The Future of Europe's Semiconductor Industry:
Innovation, Clusters and Deep Tech

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Executive Summary:

One of the fallouts from the COVID-19 pandemic is that semiconductors have become a hotly debated and analysed industry. As a result of these developments it has become apparent that the European semiconductor industry has been in relative decline for at least 30 years.

Against this backdrop national governments in Europe and the European Commission have started to reconsider the strategic importance of the semiconductor industry and the sovereignty of its assets, both tangible and intangible. Given this, the aim of this report - which forms part of the CSconnected initiative funded by the UKRI's Strength in Places Programme - is to examine the current state of Europe's semiconductor industry and to assess its potential future.

The core of the analysis stems from data gathered from expert informants across five of Europe's leading clusters, namely those located in Leuven (Belgium); Dresden (Germany); Eindhoven (Netherlands); Grenoble (France); and Cardiff (UK).

The report finds that the massive decline of the European semiconductor industry has been partly due to the structural changes occurring across the industry, especially in terms of patterns of consolidation and the growing requirements for critical mass across the value chain.

Compared to operations in North America and Asia, the European industry has become relatively less innovative and less able to access the investment and entrepreneurship required to innovate.

The above problems stem from three interrelated structural factors: (1) the structure – both organisationally and geographically – of the industry; (2) the structure of the wider European technology industry, especially in relation to digital technologies and consumer electronics; and (3) the structure of public policy interventions and investments. All of these factors have led to significant limitations and reduced the relative innovative prowess of the industry in Europe.

The industry is dominated by SMEs clustered in a limited number of city/regional locations that tend to undertake enough innovation in order to remain financially viable. However, they do not have the capacity to achieve the rates of growth required to compete effectively with counterparts elsewhere in the world. This has resulted in (1) a lack of investment; (2) the lack of start-up and entrepreneurial activity; and (3) a lack of scaling-up.

Although some commentators see the cluster model of structuring as an inherent weakness of the industry, it does provide a significant degree of diversity. However, the innovativeness of the sector will remain limited if this diversity is not coordinated and connected in a cohesive manner, particularly across the most significant clusters.

There is a need in Europe to foster more meaningful networking across the industry as well as other segments of the technology sector. Networks such as the Silicon Europe organisation should be at the centre of encouraging more cooperation and coordination across Europe's key actors.

The European semiconductor sector has suffered from the fragmented nature of Europe's technology industry as whole. This is most manifest by the lack of demand for the most cutting edge semiconductor technology by the producers of consumer durables and the like.

In order compete effectively Europe's technology industry requires significant restructuring. At present it is far too dependent on 'shallow' technologies based around the development of new mobile applications. In the longer-term the European technology industry needs to become more balanced in terms of support for both shallow and deep technologies.

It is concluded that national and regional governments, as well as the European Commission, should focus on the following five interrelated policy and investment areas:

Cluster Development – foster more meaningful innovation through public investment in human capital and skills development, business support and infrastructure development.

Industry Integration –build greater integration across value chains within Europe – including non-EU nations such as the UK - based around an ethos of open innovation and knowledge exchange.

Commercialisation and IP Protection –existing public funding programmes should place a stronger emphasis on the potential routes to the commercialisation of R&D projects.

Signals for Private Sector Investment –clusters and their key actors could benefit greatly from having support to make stronger and more enduring connections with relevant finance communities, which can be used to act as investment signals to these communities.

Start-Ups and Scaling Up - the focus of intervention should be to generate new companies with leading innovations and to scale-up these businesses to grow and become global leaders.

1. Introduction

Semiconductors, also referred as chips or integrated circuits (IC), are the hardware used as a basis for all information technology. They are essential for most modern technologies ranging from smartphones and computers to automobiles and medical devices. The production process is acknowledged to be one of most complex and knowledge intensive manufacturing processes in existence. Despite this, for the last 30 years or more the production of semiconductors has been an industry that has been rather taken for granted by policymakers, investors, and technology commentators who have tended to show a preference for the seemingly more 'glamorous' 'glamorous' and accessible consumer electronics, digital technology industries as well as high-technology services more generally. This is rather ironic given that these industries are highly dependent on the hardware underpinning the services and software these industries rely, in particular the semiconductors that allow these goods and services to perform with increasing efficiency and speed.

1.1. Context

In a change to the relative indifference to the semiconductor industry, one of the fallouts from the COVID-19 pandemic that started in 2020 has resulted in semiconductors becoming a hotly debated and analysed industry. In large part this stems from the global shortage of semiconductor supplies for many consumer products. At this time there was a renewed understanding and interest in the complexities associated with semiconductor production, and the realisation that this area of deep technology is in many ways fundamental to the effective operation of contemporary society and its economy. This is particularly the case in Europe, including non-EU nations such as the UK, whereby shortages produced bottlenecks within many industries.

As a result of these developments it has become apparent that the European semiconductor industry has seen a significant relative decline for at least 30 years at the expense of the growth of the industry elsewhere, principally North America and Asia. 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 European Union (EU) has pledged to make significant funding available to the industry – to the proposed tune of EUR145 billion – although it is unclear as to how and where this funding will be utilised.

1.2. The Aim of this Report

Given the issues indicated above, the aim of this report - which forms part of the CSconnected initiative funded by the UKRI's Strength in Places Programme - is to examine the current state of Europe's semiconductor industry and to assess its potential future. It focuses on competition and the nature of innovation, and explores how fit-for-purpose the European semiconductor industry's value chain is. It further addresses issues of scale, sovereignty and integration across the industry, as well as factors concerning investment in innovation. As well as these more market oriented issues, it also considers network factors and the role for open innovation practices and collaboration, and the potential for these practices to improve the innovative prowess and competitiveness of the industry in Europe.

As the report illustrates, the structure of the industry in Europe is such that activity is very much clustered around a small number of key locations, and accordingly the core of the analysis stems from data gathered from informants across five of Europe's leading clusters, namely those located in Leuven (Belgium); Dresden (Germany); Eindhoven (Netherlands); Grenoble (France); and Cardiff (UK). The original methodological plan was to undertake field study visits to each of the locations, with the hope being that the pandemic would have abated and travel to them would be possible. In reality travel has remained curtailed and as a contingency measure interviews were undertaken online. In-depth interviews were undertaken with leading representatives of each of the clusters, covering the CEO/managing director of the formal cluster organisation as well as another individual representing a prominent cluster member. Interviews were recorded and transcribed, with 11 interviewees providing relevant information. Within the report the empirical evidence is supplemented with other market data outlining the nature of the industry. The report begins by providing an overview of the industry and its clusters before moving on to an analysis of the key challenges and issues being faced. In the concluding section recommendations are made as to how these challenges can be addressed with a view to rebuilding Europe's semiconductor industry.

2. The European Semiconductor Industry

2.1. Key Global Locations

In terms of examining the semiconductor industry it is important to consider the four general steps that are involved, consisting: Research and Development (R&D), design, manufacturing, and Assembly, Test and Package (ATP) (VerWey, 2019). An integrated device manufacturer (IDM) conducts all four steps, which is undertaken by large players such as Intel or Samsung. Firms that specialise in design only are called 'fabless', which is an increasing feature in the industry. Firms that carry out manufacturing without any of the other four steps are known as foundries. ATP accounts for only 10% of the total value created along the semiconductor's value chain, with 45% of the value realised in manufacturing and another 45% through R&D and design (King, 2003). There are also other types of semiconductor firms with further specialisation in the value chain, including semiconductor manufacturing equipment, outsourced semiconductor assembly & test (OSAT), electronic design automation (EDA), 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 United States, manufactured in Taiwan, tested and assembled in China (USITC, 2017).

In general, the semiconductor industry has become increasingly mature and consolidated, with a small number of large firms from Europe, US and East Asia dominating most of the segments on the value chain (see Table 1). This is further consolidated by semiconductor industry's high barriers, including high fixed capital expenditure as the most important factor, also first mover advantages, economies of scale, brand recognition, stickiness and customer loyalty, and intellectual property (King, 2003). The cost of establishing a leading-edge semiconductor manufacturing firm has become prohibitive but for a few largest firms as the industry approaches the limits of Moore's Law (VerWey, 2019). The expenses related to 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, R&D, design, and manufacturing. This model has further reduced the number of firms who are able to fabricate cutting-edge chips, or alter the prevalent model to a new one in the industry.

Table 1: European, North American, and Asian Semiconductor Industries

Semiconductor industries	European	North American	Asian
Size in 2019	10% of global production	US accounts for 48% of the global supply, 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 healthcare	R&D and Intellectual Property in semiconductors, chip and electronic design, software, automation	Around two thirds 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 AMAT Broadcom Qualcomm Texas Instruments Nvidia Lam Research Western Digital AMD	Samsung Electronics TSMC SK Hynix ASE Technology Holding TEL Sony Kioxia Holdings MediaTek HiSilicon Renesas Electronics

Source: Cerulus, 2021; Deloitte, 2020; Dornbusch, 2018; SIA, 2020; Widmann, 2021; interviews by authors

2.2. The European Industry

In 1990, European firms accounted for 44% of the global chip manufacturing market according to Boston Consulting Group, particularly because of the early mobile phone market success in Europe, including Ericsson, Nokia and Siemens. However, the emergence of smart phones and lower unit labour costs in the emerging market have attracted manufacturers out of Europe and resulting in many European businesses being behind (Gooding, 2021). Taking patents as an indicator for a country's performance in the production of new technological knowledge (Engel, 2014), Europe's share declined markedly and was forced to focus on market niches that others were less interested in. However, over time it has built competencies in those marketplaces, including automotive, power electronics and micro-electromechanical systems.

As shown by Table 2, only four of the top global semiconductor companies by revenue are based in Europe. 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 European Union pose an additional 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. This shows that some of the countries may be pure electronic manufacturing spots outside of semiconductors, instead of having a focus on knowledge and advanced manufacturing production (Dornbusch, 2018).

Table 2: Top 20 Global Semiconductor Companies by Revenue in 2019

	Company	Country	Business model	2019 revenue
1	Intel	U.S.	IDM	US$65.8Bn
2	Samsung Electronics	South Korea	IDM	US$52.2Bn
3	TSMC	Taiwan	Contract foundry	US$35.8Bn
4	SK Hynix	South Korea	IDM	US$22.4Bn
5	Micron	U.S.	IDM	US$20.0Bn
6	AMAT (Applied Materials)	U.S.	SME	US$17.2Bn
7	Broadcom	U.S.	Fabless	US$15.3Bn

	Company	Country	Business model	2019 revenue
8	ASE Technology Holding (*SPIL included)	Taiwan	OSAT	US$13.8Bn
9	Qualcomm	U.S.	Fabless	US$13.5Bn
10	Texas Instruments	U.S.	IDM	US$13.2Bn
11	ASML Holding	Netherlands	SME	US$13.2Bn
12	Nvidia	U.S.	Fabless	US$10.9Bn
13	TEL (Tokyo Electron)	Japan	SME	US$10.4Bn
14	Lam Research	U.S.	SME	US$10.0Bn
15	Sony	Japan	IDM	US$9.8Bn
16	STMicroelectronics	France, Italy	IDM	US$9.0Bn
17	Infineon Technologies	Germany	IDM	US$8.9Bn
18	Kioxia Holdings	Japan	IDM	US$8.8Bn
19	NXP Semiconductors	Netherlands	IDM	US$8.7Bn
20	MediaTek	Taiwan	Fabless	US$8.2Bn

Source, Institut Montaigne, Gartner (Cerulus, 2021)

Partly as a response to the decline, the EU aims to produce the next generation leading-edge chips (2nm) by 2030. This is a rather ambitious goal and has not yet been reached by Taiwan's TSMC. The main European chip designers, such as NXP Semiconductors and Infineon Technologies, outsource most of their production to TSMC and other foundries (Bloomberg, 2021). In 2014, Europe's supply in 300mm wafer chip manufacturing was 2% and only half of that was manufactured onshore in Europe. The situation has deteriorated over the following years, and the vulnerability of global supply chains and semiconductor shortages have been highlighted by the Covid-19 pandemic (Clark, 2020).

In relation to innovation, R&D is mainly conducted in the headquarters locations or where the markets are located. Clearly, the semiconductor market has shifted to East Asia, and more R&D activities are likely to follow to these locations. This is a serious long term concern. Closing production sites due to lack of relevant investment will further result in a loss of human resources, know-how and equipment, which is difficult to regain. Consequently, the loss of production and employment will deepen existing fractures and cause further missing links to the global micro-electronics related value chain (Dornbusch, 2018).

Finally, the cumulative investment into deep tech companies in Europe surpassed US$36bn in 2016. But while investments have grown significantly over recent years in Europe, European deep tech investments are still far less than those in US and China. These two countries combined accounted for 81% of global private deep tech investments between 2015 and 2018 (Dealroom and Sifted, 2021).

2.3. Europe's Semiconductor Clusters

In this section we briefly introduce five key existing European semiconductors clusters focused on silicon based 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 CS Connected, which is largely located in Cardiff (UK). The key characteristics of each of these clusters is summarised in Table 3.

In terms of DSP Valley, the city of Leuven is relatively small (pop. c.100,000). However, it has a large international university and highly developed knowledge institutions and knowledge enterprises. In addition to being a renowned knowledge centre (e.g. Leuven Knowledge Pearl), the region has also become known for its active policy with regards 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 micro-electronics and nanotechnology is concentrated at the Catholic University of Louvain (KU Leuven) and IMEC (the Interuniversity Centre of Micro-Electronics), which has links to the University.

Dresden (pop. c. 550,000), the main location for Silicon Saxony, is the capital city of the Free State of Saxony in Germany. Over the last few decades, it has evolved into a highly attractive location for enterprises and jobs, especially in the semiconductor industry. An impressive array of semiconductor, electronic and micro-electronics industries are now clustered in the region, with it gaining a reputation as 'Silicon Saxony'. Under the support of local and regional governments, Dresden is home to Europe's largest and most successful trade association for the micro-electronics 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. Within the network are big corporations such as AMD (Globalfoundries), Infineon, Siltronic, ZMD (Zentrum Mikroelektronik Dresden) and AMTC (Advanced Mask Technology Centre Verwaltungs GmbH).

High Tech NL is located at Eindhoven (pop. c. 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 invests more than €2 billion annually in R&D activities, accounting for nearly 30% of total Dutch R&D expenditure and 45% of the R&D expenditure of Dutch based firms (Haarsma, 2008). Companies in the region are not only more R&D-intensive than those located elsewhere in the country, but also are more likely to focus on high technologies. Approximately a quarter of Eindhoven's companies fall within the category of high-tech firms, compared to a national average of only 12% (Hulsink et al., 2007).

Grenoble (pop. c. 155,000), the home of the Minalogic cluster, is a city in south eastern France situated at the foot of the French Alps, which has led to it becoming 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% 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 18 'global competitiveness clusters', or 'pôle de compétitivité', which aim to bring together firms, research laboratories and educational establishments in a specific region to develop synergies and cooperative efforts.

The newest cluster, CS Connected in Cardiff (pop. c. 370,000), originally stemmed from a joint venture agreement between Cardiff University and IQE - a leading global supplier of advanced compound semiconductor wafer products covering a diverse range of applications, supported by an outsourced foundry services portfolio that provides a 'one stop shop' for the wafer needs of the world's leading semiconductor manufacturers 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 home 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 to develop innovative new materials technologies that will enable a wide range of new and emerging applications. Since 2015 the cluster has rapidly expanded to form an emergent regional ecosystem within significant interdependencies across a range of organisations across the private sector, public sector, and academic and research organisations.

Table 3: Key Characteristics and Features of the 5 European Clusters

European semiconductor clusters	Main location and cluster age	Number of members	Key characteristics and features
Minalogic	Grenoble (France), 16 years	c. 500	60% private funded, the rest public funded Start-ups, SMEs and large groups Microelectronic, ECHO system, photonics, infrared image sensors software, artificial intelligence video, virtual reality animation and video gaming Positioning on innovation
Silicon Saxony	Dresden (Germany), organisation-20 years, cluster-more than 40 years	c. 250	Private funded Four major semiconductor fabs: Infineon, GlobalFoundries, X-FAB and Bosch fab Those 4 firms are anchor companies for the cluster and ecosystem, and do extremely well
DSP Valley	Leuven (Belgium), over 20 years	125	Mainly SMEs Nanotechnology, design tools, chips, equipment and materials for foundries, digital ecosystem, digital value chain, artificial intelligence, data, cloud computers, etc., foundations of digital technology all the way into applications Four domains of particular interest: smart mobility, smart city applications, smart industry and smart health tech applications

High Tech NL (Holland Semiconductors)	Eindhoven (Netherlands), 8 years	80	Constitutes of SME companies, Original Equipment Manufacturer companies and knowledge institutes The major company is ASML, currently creating the lithography machines for the front end Machine builders for the back end such as NXP
CS Connected	South Wales (UK), 6 years	15	The world's first compound semiconductor cluster Full supply chain, represents organisations who are directly associated with compound semiconductor related technologies, equipment manufacture, and whose products and services are enabled by compound semiconductors

Data source: interviews by authors, supplemented by official website information from each cluster

3. Innovation, Competition and Growth

In terms of generating long-run growth from innovations, this section examines the innovative and competitive capacity and capability of the European semiconductor industry, and draws on the evidence from the interviews across the five European clusters. In particular, it explores the industry's engagement in open innovation and collaborative practices, and the extent to which these practices impact on the innovative prowess and competitiveness of the industry and its clusters.

In general, 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 such as Leti and STMicroelectronics in Grenoble, Philips in Eindhoven, IMEC in Leuven, Infineon, Bosch and Siemens in Dresden. However, only during the COVID-19 pandemic and resulting strong demand for semiconductors set aside supply constraints, have European economies increasingly recognised the industry's strategic importance. More consideration has now been given for the need for strong financial support from national governments and the European Union to maximize the potential for future macroeconomic growth. Like other deep tech industries, the semiconductor sector requires longer terms of investment, longer R&D phases and more support to develop technical staff, hardware equipment and intellectual properties. However, once they reach the growth stage, they are likely to grow much faster than other tech firms and with real dividends for host economies (Dealroom and Sifted, 2021).

3.1. A Focus on Research Rather Than Commercialisation

The semiconductor industry is typically characterised by the need for high levels of upfront capital investment. First mover advantage can be significant. 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. Moreover, scale advantages can give incumbent firms advantages in further technological rounds. It should also be recognised that the global semiconductor market is not always a level playing field (Dornbusch, 2018). Interviewees in Europe indicated that self-imposed restrictions and competition regulations mean that many firms in the European industry face major disadvantages to their competitiveness. Our interviewees indicated that Europe tends to invest much more funds in science and technology rather than the further development and commercialisation of this technology compared to other parts of world, especially North America and Asia.

There is little doubt that EU policy is strongly focused on research rather than commercialisation. As a result the leading industrial clusters tend to receive little explicit public financial assistance. Some exceptions occur with industry engagement of EU-wide programmes such as Horizon 2020 and Digital Europe. Unfortunately the research outcomes from such projects are often more scholarly than commercial, and rarely link to any successful up-scaling of industrial partners with considerable potential. A corollary of the process is that Europe has successfully developed a cadre of leading researchers, high quality research infrastructure and university testing facilities. But 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 infrastructure, 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.'

> 'The strengths of the European industry lie in research rather than commercialisation.... manufacturing, distribution, commercialisation are not the strengths of Europe.'

> '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.'

> 'Not having a production Fab hurts us, and takes out a lot of the value added processes we undertake.'

3.2. The Need for Better Connectivity within Europe's Value Chain

Our respondents were unified in stressing that Europe largely missed the major technology change stemming from personal computing, and it was at that time that the success of Intel, Microsoft, Apple and others in US was reinforced. Similarly, the second wave of 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). In general the respondents argued that the innovation and technological gap between Europe and North American, Asia can only be closed either by supporting companies large inward investors to locate in Europe or by enabling European companies 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.’

> ‘The gap to real leading-edge technology should be closed, either by supporting companies like Intel to come here or to enable European companies more autonomy. Not full autonomy but more autonomy in terms of the value chain.’

> ‘In the past, companies like General Electric manufactured just about everything you needed, with their own machines, their own buildings, 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.’

Interviewees suggested that the European Commission needs to envisage the entire semiconductor value chain for technological sovereignty, geopolitical risks and ecological reasons. At present, 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 an issue, which can lead to ineffective collaboration, cooperation and clustering.

There is growing connectivity across European clusters, partly due to the Silicon Europe alliance which was established by the main clusters in Dresden, Grenoble, Leuven, as well as secondary locations in Graz and Torino. In particular, there are connections between 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 a European and global level. A lack of connectivity between elements of the European industry and then their counterparts in the US and Asia is very apparent, and relates to differing innovation capacities and capabilities, especially in terms of differences in capacity to produce ultra-thin chips. A general view across interviewees 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 exploitation routes for the research programmes that are underway and mainly as a route to scaling up.’

> ‘Some of the companies at the bottom of that value chain, especially design tool companies, cannot even have a meaningful conversation amongst themselves.’

> ‘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.’

> ‘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.’

3.3. Scope for Increased Collaboration across Clusters

As indicated above, there appears to be significant scope for collaboration across clusters in terms of knowledge and technology-sharing. Given the apparent weaknesses in commercialisation, relationships focused on establishing innovation exploitation routes should be further promoted. The Silicon Europe alliance potentially has a strong role to play in terms of stimulating open innovation and collaboration, and producing economies of scale:

> ‘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 United States or in Taiwan or in Japan if we do it together.’

> ‘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.’

A number of SMEs have already seen positive outcomes from Silicon Europe in terms of forging new innovative partnerships both within and outside of Europe. A clear message is that each semiconductor cluster in Europe it 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 is vital for Europe’s industry, and critical mass will be reliant on this cooperation. European clusters are already cooperating and working together at some level, such as in the context of sharing information and intelligence, but excepting specific publically funding projects there is a lack of large scale pan-European cooperation that will work to threaten existing industry groups in the US and Asia.

An emerging positive has been 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, amongst 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 achieve sufficient scale. It seeks to builds on and to expand collective efforts, and will require investments from the EU budget, national budgets and the private sector (European Commission, 2021).

4. Investment, Scale and Organisation

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 that allow it to innovate effectively. Furthermore, issue of the scale and the sovereignty of both investments and the nature of investments are considered.

4.1. The Investment Gap

An overriding view of interviewees related to the lack of sophisticated investors and long-term patient investment in Europe. Furthermore, there are very few private equity companies that invest in deep technology generally as it 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.’
>
> ‘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 (Euros), how on earth can you invest 100 million (Euros) in a single company?’
>
> ‘We do not have the amount of private risk capital in Europe as available in the US, and we are not able to invest the level of state capital that is being used in Taiwan or China.’
>
> ‘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. That means the value does not remain in Europe. So when a US-based company or Asian-based company put money in, the value is going there....It's the way you finance the steps between the idea and the product.’
>
> ‘The cluster lacks the level of start-up activity and scaling up that takes place in North America. Finance is an issue but the lack of skills is greater.’

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 above, there is also a clear requirement 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 and tend to be less aggressive in this sense, and it is argued that they need to be smarter and more eager to undertake high-end innovation.

4.2. Protecting Europe's Intellectual Property

The low share of proprietary IP in Europe compared to East Asia and US is coupled with the missing strong high-tech focus in manufacturing and the relative inability to turn strong R&D capability and applied technologies into marketable products. Solutions to addressing this appear to lie in the formation of new markets, but the prevalent European state aid regulation limits the capability to establish the incentives for such developments. Interestingly, while the UK has the second-highest number of design companies after the US, even in a post-Brexit world it may need to closely align itself with the EU to keep control of its own technological sovereignty, not just in semiconductors but also areas such as 5G (Moris, 2021).

More positively, there is some growing manufacturing capability such as Bosch's new facility in Silicon Saxony, but 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 around 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. However, much of the industry seems to be locked into the continuing Moore paradigm, while others see 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 leading-edge technology.'
>
> '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.'

Europe only takes up approximately 10% of global semiconductor production (Dornbusch, 2018), below its share of the global economy. The semiconductor industry develops geographically close to its demand. This causes considerable concern that the disparities between Europe and the rest of the world will increase. For the European industry, protection of intellectual property in the semiconductor technology area is vital to ensuring Europe's technology sovereignty and competitiveness.

> 'If you don't own the IP on something, you don't own the process or anything to do with it. And we've seen that with foreign investment in the past....I think sovereign capability is something we really need to make sure that we have control of.'

> 'We had some discussion with companies in China, and we clearly saw that they are coming in order to learn about what we are doing and how we are doing it, but they are not coming here to set up. They are trying to learn and go back to their country with the tricks we are using.'

4.3. The Scale and Location of Manufacturing Capacity

There is also the need to address key environmental and societal challenges and new emerging mass markets, there is a need to strengthen Europe's capacity to develop the next generation of processors and semiconductors. However, Samsung, Intel and TSMC account for approximately 55% of global total capital spending in semiconductors, and they may be the only players that have the capabilities to develop next generation foundries (Dornbusch, 2018). As a result, a key requirement is the need for Europe to have 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 10 to 15 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.'

> '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 as 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.'

> ‘We need to being 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’.

> ‘Huawei have 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’.

Significant scale is a key determinant of success in the semiconductor industry and 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 considered to very strong in designing chips and is keen to increase its fab capacity to produce small density semiconductors, while Asia’s strength lies in its large-scale manufacturing. Europe is considered to be a diluted mixture of both. Interviewees stressed that these problems can only be addressed through global partnerships:

> ‘If we need to have a five nanometre 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 and something that is existing today. So I think we need to keep going developing partnerships with the US and Asia’.

Interviewees also argued that EU competition law constrains the European industry in the world market by overly prohibiting and regulating competition. State aid regulations are seen as being outdated, with some regulation being adopted at least thirty 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 the trade and sovereignty. Open access foundries may be an opportunity and an advantage compared with more vertically integrated consolidated organisations. To achieve this, there is a requirement for greater cross-skilling, and more highly trained mechanical engineers, assembly engineers and technicians.

5. Innovation and Demand

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.

5.1. A Lack of Sophisticated Demand

The European Commission has launched the Digital Compass, a ten-year plan aimed at producing 20% of the world's semiconductors by 2030, and constructing a fabrication to produce superfast, 2 nanometre chips. This policy supports the view that Europe should establish greater technological sovereignty, whereby semiconductors are considered to be a critical technology and as a way to cope with continued global semiconductor supply chain disruptions (Gooding, 2021). However, these policies have been widely criticised for unrealistic goals. This is mainly because of the lack of significant customers in Europe. Furthermore, while the EU has realised the strategic weakness of not having advanced chip manufacturing capabilities, neither does it have the political power of the US to push TSMC or Samsung to build a new foundry in Europe. Then the Digital Compass plan was developed without perhaps realising the real costs of trying to sustain it.

A general finding of this study is that a challenge for Europe is a lack of local demand for leading-edge chips, e.g. a recognisable European mobile phone or computer producer. The leading companies that provide end products are no longer located in Europe, but instead China and US. 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, TVs, from Asia, the chip production will stay over there as will the ecosystem.’

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

5.2. Future Opportunities

From the interviews it is clear that the European semiconductor industry should seek to effectively serve some key technological areas within which Europe possesses some competitive advantages; for example, automotive, battery technology, health, environment, and safety, robotics, energy efficiency, internet developments, aerospace. These are key sectors that are likely to grow fast, and building within those verticals will create 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.'

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

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6. Conclusion: Addressing the Future of Europe's Semiconductor Industry

This report has illustrated the decline of the European semiconductor industry over the last 30 years or more. This decline has been partly due to the structural changes occurring across the industry, especially in terms of consolidation and the growing requirements for critical mass. Operations in North America and Asia have been more successful at adapting to these changing requirements. This has led to the European industry becoming relatively less innovative and less able to access the investment and entrepreneurship required to innovate. The analysis presented above clearly shows that this is related to three interrelated structural factors: (1) the structure – both organisationally and geographically – of the industry; (2) the structure of the wider European technology industry, especially in relation to consumer electronics and ICTs; and (3) the structure of public policy interventions and investments. The analysis has indicated that all of these factors have led to significant limitations and reduced the relative innovative prowess of the industry in Europe. Although this report only addresses issues relating to semiconductors, the interviews undertaken as part of the research suggest that these limitations are also likely to extend other areas of deep tech economic activity in Europe. The remainder of this section focuses on considering as to how Europe's semiconductor can best regenerate itself.

6.1. Addressing Structural Issues

Over many years the European semiconductor industry has evolved into a structure whereby activity is clustered in a limited number of city/regional locations across five or more nations. Each of these clusters focus on various elements of the value chain, but not the value chain as a whole. Furthermore, the industry is dominated by SMEs that tend to undertake enough innovation in order to remain financially viable but do not have the capacity to achieve the rates of growth required to compete effectively with global counterparts. This has resulted in (1) a lack of investment; (2) the lack of start-up and entrepreneurial activity; and (3) a lack of scaling up. Although some commentators see the cluster model of structuring as an inherent weakness of the industry, it does provide a significant degree of diversity. However, the innovativeness of the sector will remain limited if this diversity is not coordinated and connected in a cohesive manner, particularly 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 report has indicated is in need of significant investment across Europe.

Open innovation processes and knowledge exchange are at the heart of technological innovation, and even in an industry such as the semiconductor sector – whereby proprietorial knowledge is often a key factor in maintaining competitive advantage – there is a need, at least in Europe, to foster more meaningful networking across the industry as well as other segments of the technology sector. This report suggests that networks such as the Silicon Europe organisation should be at the centre of encouraging more cooperation and coordination across Europe's key actors. This would help generate some of the results from open innovation practices that have been achieved in other industries. Although a pan-European semiconductor ecosystem may seem an unachievable goal, given the current state-of-play, without a push toward this re-modelling we consider that the erosion of the industry is likely to continue.

6.2. Addressing the European Technology Industry

The European semiconductor sector has undoubtedly suffered from the fragmented nature of the technology industry as whole. As the analysis illustrates this is most manifest by 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 US. Europe clearly has its difficulties in commercialising relevant innovations, and typically semiconductor manufacturing requires enormous investment to start with, and continuous consistent monetary 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.

In order to compete effectively Europe's technology industry requires significant restructuring. At present it is far too dependent on 'shallow' technologies based around the development of new mobile applications and the like. 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. We recommend that in the longer-term the European technology industry needs to become more balanced in terms of support for both shallow and deep technologies. 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 semiconductors and other deep tech areas, as they are the long-term drivers of the innovations generated by other part of the technology industry. Unless this is achieved Europe's semiconductor industry and deep tech more generally is likely to become increasingly hollowed out.

6.3. Addressing Public Policy and Investment

Much of the two changes in structural factors indicated above are likely to be reliant on changes in the nature of public policy and the use and targeting of public investment. It is, therefore, heartening to know that the European Union has started to recognise both the economic and societal importance of the semiconductor industry, as is shown by the proposed EUR145 billion investment in the sector. Also national governments, such as those in the UK, are beginning to take 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. Both the primary and secondary collected as part of this the report suggests that national and regional governments, as well as the European Commission, should focus on the following five interrelated policy and investment areas:

Cluster Development – Europe's existing semiconductor clusters are necessarily the industry's strength. However, policymakers have tended to overlook them in favour of more 'visible' technology clusters. 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 listed below.

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 often 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 around the ethos of open innovation and knowledge exchange. Although not formally announced at the time this report was prepared, it is heartening to note that the widely anticipated European Chips Act is likely to emphasise the importance of supporting clusters in terms of pan-European and international collaborations.

Commercialisation and IP Protection – The European semiconductor industry has significant strengths with regards 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 intellectual property 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.

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 above, 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 to make 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 deep technologies.

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 above will go some way to support 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 above should be to support new or would-be entrepreneurs. Entrepreneurship in the deep tech arena is more complex and investment heavy than many other tech areas, and requires an ecosystem of support that draws upon the array of the necessary resources and skills required 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.

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