies that provide end-products are no longer located in Europe but instead in China and the USA. Therefore, the demand for semiconductors in Europe is generally less sophisticated than in North America and Asia:

> Almost all consumer electronics are manufactured somewhere in Asia. So the chip production is over there, just like for instance LCD panels or things like that. And which products do we still manufacture within Europe largely? It's like automotive cars, buses, and trucks. So that kind of chip production is still over here…. But if we keep buying iPhones, laptops, computer monitors, and TVs, from Asia, the chip production will stay over there as will the ecosystem. (Interviewee 7)

Nevertheless, Europe does possess relative strengths within the embedded systems and materials sectors, with the main reasons for this being relatively strong industrial sectors that act as application sectors for microelectronics technology (MGI 2022). In basic products, Europe's position in value creation is weakest, and the possibility of future European intersectoral innovation and growth therefore lies in transferring semiconductor-based elements into embedded systems (Van der Velde et al. 2013; MGI 2022). This is a European strength alongside R&D in equipment, materials, and some basic products that lead global markets (Dornbusch 2018).

Finally, interviewees made it clear that the European semiconductor industry should seek to effectively serve key technological areas within which Europe possesses some competitive advantages, for example, automotive, battery technology, health, environment, safety, robotics, energy efficiency, internet developments, and aerospace. They argue that these are key sectors for Europe and are likely to grow fast, so building within these verticals should create further demand for semiconductors:

> I think future-oriented applications in health and bioscience is where things are going to happen. Also, battery technology, for instance, can be a key component for development and more generally societal challenges in health, environment, and safety. (Interviewee 6)

> In order to target the key verticals we have consolidated a number of our internal facilities to achieve economies of scale. (Interviewee 9)

As a means of achieving this, interviewees strongly argued that there is a need for a more integrated European value chain and ecosystem in order to better facilitate pan-European technology transfer:

> Our supply chains are highly fragmented. To go from the wafer right the way through to the end process, you're talking about at least ten to fifteen different processing steps normally by different parts of the supply chain. So they are very large and fragmented supply chains, which incidentally is part of the reason we have a semiconductor shortage right now, because no one really understands exactly how those supply chains work. (Interviewee 2)

> Even if we have a global fair market and global trade works without any geopolitical tensions, you have geophysical risks that can have an impact. Fukushima was an event with a major impact on our industry. So for geophysical reasons, and last but not least, ecological reasons, it makes sense to produce in your own region. Instead of travelling thousands of miles back and forth it makes sense to have semiconductor production in Europe. (Interviewee 5)

> We need to be able to interface ourselves with silicon foundries all over the world, and also be able to work with people, experts in packaging and in testing, in order to provide our customers, even in production, with devices ready to use in their application. (Interviewee 8)

> Huawei has started to secure parts of our supply chain, which is already vulnerable to single-point failure. Just replicating the capacity of fabs globally is a waste of money. (Interview 10)

5. Public policy considerations

In order to consider the potential public policy recommendations that may address the erosion of competitiveness across Europe's semiconductor industry it is necessary to interpret the analysis presented earlier. Overall, the analysis indicates that the problems stem from two interrelated structural factors: (1) the structure, both organisationally and geographically, of the industry and (2) the structure of the wider

European technology industry, especially in relation to consumer electronics and information and communication technologies. The analysis indicates that these factors have led to significant limitations and reduced the relative innovative prowess of the industry in Europe.

First, it is clear that the European semiconductor industry has evolved a structure whereby activity is clustered in a limited number of city/regional locations. In general, each of these clusters focuses on various elements of the value chain, but not the value chain as a whole. Furthermore, the industry is dominated by SMEs (Silicon Europe 2022), and these tend to undertake enough innovation to remain financially viable but do not have the capacity to achieve the rates of growth required to compete effectively with global counterparts. According to the above analysis, this has resulted in (1) a lack of investment, (2) a lack of start-up and entrepreneurial activity, and (3) a lack of scaling up.

Although some scholars see the cluster model of structuring as an inherent weakness of the industry, it also provides a significant degree of diversity (Engel 2014, 2015; Ferras-Hernandez and Nylund 2019). However, the innovativeness of the sector is likely to remain limited if this diversity is not coordinated and connected in a cohesive manner, especially across the most significant clusters. In the past, networks such as Silicon Europe have been funded as one-off projects often based on research activity rather than the commercialisation end of the innovation process, which this analysis suggests is in need of significant investment across Europe.

Open innovation processes and knowledge exchange are at the heart of modern technological innovation (Huizingh 2011; West and Bogers 2014; Chesbrough 2017), and even in an industry such as the semiconductor sector—whereby proprietorial knowledge is often a key factor in maintaining competitive advantage (DiBiaggio et al. 2014)—and in Europe, there is a need to foster more meaningful networking across the industry, as well as other segments of the technology sector (Kapoor and McGrath 2014; MGI 2022). This suggests that networks such as the Silicon Europe organisation should be at the centre of efforts to encourage more cooperation and coordination across Europe's key actors. This is likely to assist in generating some of the results from open innovation practices that have been achieved in other industries (West and Bogers 2014; Chesbrough 2017; Huggins and Thompson 2017). Although a pan-European semiconductor ecosystem may seem an unachievable goal, given the current state-of-play, without a push towards this remodelling the erosion of the industry is likely to continue.

Second, the European semiconductor sector has undoubtedly suffered from the fragmented nature of the technology industry in Europe as a whole. This is most manifest in the lack of demand for the most cutting-edge semiconductor technology by the producers of consumer durables and the like. One upshot of this is that innovative firms and entrepreneurs originally located in Europe often migrate to locations elsewhere, especially the USA (Walsh et al. 2005; Dornbusch 2018; VerWey 2019). Europe has its difficulties in commercialising relevant innovations, and typically, semiconductor manufacturing requires a significant investment to start with and continuous consistent finance and human capital to sustain it. Indeed, this is the main reason that the semiconductor manufacturing has become so highly consolidated in the past few decades (Yeung 2022a,b).

In order to compete and grow effectively, Europe's technology industry requires significant restructuring. At present, it has become too dependent on digital technologies based on the development of new mobile applications and the like (European Commission 2018; MGI 2022). These technologies have given significant vibrancy to many locations around Europe, particularly large capital cities such as London, Paris, and Berlin, and they have successfully attracted significant financing from venture capitalists, many of which are based in these same cities (Chen et al. 2010; Florida and Mellander 2017; Adler and Florida 2021). In the longer term, the European technology industry needs to become more balanced in terms of support for both digital technology applications and enabling technologies such as semiconductors. It may be no coincidence that Europe's semiconductor clusters are located in more provincial cities and regions, which are perhaps beyond the radar of private-sector investors. Either way, there is no doubt that there should be more visibility given to the significance of enabling technologies such as semiconductors as they are the long-term drivers of the innovations generated by other parts of the technology industry (Nambisan et al. 2019). Unless this is achieved, Europe's semiconductor industry is likely to become increasingly hollowed out.

Addressing the structural factors indicated earlier is likely to be reliant on changes in the nature of public policy and the use and targeting of public investment. It is heartening, therefore, to note that the EU has started to recognise both the economic and societal importance of the semiconductor industry through its European Chips Act (European Commission 2022). Also, national governments, such as those in the UK, are beginning to consider new policy decisions regarding the technological sovereignty of the industry. These are all positive developments, but the crux of the matter for ensuring the rejuvenation of the sector lies in the nature of these policies and investments. In other words, it is vital that the European Chips Act and the associated national and regional government intervention focus on the primary challenges that the industry is facing in its bid to grow and improve competitiveness. Based on the above analysis, five interrelated policy and investment areas are key factors to realising this.

5.1 Cluster development

Europe's existing semiconductor clusters are necessarily the industry's strength. It has now become transparent that these clusters are a crucial asset for Europe's technology industry as a whole. Therefore, they should be supported in ways through which they can become more meaningfully innovative through public investment in human capital and skills development, business support, and infrastructure development, as well as the following four policy areas.

5.2 Industry integration

Although Europe's semiconductor clusters are the industry's strength, in order to thrive, there is a requirement for sustained support and investment that generates greater cooperation, coordination, and connectivity. The value chains across the semiconductor industry are sophisticated and complex, and efforts to build greater integration will support the promotion of these value chains within Europe—including non-EU nations such as the UK—and a culture based on the ethos of open innovation and knowledge exchange.

5.3 Commercialisation and IP protection

The European semiconductor industry has significant strengths with regard to its innovation capability. However, much of this lies 'upstream' and within the research undertaken by leading universities and research institutes across Europe. These have often benefitted from the lion's share of the public funding and investment provided to the industry, especially that related to European Commission programmes. It is clear that it is often easier for governments to provide funding to universities, research institutes, and the like, rather than directly to companies, whereby issues of competition regulation and state aid are involved. This approach tends to limit the rate of commercialisation of the research undertaken within Europe and the protection of the IP that underlies these innovative activities. Although wholesale changes are likely to be difficult to implement in this area of funding, it is recommended that existing funding programmes place a stronger emphasis on the potential routes to the commercialisation of R&D projects.

5.4 Signals for private-sector investment

A lack of venture capital, along with investment in general—especially compared to that available in North America—is further limiting the commercialisation issues indicated earlier and is prohibiting the growth of the key clusters. As already noted, the industry is a complex one that is often located in cities and regions without a preponderance of venture capital or other sources of entrepreneurial finance. In this respect, clusters and their key actors could benefit greatly from support in making stronger and more enduring connections with relevant financial communities. These connections can be used to act as signals to these communities of the potential opportunities to invest in leading enabling technologies.

5.5 Start-ups and scaling up

Perhaps, the most important ingredient for ensuring a successful future for Europe's semiconductor industry—at the least in the medium term—is to generate new companies with leading innovations and to scale up these businesses to grow and become global leaders. All of the four factors highlighted earlier will go some way to supporting this development, but it is clear that there is a requirement for specific entrepreneurial support across Europe's industry. Start-ups within clusters remain limited, and incumbent companies do not appear to realise their growth potential. Furthermore, spinout firms from universities and research institutes are relatively infrequent. Given this, an important component of the 'cluster development' recommendations indicated earlier should be used to support new or 'would-be' entrepreneurs. Entrepreneurship is likely to be more complex and investment-heavy than in many other tech areas and will require an ecosystem of support that draws upon the array of the necessary resources and skills needed to establish and grow an innovative business. This needs a significant degree of policy intelligence in terms of correctly targeting the appropriate segments of the industry, and design firms appear to be the best initial opportunity to develop economies of scale across clusters and within their ecosystems.

The EU's (European Commission 2022) Chips Act mentions the majority of the factors mentioned earlier, which is clearly a step in the right direction. However, questions remain as to whether or not these microeconomic policy challenges will receive the due attention and funding they require, or will instead the policy focus concern factors such as trade protection, especially relating to exports to China. Some commentators suggest that the Chips Act is overly focused on seeking to control international supply chains rather than addressing the more fundamental issues highlighted earlier (Miller 2022b). Similarly, others have concluded that the EU's bid for 'chip nationalism' is folly and that the Chips Act will not have the financial capacity to support the regeneration of the niches and specialisms contained within Europe's semiconductor clusters (Meyers 2022). If these scenarios come to pass, it is clear that despite the policy rhetoric of enhanced entrepreneurship and innovation within the Chips Act, its impact on these measures is likely to be relatively weak and much more diluted than is required. Furthermore, while a degree of sovereignty and self-sufficiency may improve competitiveness, at least in the short term, this is likely to have a negative impact on the types of open innovation and connectivity that will be at the heart of determining the long-term future of the industry across Europe.

As mentioned earlier, the Chips Act and future interventions need to give serious consideration to temporal issues by addressing the rather fine balancing act of accounting for both short- and long-term challenges. In practical terms, this requires that the funding available for addressing the innovation challenge will need to be administered and distributed in a manner that will best ensure its maximum impact. To achieve this, there should be a strong element within the Chips Act that, especially concerning the Chips Fund and the Chips for Europe initiative, is focused on robustly monitoring and evaluating the impact of assistance provided for innovation, particularly funding for R&D, upskilling, and human capital development. Measuring the impact of these public investments is difficult because they are often intangible assets and are utilised through complex decision-making processes (Montresor and Vezzani 2016). Therefore, the value of such investments is not always easily visible or immediately apparent as they are absorbed either directly or indirectly within firms and research organisations (Orlic et al. 2019; Mulligan et al. 2022). This can lead to issues with regard to measuring the achievements of interventions, i.e. the additional value that has been accrued as opposed to what would have occurred in any case through existing resources or shifting these resources from one organisation and/or location to another, i.e. deadweight or displacement effects (Lenihan and Hart 2006).

Without the ability to rigorously evaluate the impact of interventions, the resulting lack of clarity may lead to policymakers withdrawing future finance. Finally, as well as evaluating the impact of funding, the intervention itself must be targeted at those firms and research organisations in the semiconductor industry that possess traits that Lenihan et al. (2019) describe as being 'motivationally relevant elements' of human capital and related innovation activity. In other words, in order to avoid the wastage of limited resources, they should be targeted at decision makers that are committed to positive change and addressing the current limitations of Europe's semiconductor industry.

6. Conclusion

In the context of the relative decline of the European semiconductor industry over the last 30 years, this paper has examined the extent to which the structure of Europe's semiconductor industry is fit for purpose to achieve the required rates and forms of innovation to compete globally. Theoretically, it has developed a contemporary extension of the Schumpeterian growth model, principally through the addition of the notion of 'open innovation' to address the importance of networks across firms, organisations, and places. These networks are particularly relevant to a high-technology industry such as semiconductors, given that there is a significant level of interdependency across firms operating within complex supply chains. Furthermore, the industry is spatially concentrated with activity taking place within a discrete number of regional clusters, and such clusters not only contain their own intra-regional networks but also require connectivity to knowledge for innovation through inter-regional clusters.

Interestingly, the adoption of an open innovation conceptualisation of competition runs somewhat counter to those of policymakers in both Europe and the USA. Both are formulating competitiveness interventions from the perspective of trade restriction across supply chains, which is likely to result in more closed forms of innovation across the industry. This paper has argued that the European industry has already suffered from a lack of connectivity coupled with a lack of investment and high-grade demand from European customers. It is to be hoped that elements of the European Chips Act will begin to address these concerns. However, there is also a real concern that other elements of the European Chips Act related to supply chain control and restriction will actually have the opposite impact. Due to the closing of supply chains, the industry may become even less innovative and competitive over time and, therefore, less able to access the investment and entrepreneurship it requires.

In summary, this paper provides a case study of the challenges the European semiconductor industry faces in the light of heightened global competition. It has achieved this principally through a qualitative methodological approach coupled with a range of related secondary data. It largely reports and analyses the viewpoints of those operating within the key clusters across Europe. Potentially, this could contain some limitations as views may differ across other parts of the semiconductor value chain. However, this does not compromise the validity or reliability of the grounded analysis stemming from the cluster-level data. Indeed, the interviews undertaken as part of the case study suggest that the growth and competitiveness challenges raised are also likely to extend to other areas of high-technology economic activity in Europe (MGI 2022).

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