Department of Law

Master of Science in Law, Digital Innovation and Sustainability

Chair of Managing and Financing the Transition

Managing Critical Raw Materials between industrial and climate policies: the case of the EU Chips Act

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1. Introduction

In the early 1970s, the issue of the finite nature of resources came to light. A major factor in this debate was the publication of the report *Limits to Growth* by the Club of Rome (1972). The report was built on a computer model, the World3, which tracked the world's economy and environment. The team followed industrialisation, population, food, resource use and pollution, as shown in Figure 1. They modelled data up to 1970 and then developed a series of scenarios until 2100 based on whether humans would have taken serious action on environmental and resource issues. The worst-case scenario, also known as the "*business-as-usual*" scenario, predicted an overshoot and collapse in the economy, environment, and population before 2070. The main take-home point from the report is that the Earth is finite and that the idea of unlimited growth without environmental externalities is quite unrealistic.

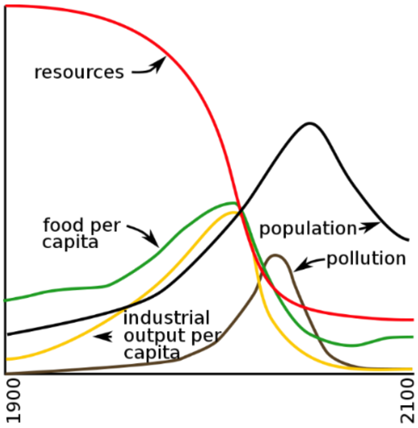


Figure 1 - World3 Model Standard Run (The Limits to Growth, 1972)

Plus, at that time, most Western countries were facing the impact of the oil price crisis, which was a striking demonstration of the industrialised countries' dependence on the supply of raw materials from the global market. There has been much speculation about the future reliability of raw material supplies ever since.

At present, the dominant economic system has already crossed the boundaries of our planet; therefore, we now need both a cleaner and a more interconnected world. Climate change is caused by significant greenhouse gas emissions, over-fertile farmland, massive loss of forests and grasslands, overfishing of the ocean, and over-consumption of raw materials. All this is caused by anthropogenic activities to satisfy what Brand and Wissen (2021) call "*the imperial mode of living*".

Raw materials have affected the development of civilisation to the point where entire periods have been defined by the predominant material used (e.g. Stone Age, Bronze Age, Iron Age). The importance of one raw material over another changes over time. One example is the revolution brought about by crude oil in the 20th century and how the world is now struggling to emancipate from it. The shift in the relevance of a specific raw material does not depend only on scientific discoveries, as for crude oil and plastic as its by-product, but also on specific needs that change in time and space.

Nowadays, a sort of raw materials hierarchy exists for each country, or better, geographic area. The ranking is mainly determined by two variables: economic and strategic importance and security of supply. According to the European Commission, a category worth attention is the one made of the so-called Critical Raw Materials (CRMs). The raw materials falling inside this class are very strategic and, at the same time, their security of supply is not always guaranteed.

As Hache et al. (2021) write, a strategic material is used in many industrial sectors; it is difficult to find a suitable substitute for industrial applications in the short term; it is employed in a large number of industrial applications; it has limited recycling potential and a high economic value; production and reserves are geographically concentrated, and its production can generate major environmental externalities.

These characteristics make Critical Raw Materials and the regulations related to them worthy of an in-depth analysis.

The European Commission's communication "*Investing in a smart, innovative and sustainable industry: A renewed EU Industrial Policy Strategy*" (2017) pointed out two major industry trends: digitalisation and decarbonisation. In fact, CRMs' high strategic rate comes from the fact that they will fuel both the digital and the ecological transition (the so-called twin transitions) and, as such, are vital to delivering both climate and digital ambitions, respectively stated in the European Green Deal (2019) and the Digital Compass (2021). On the other hand, the low security of supply rate is due to the little amount of such resources in European territories and the high dependence on imports from foreign countries.

For some years now, we have heard about the race to digital sovereignty. It is conceived as a race because, like the Space Race held in the last century, in the digital universe there are no borders, therefore, sovereignty must be conquered. Digital sovereignty concerns not just control over data but also technological competitiveness. According to the European Parliament (2020), digital sovereignty means

> *promoting the notion of European leadership and strategic autonomy in the digital field. Strong concerns have been raised over the economic and social influence of non-EU technology companies, which threatens EU citizens' control over their personal data, and constrains both the growth of EU high technology companies and the ability of national and EU rule-makers to enforce their laws. In this context, 'digital sovereignty' refers to Europe's ability to act independently in the digital world and should be understood in terms of both protective mechanisms and offensive tools to foster digital innovation (including in cooperation with non-EU companies).*

Therefore, the EU is trying to find its own market share among some big players, such as American and Chinese companies and in a data-driven world, it is vital to ensure competition and market access to European industries effectively. In fact, this new paradigm is crucial to understanding geopolitical alliances, economic interests, and national policies.

As a matter of fact, not just CRMs but also technology will enable the ecological transition. In fact, metallic raw materials are necessary to manufacture energy-efficient wind and solar generating facilities, hydrogen storage, batteries, etc. Furthermore, digital technology is by nature a driver of solutions in favour of the ecological transition. Smart cities, smart grids and home automation contribute to more efficient energy management. More broadly, low-carbon technologies play a fundamental role in Europe’s transition towards a clean, secure, and competitive economy.

However, it is important to underline that digitalisation and clean energy technologies can create new raw materials dependencies that can be just as problematic as the reliance on fossil fuels. In fact, price and supply volatility concerns will not disappear in an electrified and renewable energy scenario. While different from the risks associated with hydrocarbons, particularly oil (characterised by cyclical price spikes), minerals do present some vulnerabilities that need to be addressed. As will be seen later, geographical resource concentration is a significant issue, and, in some cases, a single country alone is responsible for about half of a mineral's global supply. Besides, many sites are subject to significant climatic hazards that could jeopardise the regularity of extraction. For example, more than half of all lithium and copper production today is located in areas with high levels of water stress. Some of the regions among the largest producers, such as Australia, China and Africa, are prone to extreme heatwaves and flooding (IEA, 2021). Circular economy strategies such as lifetime extension, servitisation, and recycling can help alleviate these hazards. Still, they may not be enough to offset the increase in resource extraction and their economic, social and environmental issues.

Moreover, effective regulations are needed to address resource impacts, including emissions associated with mining and processing, inadequate waste and water management risks, and effects on worker safety from human rights violations (such as child labour) and corruption.

Generally speaking, more effective resource governance is imperative. To manage potentially detrimental trade-offs, policymakers should carefully assess the drawbacks (such as severe environmental damage or low economic growth with negative effects on local communities), particularly with extensive knowledge of local circumstances and employing deliberative procedures. As a result, in the absence of effective mitigation measures, politicians and stakeholders may face an ethical dilemma in which a reduction in global carbon emissions is linked to various socio-environmental concerns.

In this regard, this thesis will offer an overview of the CRMs that will enable the digital and ecological transition and their problems, particularly the ones about geopolitical implications, environmental consequences and supply chain disruption. A striking example of raw materials subjected to such issues are semiconductors such as silicon, gallium and germanium, which are at the core of the twin transitions. As already said, effective resource governance is vital, especially when it comes to CRMs which are of considerable economic importance and characterised by the potential for global supply disruption, as was the case of the semiconductor crunch due to the Covid-19 pandemic. In particular, this thesis will focus on the EU Chips Act as a European strategy for semiconductors’ supply in the digital and ecological transition context.

European industrial policy, promoted by Article 173 of the Treaty on the Functioning of the European Union (TFEU), aims to make European industry more competitive so that it can maintain its role as a driver for sustainable growth and employment in Europe. This is being done in light of the digital transition and the transition to a carbon-neutral economy, as stated by the European Parliament, but this has not always led to adopting strategies that have ensured better conditions for the EU industry. In this specific case, it can be assessed not only by analysing the semiconductor ecosystem and its complex global production chain but also through the study of existing European climate policies that could negatively affect the success of the targets promoted by the EU Chips act.

In detail, the second chapter gathers the literature review on Critical Raw Materials, the specific field in which they are used and why the attention has been drawn to minerals and metals. The third chapter focuses on the three main issues related to CRMs: first geopolitical concerns and, in particular, resource concentration and potential trade barriers are outlined; afterwards, the risk of supply chain crunch is analysed; and finally, the environmental issues are dealt with. Chapter four reports the semiconductor ecosystem after having defined what semiconductors are. Firstly, it presents how the industry works and then how the supply chain is distributed across the globe to show its fragmentation and the main countries involved. Here, to demonstrate the fragility of this supply chain, two examples are reported: the shortage due to the Covid-19 pandemic and the potential risks posed by the Ukrainian war. Lastly, to show the three specific issues related to semiconductors as an example of CRMs, their Life Cycle Assessment is outlined with a focus on CO2 emissions. The fifth and last chapter reports the method to answer the research question and hence the assessment of the EU Chips Act first, through the pros and cons of the proposal regulation itself and then through the cross-analysis with the EU Emission Trading System and the Carbon Border Adjustment Mechanism but also analysing the potential impact on the achievement of the net-zero emissions target by 2050. Finally, the results will be discussed.

1.1. Research Question

This analysis aims to answer the following research question: is the Regulation proposal "*EU Chips Act*" a successful strategy to secure the supply of semiconductors and ensure Europe the coveted 20% market share? How is this target achievement affected by European climate policies?

1.2.Scope

The purpose of this thesis is to assess the suitability of the European strategy for semiconductors' supply and, in particular, of the EU Chips Act Framework through a general analysis of the semiconductor's ecosystem and a cross-analysis with other European approaches to reduce CO2 emissions. The project is inserted in the context of Critical Raw Materials and their problems, namely geopolitical concerns, supply chain crunch and environmental impact. In fact, the EU Chips Act has been designed as a strategy for securing the semiconductors' supply in Europe after the crunch caused by the Covid-19 pandemic and for gaining a significant market share in order to compete with foreign competitors realistically. Still, the environmental impact remains, and it shouldn't be underestimated. Therefore, a Life Cycle Assessment of semiconductors will be provided. Besides, from a cross-analysis of European strategies for Green House Gases (GHGs) emissions reduction turns out that the Chips Act's weaknesses could be more significant than its strengths. The main focus will be on the European Emissions Trading System (ETS) and the implications on the net-zero targets to be achieved by 2050.

This is a clear example of the latent clash between European climate and industrial policies and their difficult coexistence in a supranational organisation that takes shape in a wide range of both ideological and practical contradictions. Hence, this analysis suggests a policy angle based on an integral and broad approach, a view the regulator rarely embraces. Regulators should thoroughly design policies considering the correct type of funding and a precise roadmap for implementation when industrial policies potentially conflict with climate policies. Therefore, they should adopt the approach of the so-called green industrial policies.

1.3.Literature review

A literature review analysis has been carried out to answer the research question.

This thesis' method is the result of an independent analysis based on the assumption that the European semiconductor manufacturing industry would be subjected to the European Emissions Trading System. More broadly, this example fits in the field of literature on the relationship between industrial and climate policies (Meckling, 2021; Naudé, 2013), leading to the conclusion that green industrial policies can reconcile these two paths in support of decarbonisation (Rodrik, 2014; Altenburg & Assmann, 2017).

Since the geographical focus is Europe, most of the desk analysis has been carried out on European reports (European Commission, 2020a; British Geological Survey et al., 2017; European Commission, 2014) and regulatory acts (Proposal for a Regulation of the European Parliament and of the Council establishing a framework of measures for strengthening Europe's semiconductor ecosystem (Chips Act), 2022). Nevertheless, scientific papers were the main sources of the semiconductor section (International Roadmap for Devices and Systems, 2020; Alam et al., 2020; Bauer et al., 2020; OECD, 2010).

1.4.Methodology

The first part of the thesis is the result of a thorough desk analysis, literature review, and text-based analysis of scientific papers, documents, and reports, as explained in the previous paragraph. Secondary research has been applied to frame the context of Critical Raw Materials, their criticalities, and the semiconductor ecosystem. Thus, it has been possible to gather the prerequisite information for the method analysis.

The second part, the one that assesses the suitability of the EU Chips Act through the cross-analysis, is mainly based on the assumption that the EU semiconductors plants would be subjected to the European ETS. Other than the first part of the literature review, this part is also endorsed by secondary data elaboration carried out in Excel. The data have been gathered through databases and papers. Data have been cleaned, manipulated, and cross-checked to analyse their trend through the years.

1.5. Contribution and limitations

This thesis fits between the existing scientific literature on CRMs and semiconductors and the European regulatory framework. The novelty lies in its analytical transversality and, in particular, in the will to test a proposal for European Regulation (the EU Chips Act) in the area of industrial policy through a cross-analysis with existing European climate policies. In fact, such analysis suggests to the European regulator to adopt green industrial policies for the well management of the twin transitions.

The project’s main limitations are data-related but also due to the complexity of the semiconductors’ environment. For what concerns the former issue, data are fragmented by country, and there is a widespread reluctance by industries to disclose data and information. Regarding the latter, semiconductors are used in a wide range of products (from memories in electronic devices to thin-film in photovoltaic cells), making it difficult to grasp the industry’s overall impact, especially from the environmental point of view, through a comprehensive approach.

2. Minerals and metals: Critical Raw Materials underpinning the transition

Raw materials are vital to the global economy. They form a strong industrial base that produces a wide range of commodities and modern technology.

The twin transitions are needed for a more sustainable future from all points of view: social, economic and environmental. But even though the ultimate goal is to achieve net-zero emissions, which will be possible through green energy from renewable sources such as sun and wind, the transition still requires finite resources to make it work.

The raw materials underpinning the ecological and digital transition are mainly minerals and metals. The difference between metals and minerals is that the former are elementary substances or elements (e.g. silver or copper) while the latter are compounds of elements that can be found in the Earth’s crust (e.g. sand or iron ore) (Minerals and metals, n.d.).

From a European point of view, the digital and ecological transition represents a challenge not just for the transformative change it implies but also because the European Union industry is significantly dependent on imports for many raw materials and, in some cases, is highly exposed to vulnerabilities along the supply chain. As shown in the matrix below, based on economic importance and the level of risk to supply, some raw materials are evaluated as "critical" and as such are included in the EU Critical Raw Materials (CRMs) list. The critical aspect of raw materials is not absolute and depends on the scale adopted; in fact, it is important to underline the geographical approach of this thesis, which is the European one.

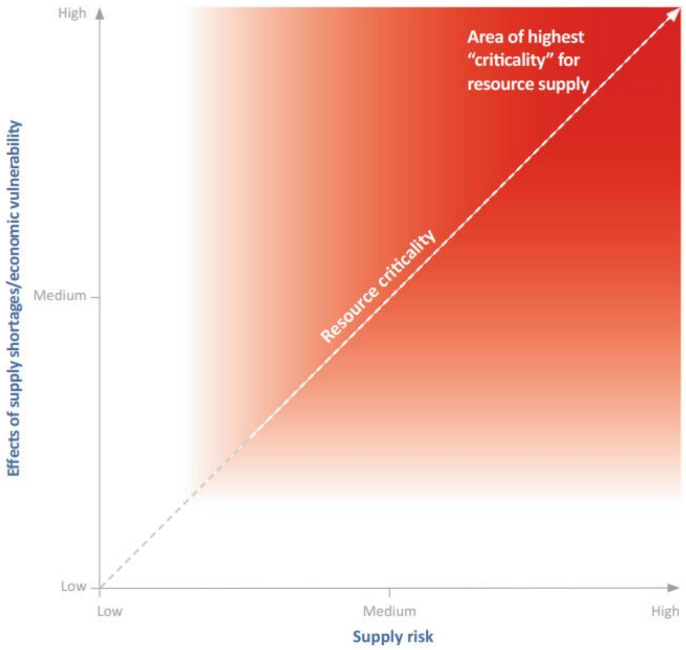


Figure 2- Criticality Matrix for Raw Materials (Wellmer et al., 2019)

The EU Critical Raw Materials list aims to be a functional tool to support an informed decision-making process and in doing so hold up both European and national policymakers when outlining trade agreements and industrial polices. It also points to direct investments in the right direction fostering and guiding innovation through national or European programmes (European Commission, 2020a).

The European Commission established the Raw Material Initiative in 2008 to improve manufacturing industries' competitiveness and hasten the transition to a resource-efficient and sustainable society.

The Raw Materials Initiative is built on three pillars with the following goals:

I. ensure fair and sustainable raw material supply from global markets;
II. foster sustainable raw material supply within the EU;
III. increase resource efficiency and supply of secondary raw materials through recycling.

The Initiative was consolidated in 2011 when the Commission published the first CRMs list. As mentioned in the introduction, a shift in the prominence of one raw material over others can occur and also the risk of supply can diminish or increase. Such dynamism justifies the review of the CRMs list by the Commission every three years. In the fourth and last list (European Commission, 2020a) 30 elements are present, three more compared to the 2017 list and sixteen more than the first list of 2011. However, some elements inserted in the 2017 list were erased from the 2020 list. This depends on the raw material-supply situation which is continuously influenced by current events and can change at any time. Although these evaluations and lists of critical resources provide a short-term perspective of the situation, they ensure an important orientation for a correct assessment of the action to undertake to secure raw materials supply.

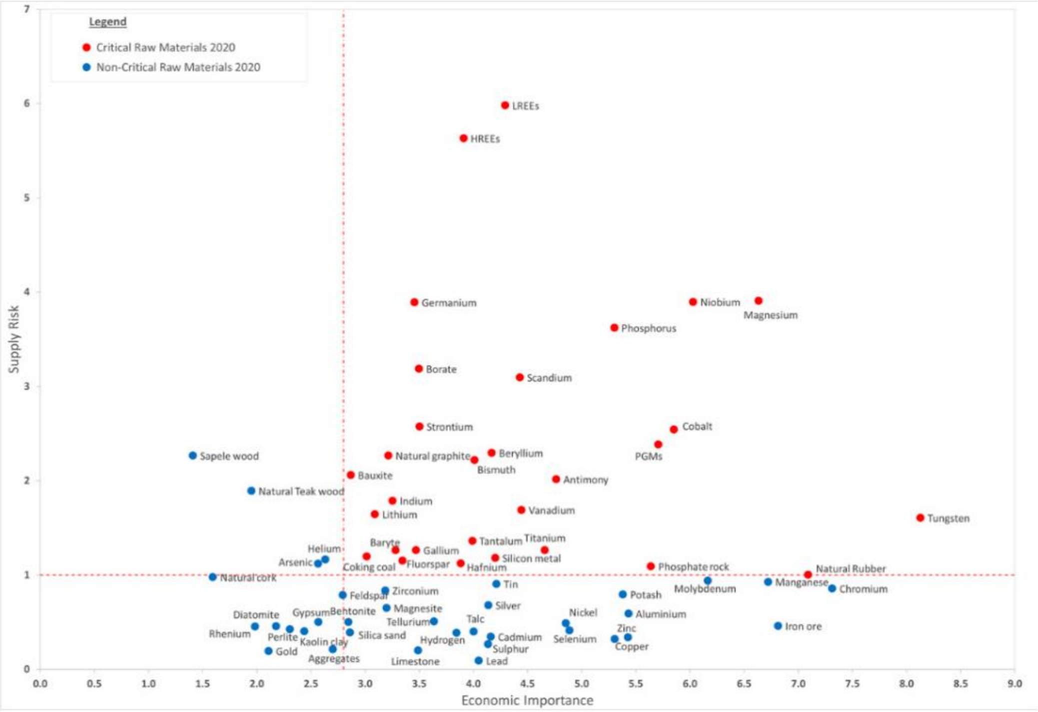


Figure 3 - Critical Raw Materials (CRMs) chart (European Commission, 2020a)

Such initiatives are common also in other countries such as the USA (CHIPS for America Act, 2020) or Japan (Partial Revision of the Act on the New Energy and Industrial Technology Development Organization, 2022), whose economies are heavily dependent on the import of raw materials.

2.1. Methodology to identify CRMs

There are different methods to assess resource criticality. Here will be reported the one used by the Commission in the CRMs list (European Commission, 2017; British Geological Survey et al., 2017). In general, the term “criticality” implies many risks, among others, a geological risk of lack of resource availability due to demand pressure, a geopolitical one concerning the concentration of production in the hands of a few producing countries, economic risks such as embargoes, trade policy restriction, market manipulation, production risk due to under-investments, joint production and finally an environmental and social risk of emissions, health consequences and mining conditions.

The criticality assessment carried out by the European Commission is based on a wide range of materials: 83 for the 2020 list and 78 in the one published in 2017. This enables the identification of any crucial materials that may move from a non-critical to a critical status or vice versa. Moreover, the methodology tries to facilitate comparability and coherence as much as possible from one list to the other (British Geological Survey et al., 2017).

Two main parameters form the basis of the methodology used by the European Commission: Economic Importance (EI) and Supply Risk (SR).

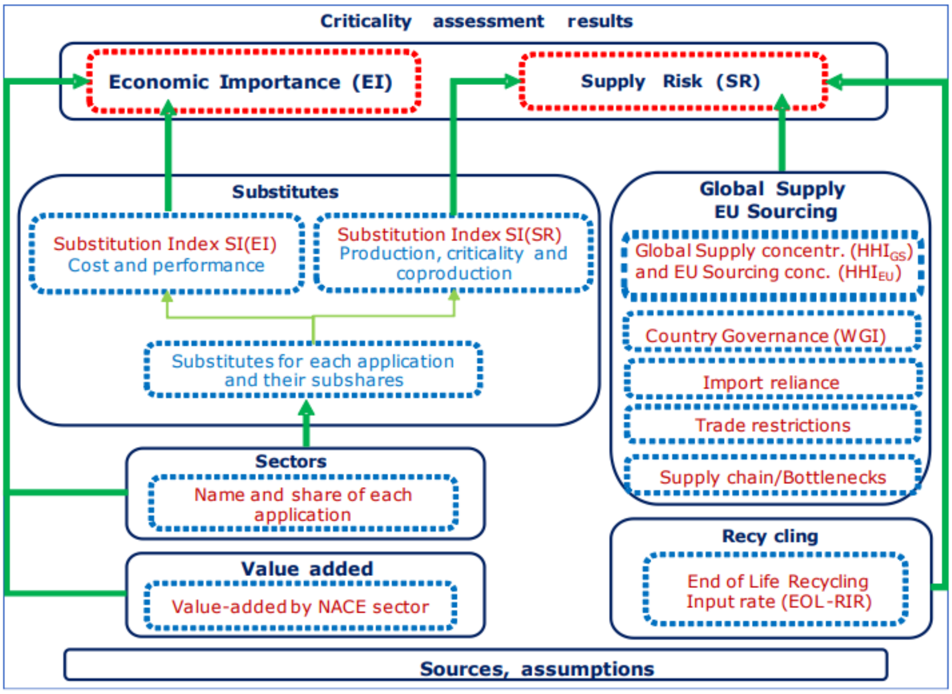


Figure 4 - Overall structure of the revised criticality methodology (British Geological Survey et al., 2017)

The list of critical raw materials is established based on the assessed raw materials that meet or exceed the European Commission's requirements for both dimensions (SR ≥ 1 and EI ≥ 2.8). In terms of criticality, there is no ranking order for raw materials (Ibid.).

The calculations are based on an average of data from the previous five years. Priority, quality, and data availability are all considered for various aspects (European Commission, 2017a).

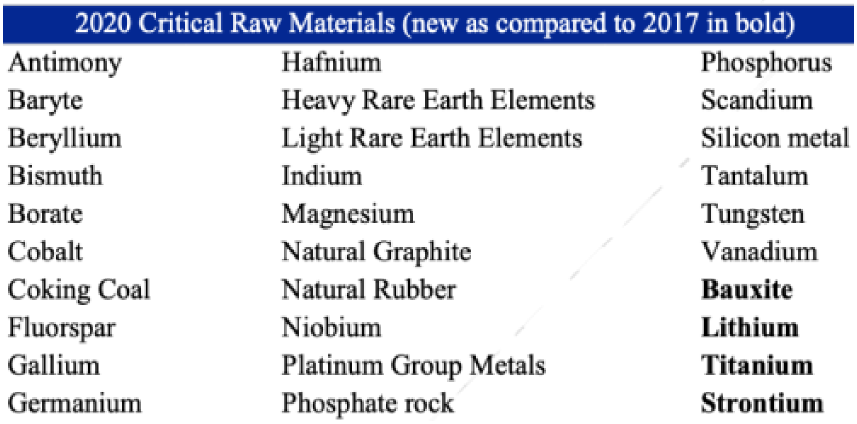
The methodology also provides the involvement of stakeholders through consultations. The goal of the stakeholder engagement is to ensure that industry and scientific stakeholders have the chance to provide expert opinions on specific issues and, as a result, enhance the outcomes. Furthermore, the consultations ensure that the study's findings are optimally validated before being shared and utilised (British Geological Survey et al., 2017).

In particular, the EI parameter attempts to provide insights into the economic importance of a material in terms of end-use applications and the value-added (VA) of associated EU manufacturing sectors at the NACE Rev. 2 level. The substitution index (SIEI), based on substitutes' technical and cost performance for certain applications, corrects the economic importance (European Commission, 2017) and it is a risk-reduction parameter.

On the other hand, the SR parameter indicates the likelihood of a disruption in the material's supply to Europe. It is determined by the concentration of primary supply from countries that produce raw resources, as well as their governance and trade performance. The two categories of producing countries — worldwide suppliers and countries from which the EU sources raw materials — are proportionally taken into account depending on the EU import reliance (IR). SR is calculated at the material's bottleneck stage (i.e. extraction or processing), which poses the most significant supply risk to the EU. In this case recycling constitutes the risk-reduction parameter (Ibid.).

2.2.Which are they

This thesis will focus on those CRMs listed in the 2020 list published by the European Commission, which are indicated below.



2020 Critical Raw Materials (new as compared to 2017 in bold)		
Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural Graphite	Vanadium
Coking Coal	Natural Rubber	**Bauxite**
Fluorspar	Niobium	**Lithium**
Gallium	Platinum Group Metals	**Titanium**
Germanium	Phosphate rock	**Strontium**

Figure 5 - 2020 EU list of Critical Raw Materials (European Commission, 2020a)

As already said, these resources are also critical because of their strategic importance in some key economic sectors. The industrial ecosystems in which critical resources are more relevant are “Aerospace & Defence”, “Electronics”, “Mobility & Automotive”, and “Renewable energies” (European Commission & Joint Research Centre, 2020).

Some concrete examples will now be provided to show the importance of CRMs in the development of the four sectors mentioned above.

2.2.1. Defence and Aerospace sectors

Because substitutes cannot always guarantee the same performance, the EU defence industry, like many other economic sectors, relies on a wide range of materials with specific features that make them vital for fabricating components used in military applications.

Drones are a striking example of the employment of some critical resources to construct strategic tools. Defence and Aerospace play a vital role both at the national and European levels and they set the circumstances for a territorial system's security, stability, and expansion. It is also at the cutting edge of technological advancements for their employment and as an experimental field. It is, in fact, an innovation-driven industry with a high concentration of knowledge, capital, and technology, resulting in significant investments in R&D and skilled employment (Coykendall et al., 2021).

Drones are employed for a wide range of civil and industrial purposes. Remote sensing for agricultural aerial monitoring and investigation, infrastructure inspection, border monitoring and surveillance, research and development, and other data-collection operations, as well as the transportation of commodities, such as parcels in the logistics industry, are among them (European Commission & Joint Research Centre, 2020).

Moreover, their demand is expected to grow in the following years (European Drones Outlook Study - Unlocking the value for Europe, 2016).

Figure 6 shows the use of resources for drones' construction and as can be seen, most of them are CRMs. Drones are made of 48 raw materials, 15 of which, among them cobalt, lithium, titanium, silicon, and many others, are flagged as critical to the EU economy. China is the major supplier of CRMs for drones, delivering more than 40% of CRMs (European Commission & Joint Research Centre, 2020).

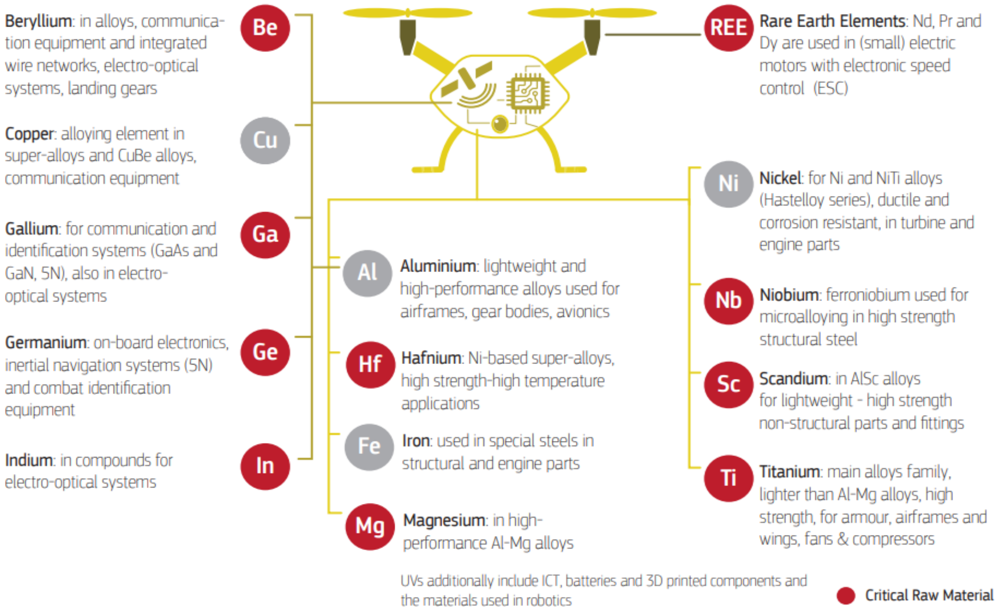


Figure 6 - Raw materials in drones (European Commission & Joint Research Centre, 2020)

2.2.2. Electronics and Digital sectors

As far as the Electronics and Digital fields are concerned, digital innovations are revolutionising the globe at a breakneck pace, altering the way people communicate, live, and work. Plus, the EU is aiming for technological sovereignty in several crucial digital technology fields (such as blockchain, quantum computing, and data sharing) (European Commission & Joint Research Centre, 2020). Information and Communication Technologies (ICT) are more of a transversal example since they affect and enable innovation and the quality of life. Besides, a wide range of digital technologies contains different critical resources. As it can be seen in Figure 7, most raw materials in ICT are deemed crucial, thus affecting industrial development at different levels. The essential raw materials in these technologies include boron, cobalt, gallium, germanium, graphite, indium, lithium, magnesium, PGMs, REE, silicon metal, and tungsten.

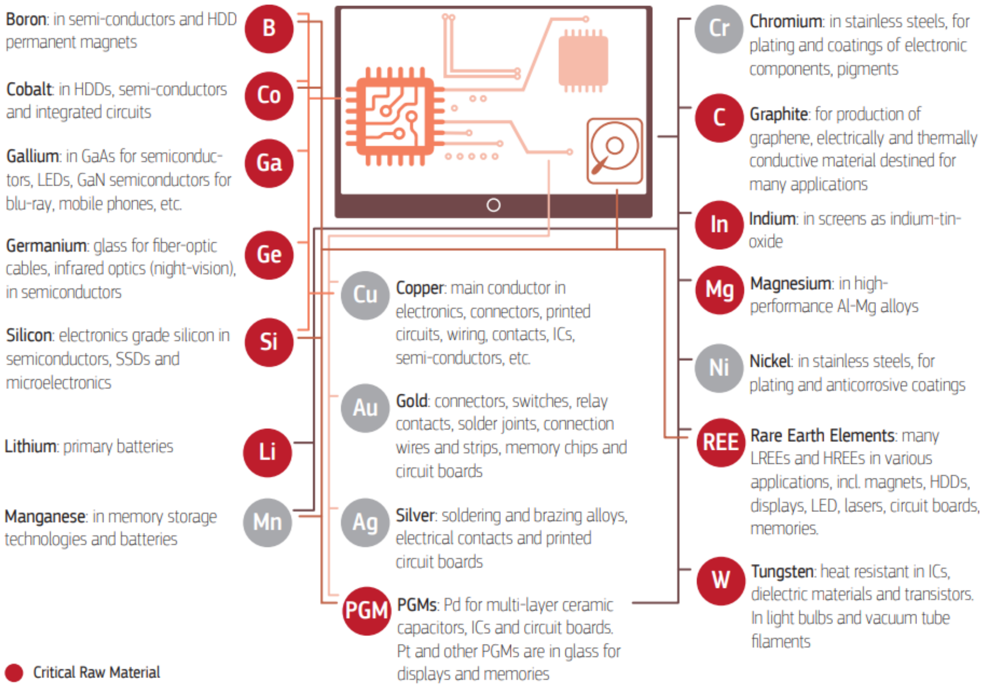


Figure 7 - Raw materials in digital technologies (European Commission & Joint Research Centre, 2020)

2.2.3. Mobility and Automotive sectors

The Mobility and automotive sector are rather dynamic ones. Innovation in such an ecosystem is driven not just by end-users needs but also by improving the performance of e-mobility and, in particular Electric Vehicles (EVs). In fact, according to the JRC, "*a storm of new technologies and business models is transforming everything about how we get around and how we live our lives*" (European Commission & Joint Research Centre, 2019).

A wide range of technologies must be further developed to enable the transition to a cleaner, automated, connected, and low-carbon mobility. The deployment of e-mobility will be fuelled by batteries, Fuel Cells (FCs), traction motors, and ICT technologies.

In particular, REEs (neodymium, dysprosium and praseodymium) and boron will be in most electric vehicles' motors. Mobile energy storage will require CRMs such as lithium, cobalt and natural graphite in Li-ion batteries and platinum in FCs. Structural parts and lightweight structures of vehicles will require materials such as magnesium, niobium, silicon metal and titanium. Gallium, germanium, and indium will be used in sensors, displays, circuits, and other electronic components as cars become more electronic (European Commission & Joint Research Centre, 2020).

For example, the Li-ion battery is becoming a mature technology and is now used in various applications. Compared to contemporary lead-acid batteries, it provides better power and energy performance. While Li-ion batteries are critical for defence applications, civilian demand for portable electronic devices, stationary energy storage, and EVs is driving their development and future adoption (Ibid.). Nickel, cobalt, aluminium, and manganese are among the metals used in lithium metal oxide batteries.

Cobalt, natural graphite, and lithium are the main CRMs on the 2020 list, out of all the materials currently utilised in battery manufacturing. While silicon metal, titanium, and niobium are at the centre of research to improve durability, energy density, and safety in future Li-ion battery types (Ibid.).

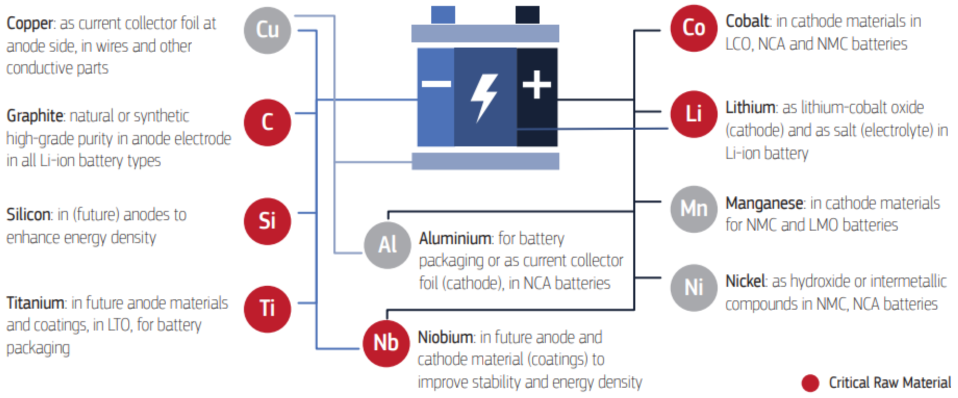


Figure 8 - Raw materials used in batteries (European Commission & Joint Research Centre, 2020)

2.2.4. Renewable energy sector

Many technologies are utilised to transform renewable resources into electricity (e.g., wind turbines and solar panels), store that energy (e.g., rechargeable batteries), improve manufacturing processes (e.g., robotics and 3DP), and facilitate electricity conversion and transfer via smart grids and in general using digital technologies.

Wind power is one of the fastest-growing renewable energy technologies, and it has the potential to provide a considerable portion of electricity when combined with solar photovoltaic (PV).

Given the intermittent nature of wind and sun as energy sources, storage technologies such as Li-ion batteries and fuel cells are key components of a low-carbon electrical system. They enable the production of low-carbon electricity and store it for later use.

Because of the deployment of the technologies described above, the transition to low-carbon energy systems will result in considerable changes in raw material requirements. Permanent magnets used in high-performance wind turbines, for example, contain important REEs such as dysprosium, praseodymium, and neodymium. Robotics, solar PV, and digital technologies all require CRMs such as borates, gallium, germanium, indium, and silicon metal. CRMs like cobalt and natural graphite are used in batteries, and they're also needed in 3D printers and digital technologies. Platinum is employed as a catalyst in FCs and digital applications, such as hard disk drives (European Commission & Joint Research Centre, 2020). Overall, the renewable energy sector necessitates a large number of raw materials.

Take for example a wind turbine generator. The rare earth elements, such as neodymium, praseodymium, and dysprosium, are essential components of the most powerful magnet material, neodymium-iron-boron (NdFeB) which is used in permanent magnet synchronous generators (PMSG) and employed in most wind turbine layouts (Ibid.).

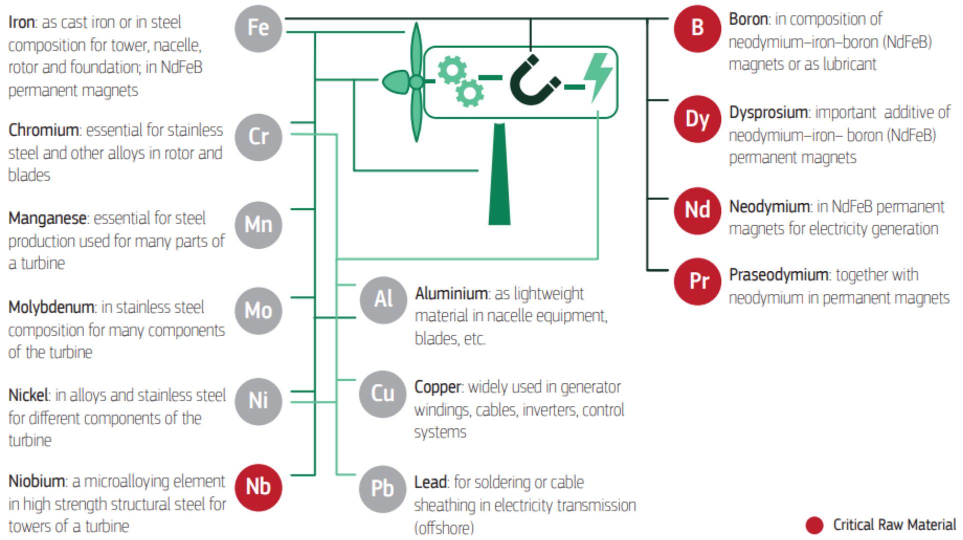


Figure 9 - Raw materials used in wind turbines (European Commission & Joint Research Centre, 2020)

2.3.Why are they underpinning the transition?

With the exploitation of new fossil-fuel deposits through fracking, deep-sea drilling, and other breakthroughs in exploration, production, and utilisation, the fossil-fuel era would undoubtedly be continuing today and into the future if it weren't for climate change. As stated by Hafner and Tagliapietra (2020),

> *The fossil-fuel era is ending not by running out of fossil fuels but for a wholly different reason, indeed a quirk of quantum physics. As great nineteenth century scientists including Fourier, Tyndall and Arrhenius came to realize that fossil fuels have a pesky side effect. When they are combusted, they release carbon dioxide (CO2) into the atmosphere, and CO2 has the quantum physical property of absorbing electromagnetic radiation at infrared wavelengths. The implication? Atmospheric CO2 warms Earth by trapping infrared radiation that would otherwise radiate from Earth to outer space.*

By shifting power generation from coal, oil, and gas to zero-carbon energy sources (wind, solar, geothermal, hydro, ocean, biomass or nuclear) and using that zero-carbon power to provide energy for downstream uses such as transportation, buildings, and industry, scientists and engineers believe that decarbonisation by 2050 is feasible. Indeed, downstream uses, such as light-duty battery-electric vehicles and electric heat pumps for residential heating, whose technologies are already developed, should be directly implemented as much as possible. When direct electrification is not possible, zero-carbon energy should be utilised to make synthetic (or "green") fuels like hydrogen, green methane and other fuel carriers that can be burned without producing CO2 (Hafner & Tagliapietra, 2020).

So, the goal of zero net emissions by 2050 requires electrification efforts and diversification of energy sources, thus resulting in a significant increase in raw materials demand. Indeed, with the transition of the European industry toward climate neutrality, the current dependence on fossil fuels will be gradually and partially replaced by a dependence on minerals and metals.

Renewable energy investments are typically associated with a double dividend since they reduce CO2 emissions while also reducing fossil fuel imports (Criqui & Mima, 2012). This partial emancipation from the economic and geopolitical issues of traditional energy security, particularly the availability and accessibility, must be examined in a broader context, considering the materials required to construct and implement low-carbon technologies (solar, wind, storage, electric vehicles, etc.). Indeed, the necessary levels of investment in these technologies could result in a significant increase in minerals and metals demand, as well as significant economic and geopolitical shifts in the various raw materials markets (Hache et al., 2021).

In fact, the mineral and metal demand are expected to grow in the following years due to not just decarbonisation but also because of the growing population, digitalisation and industrialisation, mainly in lower-income countries (World Bank Group, 2017). According to the OECD (2019), increased material consumption, combined with the environmental repercussions of material extraction, processing, and waste, will put further pressure on the planet's resource storage, jeopardising improvements in well-being. Suppose the resource implications of low-carbon technologies are not addressed. In that case, there would be a risk that shifting the burden of reducing emissions to other parts of the economic chain will simply result in new environmental and social problems, such as resource depletion, metal pollution and habitat destruction.

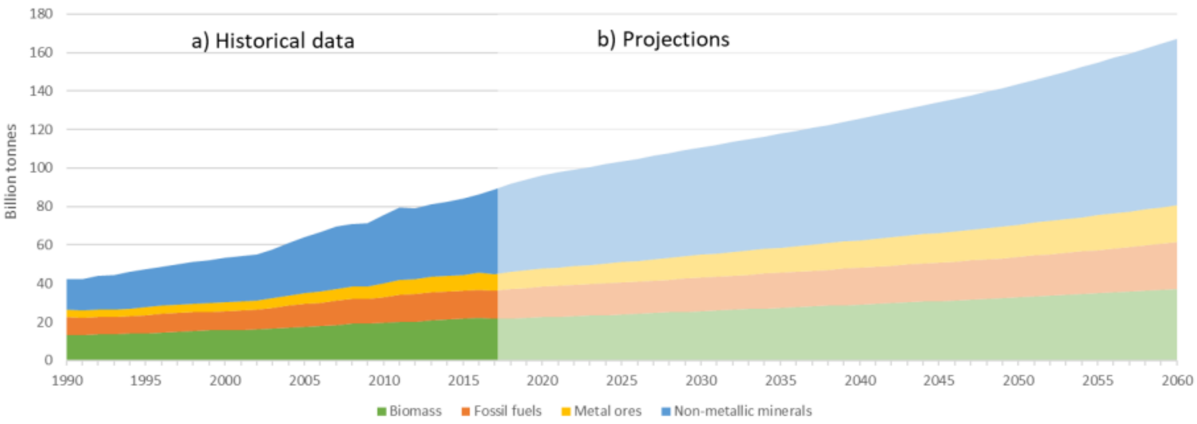


Figure 10 - Global material use by resource type: a) historical data (world, 1990 - 2017) and b) projection (world, 2018 - 2060) (European Commission & EIP on Raw Materials, 2021)

Thus, the secure supply of raw materials from both primary and secondary sources is the precondition for European industries' competitiveness and resiliency, along with ongoing research and innovation policies for alternative and more sustainable product design to achieve the green and digital transition.

3. Minerals and metals criticalities

Considering what has been said, an in-depth analysis of the raw materials' criticalities underpinning the twin transitions is deemed appropriate for the purpose of this thesis. In the following paragraphs, their three main issues will be discussed, namely, the geopolitical concerns that arise from the possession of raw materials' deposits, the possibility of supply chain disruption due to both external shocks and countries' economic measures such as trade barriers and finally their environmental impact mainly associated with mining. However, due to the different processes CRMs are subjected once incorporated in final products, it is difficult to assess the overall environmental impact.

3.1. Geopolitical concerns

Physical power, particularly control over primary resources (e.g. crude oil, minerals, metals, etc.), influences a country’s economic prosperity and national security. As a result, the distribution of raw materials significantly impacts international relations. In fact, at the basis of the CRMs list, there is the acknowledgement that access to certain raw materials is an increasing concern in the European Union to be more competitive. Lack of strategic materials may leave a government vulnerable to disruption along the supply chain of a specific product that require critical resources. At the same time, its industries would lose economic competitiveness in the market.

Because the twin transitions rank so high on the EU policy agenda, they will alter EU-neighbourhood relations and redefine Europe's global policy priorities with far-reaching geopolitical implications. On 10 March 2020, the European Commission presented ‘A New Industrial Strategy for Europe’. It seeks to strengthen Europe's open strategic autonomy, warning that the transition to climate neutrality could replace Europe's current reliance on fossil fuels with a dependence on raw resources, many of which we import from other countries and for which global competition is intensifying. As a result, the EU's strategic autonomy in these sectors will need to be grounded in varied and undistorted access to global raw material markets.

The geopolitical concerns should be addressed from a broader perspective which also entails the gradual abandonment of fossil fuels. Certainly, Europe’s exit from fossil-fuel dependency will adversely affect several regional partnerships and may even destabilise economically and politically. Moreover, around 20% of the world's crude oil imports come from Europe. The drop in oil demand caused by Europe's transition to renewables would influence the global oil market, decreasing prices and reducing the income of leading exporters (Wolff, 2021).

Moreover, the geopolitics of strategic raw materials conceals a double dimension: whether one is a producing country, whose primary concern is resource development, or a consumer country, for which the security of supply is central.

The geopolitical dimension, particularly the reliability of suppliers, behind raw materials’ criticality cannot be quantified and transposed into an index. Therefore, a qualitative analysis of the complex and dynamic nature of the relations as well as the balance of powers between the client country and the supplier should be deemed more appropriate. In fact, criticality largely depends on the identity of the supplier country vis-à-vis the importer but also on the economic and political interests of a state, of which it is a reflection.

For example, as stated in the last Draft of the critical minerals list of the US Geological Survey (USGS) (2018), one of the metrics used by the American government to assess resource criticality is the U.S. net import reliance (NIR) statistics published annually in the USGS Mineral Commodity Summaries. NIR, an indicator of foreign dependency, is computed as the amount of imported material minus exports and changes in government and industry stocks and is expressed as a percentage of domestic consumption. A mineral item that is not produced in the United States, for example, has a NIR of 100%. As stated in the Draft

> *12 out of the 26 commodities with high United States NIR are sourced primarily from China. However, high NIR should not be construed to always pose a potential supply risk. For example, three of the commodities deemed critical or near critical are primarily imported from Canada, a nation that is integrated with the United States defence industrial base.*

This formulation makes us understand that the criticality comes from the country's identity. It also illustrates the difference between import reliance and import vulnerability, the latter being a material with high NIR sourced from a country with high governance risk.

As stated by Hache et al. (2021), the two worrying dynamics at the core of the energy and digital transition are two. The first one is geological, and it is about the rising consumption of goods containing critical resources which could lead to shortages. The second one is about market cartelisation, thus generating strategic dependencies.

As for the first dimension, by 2030 the EU forecasts demand for lithium, cobalt, and rare earths to increase by eighteen times, five times, and ten times, respectively, for electric car batteries and energy storage. Lithium consumption is expected to increase by about sixty times by 2050, while cobalt demand is expected to increase by around fifteen times (Halleux, 2022). By developing its own supply of lithium, cobalt, and rare earths, the Commission aims to become 80% self-sufficient in lithium by 2025 whilst also diversifying its imports, with a high probability of failure. It also plans to have its own refining and mining facilities ready by 2030 (Šefčovič, 2020).

This rising demand brings us to the second dimension stated by Hache et al. (2021). Since China is the largest producer of such raw materials, there is a risk of market centralisation. Europe has, in fact, identified its strategic dependencies in the "*Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery*" (2021) as one of the lesson-learned from the Convid-19 pandemic. According to the same document, strategic dependencies are those "*dependencies that are considered of critical importance to the EU and its Member States' strategic interests such as security, safety, health and the green and digital transformation*". However, it is necessary to examine the nature of the reliance and the level of risk involved within these areas. In fact, a critical first step toward greater resilience is identifying and addressing the EU's strategic dependencies. Furthermore, it is essential to maintain competitiveness and encourage investment in technologies vital to Europe's future.

The assessment of strategic dependencies entails identifying them and determining whether they are strategic and pose a risk to the EU's core strategic interests.

As shown in the previous paragraph, most resources used in Li-ion batteries are critical raw materials, and as Figure 11 explains, overall, only 1% of all batteries' raw materials are produced in the EU. For example, the Democratic Republic of the Congo produced 54% of global cobalt mining output, followed by China (8%), Canada (6%), New Caledonia (5%), and Australia (4%). China produces refined cobalt (46%), followed by Finland (13%), Canada and Belgium (both 6%) (European Commission & Joint Research Centre, 2020). Chile

(40%), Australia (29%), and Argentina (16%) contribute around 90% of worldwide lithium mine output, mainly from brine and spodumene sources. Most of the world's lithium hard-rock minerals refining plants (45%) are located in China while refined lithium capacity from brine operations is dominated by Chile (32%) and Argentina (20%) (The European Green Deal, 2019).

Existing requirements for natural graphite include flake size and carbon content. These are often done through additional refining procedures, with China having the majority of the capability for spherical graphite manufacturing (Roskill, 2018). Anode materials, as well as Nickel Manganese Cobalt (NMC) oxide and Lithium Cobalt oxide (LCO) processed materials, are primarily supplied by China, whereas Nickel Cobalt Aluminium (NCA) oxide cathode materials are primarily supplied by Japan. The EU relies entirely on anode and NCA cathode material supplies, importing roughly 18% of NMC materials and 15% of LCO materials from China (European Commission & Joint Research Centre, 2020).

For example, Asia and in particular China, Japan, and South Korea, supplies 86% of the world's processing materials and components for Li-ion batteries. With only 8% of the supply, the EU27 has a limited part of the market. Other countries only deliver 8%, leaving very little room for supply diversity (Ibid.).

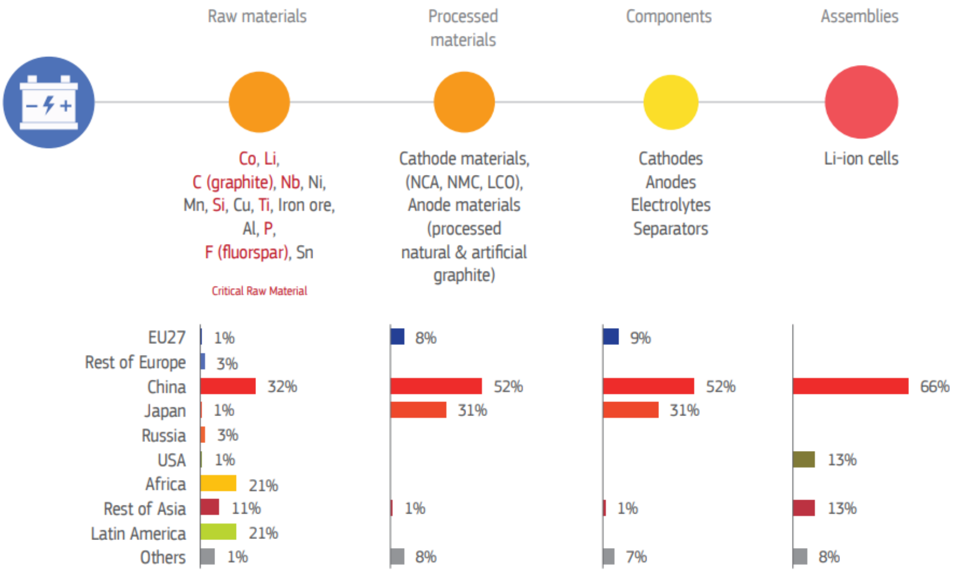


Figure 11 - Li-ion batteries' key players along the supply chain (European Commission & Joint Research Centre, 2020)

The EU, on the other hand, is heavily investing in the battery value chain. From 3 GWh produced in 2018 (and a world capacity of 150 GWh), the EU capacity estimated to be available in 2021-2023 is expected to climb to 40 GWh (Tsiropoulos et al., 2018). Simultaneously, Chinese businesses will significantly increase Li-ion cell production capacity, ensuring China's supremacy in the battery market. Original equipment manufacturers, cell manufacturers, and suppliers will most likely fight global trade wars to safeguard their battery supply chains and access to the five key battery raw materials - lithium, cobalt, nickel, graphite, and manganese – through tariffs and trade barriers.

Finally, the EU will need to develop new trade and investment agreements, new financial and technical aid models, and, more generally, a new approach to international diplomacy to stimulate sustainable investments and growth. This international effort will inevitably spill over into relations with the US and China, who have different perspectives on promoting sustainable development and conducting international climate negotiations. Relationships with other nations whose export interests are directly affected, such as the Gulf states and Russia, will be altered as well.

All these EU's foreign policy initiatives will elicit a geopolitical response from its international allies. Cooperation in the implementation of complementary climate policies to competitive initiatives to redirect trade and investment flows will be among the responses.

3.2. Supply chain crunch

Supply chain vulnerabilities concerns arise from a geological factor of resource concentration at a country level resulting then in a series of other issues such as concentration of global production of primary raw materials and sourcing to the EU, the governance of supplier countries, including environmental concerns, the contribution of recycling (i.e. secondary raw materials), substitution, EU import reliance and trade restrictions in third countries.

A shortage in minerals and metals supply is different from an oil supply crisis since the former are infrastructure components. This means that consumers who drive gasoline or diesel vehicles will be affected by higher pricing if there is an oil supply shortage. On the other hand, a shortage or price surge in minerals and metals solely affects the supply of new infrastructures such as EVs or solar panels. Existing EV drivers and solar-powered electricity users would not be affected (IEA, 2021). Nevertheless, clean energy technologies and ICT supply chains can be even more complicated and concentrated than those for fossil fuels (and, in many cases, less transparent).

The COVID-19 crisis has highlighted the need for supply security by causing disruptions in large international supply chains and jeopardising critical European industrial ecosystems' competitiveness. Indeed, bottlenecks along a supply chain can lead to high commodity prices and market volatility.

The raw material supply situation has deteriorated significantly in the previous decade, owing to the rapid growth of emerging markets, particularly China, and the increasing diversification of metals and minerals with very specific properties required to enable the twin transitions (Glöser et al., 2015).

Primary resources in Europe are not being fully utilised to ensure enough and timely supplies to meet domestic demand. In fact, Europe relies heavily on raw material imports because its raw material resources and exploitation activities are modest. In the EU, the manufacturing industry (i.e. the production of end products and applications) and the refining industry (metallurgy, etc.) are often regarded as more important than the extractive industry (e.g. mining activities). In fact, the value chain of raw materials is not fully and homogeneously covered by the European industry, with a pronounced imbalance between the upstream steps (extraction / harvesting) and the downstream steps (manufacturing and use). Nevertheless, the need for primary materials, such as ores and concentrates, and also for processed and refined materials is crucial for the wealth and survival of the European industries and their associated jobs and economy (European Commission & Joint Research Centre, 2020).

The problem is that even when some raw materials are mined in Europe, like lithium, they have to leave Europe for processing. Indeed, technologies, capabilities, and skills in refining and metallurgy are crucial in the value chain.

For what concerns the concentration problem, in some cases, a single country is responsible for around half of the worldwide production. The Democratic Republic of the Congo and South Africa are responsible for some 70% of the global production of platinum and cobalt, respectively. China accounted for 60% of global REE production in 2019 (albeit down from over 80% in the mid2010s). The fact that many metals' processing, smelting, and refining are concentrated in a small number of nations increases the risk of supply disruption. For nickel, China has a refining share of roughly 35%, 50-70% for lithium and cobalt, and 90% for REE processing that converts mined output into oxides, metals and magnets (European Commission & Joint Research Centre, 2020).

As it is possible to notice from the map below, the European supply of some CRMs is highly concentrated. For example, 98% of Rare Hearts Elements (RHEEs) supplied to the EU come from China. This increases the risk of supply shortages and supplies vulnerability along the value chain.

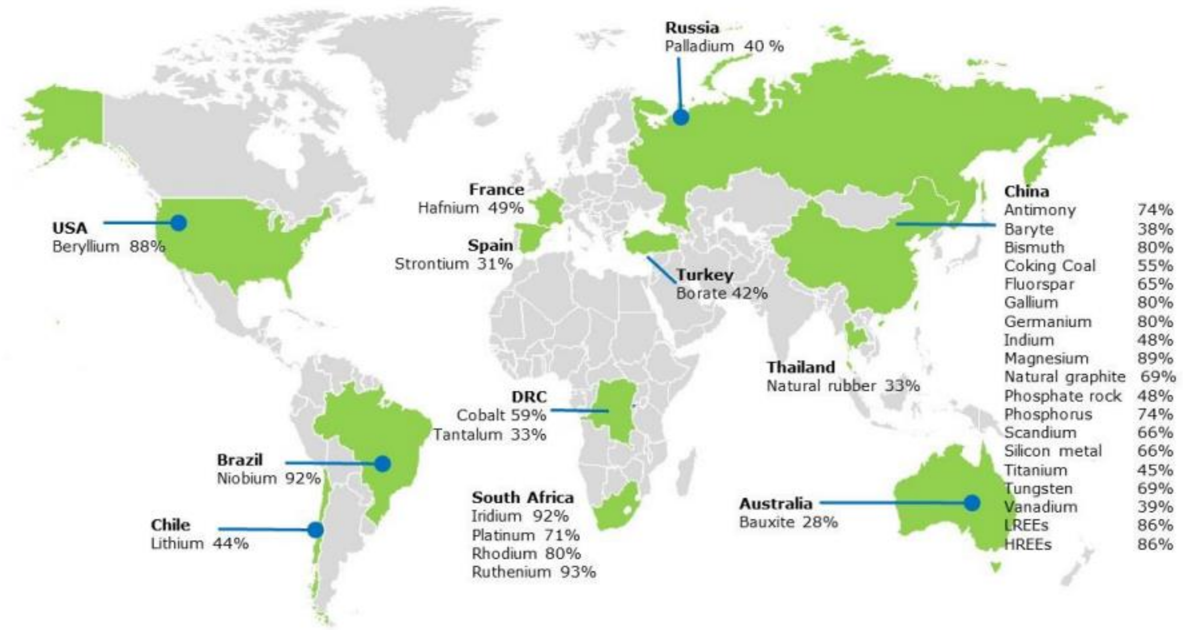


Figure 12 - Biggest supplier countries of CRMs to the EU (European Commission, 2020a)

In addition to high concentration, some producing countries closely control and limit the export of raw materials, intermediates, and metals in order to protect their domestic industries, thus enacting export restrictions that are frequently viewed as anti-competitive. Such supply constraints, which impact supply conditions and price volatility, can adversely affect all supply chain actors.

Mineral and metal mine production frequently relies on large-scale investment projects that might take years to complete, making them unable to respond rapidly to short-term fluctuations in demand or vulnerable to suppliers' market manipulation (Ibid.).

As a result of these circumstances, there is a possibility of supply shortages for a variety of metals and minerals in the EU. The impact of an interruption in raw materials supply could be a loss of competitive economic activity in the EU, as well as a reduction in the availability of certain strategic finished products in some situations.

The IEA (2021) predicts that "*looking further ahead in a scenario consistent with climate goals, expected supply from existing mines and projects under construction is estimated to meet only half of projected lithium and cobalt requirements and 80% of copper needs by 2030*."

In general, IEA has released six recommendations to secure resource supply:

1. Ensure adequate investment in a variety of new supply sources.
2. Encourage technological innovation at every stage of the value chain.
3. Scale-up recycling.
4. Enhance supply chain resilience and market transparency.
5. Mainstream higher environmental, social and governance standards.
6. Strengthen international collaboration between producers and consumers.

The Commission is now focusing on the diversification of suppliers and pursuing international partnerships also implementing digital solutions to get more flexible supply chains. In some cases, strategic stockpiling can help governments withstand short-term supply disruptions.

3.3.Environmental concerns

Even if CRMs allow the twin transitions to reduce CO2 emissions through renewable technologies and digitalisation, this does not mean that they do not have an environmental impact themselves.

The environmental impact of raw materials is quite difficult to compute. Data are incomplete, so the most precise way to determine the global environmental impact of one critical raw material in an application is to consider both the environmental impact of producing one tonne of that CRM and the number of tonnes of the same raw material needed for the global production of the application under consideration (Bachér et al., 2020).

But since the environmental impact is not limited to the mining and processing phase, a Life Cycle Assessment of each CRM should be deemed the most accurate way to determine their actual impact. For example, critical raw material mining poses a significant environmental risk in the nations where it is carried out, which are frequently countries with poor environmental legislation. These dangers are linked to geological conditions at the extraction site, such as the presence of heavy metals in the ores; mining and extraction technology, which can result in ecosystem destruction through open-pit mining; and natural conditions at the extraction site, such as if it is located in a water-stressed region (Ibid.).

In general, there are different categories of environmental risks depending on the type and the scale of the consequences (global or local). As stated in the EEA report (Ibid.), the main environmental risks associated with the mining, extraction, refining and production stages of CRMs are:

- The mineralogical and geological characteristics of the extraction site. This is the case, among others, for rare-earth elements that are typically present in nature in association with radioactive elements, such as uranium and thorium. Others, such as cobalt, boron, gallium, and tungsten, are commonly found in heavy metals that are toxic to humans and the natural environment when released during extraction.
- The effects of particular mining and extraction technologies and processes. Critical raw material mining processes frequently present threats to vegetation, as well as impacts on groundwater levels or land usage, due to mining and stockpile deposition. The employment of toxic reagents and other auxiliary compounds in the extraction process of resources like beryllium, palladium, niobium and rare-earth elements exposes to significant environmental dangers.
- The natural environment and conditions at the location where mining and extraction activities take place. Limiting the establishment of mines vulnerable locations and implementing sufficient permitting procedures and monitoring systems help mitigate these hazards. Most countries have created protected areas where mining is prohibited to preserve their national ecosystems. Plus, natural disasters such as hurricanes, flooding, earthquakes, and landslides affect most of the world's raw material mining areas.
- Local and national governance systems. Environmental risk management of critical raw materials is of fundamental importance. It necessitates monitoring and control mechanisms, establishing strict permitting procedures to avoid local pollution and ecosystem loss, and implementing suitable, site-specific prevention and emergency plans. Efficient and effective local and national governance structures are essential to establish and then enforce such risk management methods. Unfortunately, most crucial raw material mining and extraction activities are developed in countries with medium or poor environmental performance. This is especially true for cobalt and tantalum (both mainly coming from the Democratic Republic of Congo). Furthermore, deficient management and control of site-specific environmental concerns frequently result in local pollution and ecosystem damage, putting significant strain on local communities.

To sum up, the environmental impact of raw materials is quite difficult to compute due to the complexity of their value chain and the different use they are employed to. So, it is not sufficient to just consider risks related to mining and extraction; it would be more appropriate to consider even indirect consequences such as the CO2 emissions produced during the extraction and refining of oil to provide the fuel for the production of a chemical reagent used during processing or to extract a specific raw material from mined ore. In general, other impacts are freshwater eutrophication, high energy consumption, human toxicity, and terrestrial acidification impacts.

The environmental implications of critical raw materials are both local and global. They include both direct and indirect effects resulting from resource utilisation, waste formation, and emissions during the manufacturing process.

4. Semiconductors’ ecosystem

4.1. What are semiconductors

Semiconductors are the backbone of the modern economy. They are materials required to operate solar cells, transistors, Internet of Things sensors, self-driving car circuits, etc. Semiconductors are strategic materials thanks to their electrical conductivity characteristics which are unique. Indeed, they are materials whose electrical conductivity value is higher than insulators (such as glass or rubber) and lower than conductors (such as copper or silver). Semiconductors are vital to electrical devices because they govern how, when, and where electricity flows thanks to this hybrid state between conductors and insulators (Encyclopaedia Britannica, s.d.).

Semiconductors are also called chips or Integrated Circuits (IC), but it is important to differentiate. In fact, according to the definitions provided by the EU Chips Act (2022), “*‘chip’ means an electronic device comprising various functional elements on a single piece of semiconductor material, typically taking the form of memory, logic, processor and analogue devices, also referred to as ‘integrated circuit’*”.

The most common products and components built with semiconductor materials include, among others, transistors, Light-emitting diodes (LEDs), diodes, integrated circuits, etc. The sectors in which they are used range from Artificial Intelligence (AI) to clean energy technologies and from communication to automotive. As a matter of fact, semiconductors shape how Europe's green and digital revolution will unfold by determining the qualities of the products in which they are incorporated, such as security, privacy, energy efficiency, and performance.

Semiconductors are not properly raw materials but rather processed materials mostly coming from three resources, namely silicon, germanium, and gallium, all three CRMs. This is why they are subjected to all the problems mentioned in the previous paragraphs. In fact, they have been at the centre of a significant supply crunch after the Covid-19 pandemic; they will enable both the digital and ecological transition; they arise geopolitical concerns due to the characteristics of their fragmented and interconnected supply chain. Finally, their environmental impact is most of the time left aside, but it would be interesting to go through their Life Cycle Assessment, as shown in paragraph 4.4.

4.2.The semiconductor industry

The semiconductor industry is very complex. Its supply chain encompasses Research and Development (R & R&D), design, manufacturing and assembly, testing, and packaging (ATP), which comprises input production and end-user distribution. The production phase and its inputs are supported by R&D. Semiconductor manufacturing equipment (SME), materials, design software (called electronic design automation, or EDA), and intellectual property related to chip designs (called core IP) are all inputs used in the production phase. The design and fabrication segments, as well as the SME, are the most valuable and technologically challenging parts of the whole process. EDA and core IP are crucial components that require a lot of expertise and hard skills (Khan et al., 2021).

The three steps underpinning production either occur in a single firm — an integrated device manufacturer (IDM) that sells the chip — or in separate firms, where a fabless firm designs and sells the chip and purchases fabrication services from a foundry and ATP services from an outsourced semiconductor assembly and test (OSAT) firm (Ibid.).

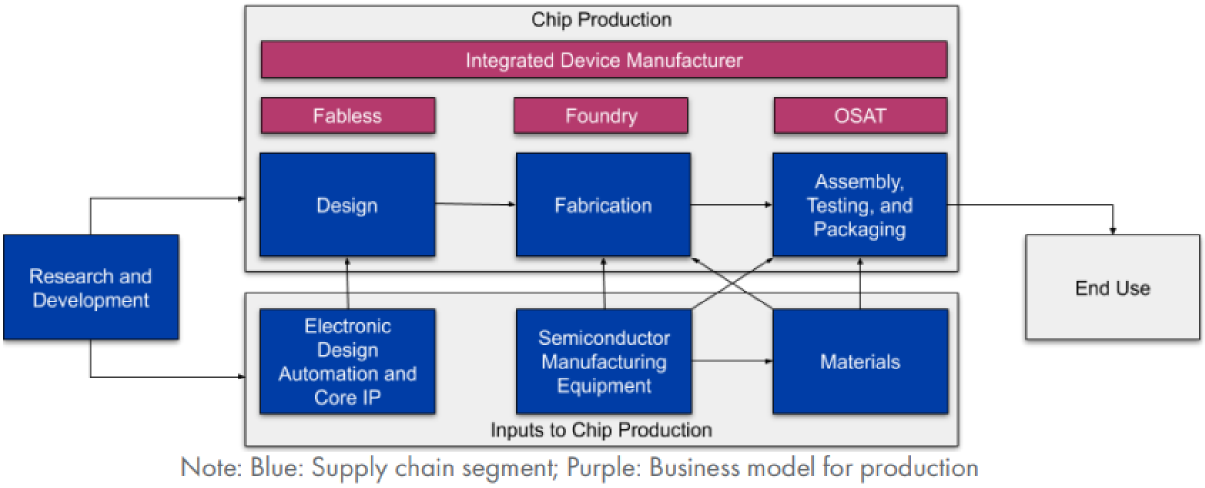


Figure 13 - The semiconductor supply chain (Khan et al., 2021)

To make things clear, I will now go through the main steps along the value chain before making some considerations on the global supply chain. Each of these step divisions feeds its resources up the value chain until the creation of the final product, the chip.

First, Chip IP Cores, also known as semiconductor intellectual property blocks, are reusable design components utilised to create advanced IC; indeed, IP cores are exchanged as rights to use and duplicate the design. In the absence of pre-designed IP blocks as a starting point, it would be nearly impossible to devise new IC designs (European Commission et al., 2009).

Another crucial production input are Electronic Design Automation (EDA) Tools. EDA is a market segment that includes software, hardware, and services that help define, plan, design, implement, verify, and eventually manufacture semiconductor devices or chips. Semiconductor foundries, or fabs, are the principal providers of this service. It takes two to three years and a skilled engineering team using EDA tools to design a complex logic chip (Gianfagna, 2021).

At the very base of a semiconductor wafer there are specialised materials and chemicals. Over hundreds gases are used such as bulk gases (oxygen, hydrogen, nitrogen, helium, carbon dioxide, argon) and other toxic gases (nitrogen trifluoride, fluorine, diborane, phosphine, boron trifluoride, silane, etc.). Plus, the semiconductors materials, in particular silicon, have traditionally been the substrate used to manufacture semiconductors but alternative materials such as gallium arsenide (GaAs) and indium phosphide (InP) have lately been employed too (Blank, 2022).

These materials need to be modelled by SME to finally get a chip. Semiconductors are created on polycrystalline wafers which are made in crystal growth furnaces. Several hundred chips can be made from a single 300-mm silicon wafer and tens of millions of transistor circuits can be found on a single chip. These circuits are created using the photolithography process which uses materials such as photoresists and photomasks as technologies (Ibid.).

For decades, the computer and semiconductor industries have worked together to propel the electronics industry forward. This combination has resulted in smaller and faster components, allowing for increasingly more powerful computing machines (International Roadmap for Devices and Systems, 2020).

The transistor dimension has traditionally been linked to the process technology in semiconductor manufacture. Nanometres (nm) are used to measure the process "node." Smaller process nodes result in smaller transistors, which are faster and more power-efficient. Today's state-of-the-art process node is 10 nm with top players producing 5 nm process nodes. While 3 nm nodes are in development and 2 nm are in pre-production. Last year, IBM announced the world's first 2 nm semiconductor chip design, one of the industry's significant advances. The business created the world's first 2nm chip. However, the smaller the chip, the higher the price to produce it (and the energy required).

Finally, Wafer Fab Equipment (WFE) are the machines that physically manufacture the chips. These are some of the world's most complex and expensive machines. They manipulate the atoms on and below the surface of a piece of silicon ingot.

To simplify, manufacturing a semiconductor chip involves the following process steps: oxidation, photolithography, doping, thin film deposition, etching, realisation, and Chemical Mechanical Planarization (CMP) (OECD, 2010).

The above description oversimplifies the technical process, but it conveys the high-level stages involved. In reality, each step is extremely complicated and requires multiple sub-steps. Besides, semiconductor manufacture is an iterative process in which the procedures are repeated to produce transistors in numerous layers on wafers. Furthermore, the atomic precision of the fabrication process necessitates clean environments, which can obstruct chip production. A semiconductor's manufacturing process typically takes 10 to 30 days (International Roadmap for Devices and Systems, 2020).

Moreover, such industry has grown vertiginously in the last decades and is expected to grow even more in the next years. The Semiconductor Industry Association (SIA) stated that worldwide semiconductor industry sales were $555.9 billion in 2021, the highest-ever annual total with a 26.2% rise over the $440.4 billion total in 2020 (Ravi, 2022).

4.3. Semiconductor global supply chain

The semiconductor industry is a global and complex supply chain. With semiconductors being the fourth most traded commodity in the world after crude oil, cars and refined oil (Jeong & Strumpf, 2021), an in-depth analysis of the main actors involved along their supply chain is deemed appropriate.

Within the semiconductors supply chain, industries often specialise in particular process steps (design, fabrication, assembly) or technology (memory chips, CPUs, etc.) in pursuit of economic efficiency. No region has the whole manufacturing stack in its own territory; in fact, no country has achieved the so-called "technological sovereignty" or "self-sufficiency." In fact, the demand for deep technical expertise and scale has evolved in a highly specialised global supply chain, in which different regions play diverse roles based on their comparative advantages. For example, because of its world-class universities, an enormous pool of technical talent, and market-driven innovation ecosystem, the United States leads in the most R&D-intensive activities, in particular in the fields of electronic design automation (EDA), core intellectual property (IP), chip design, and SME. On the other hand, East Asia, in particular, Taiwan is a leader in wafer manufacture while China is a market leader in ATP (Varas et al., 2021).

Due to this highly geographical specialisation, profound interdependencies and high labour divisions characterise this supply chain, especially across the whole production process, as shown in Figure 14. This leads to vulnerabilities across the supply chain that each region needs to address in a specific manner.

The following is a realistic example that shows the international dimension of the supply chain where (1) designs are created, (2) silicon ingots are fabricated from pure silicon and sliced into wafers, (3) bare wafers are made into fab wafers, (4) the wafer dicing process takes place, (5) chips are assembled, packed and tested, (6) chips are shipped for the inventory, (7) they are integrated into consumer goods by the end product manufacturer and finally (8) costumers buy the final product. It has been argued that a semiconductor product could travel 70 or more times across international borders before reaching the end-user (Alam et al., 2020).

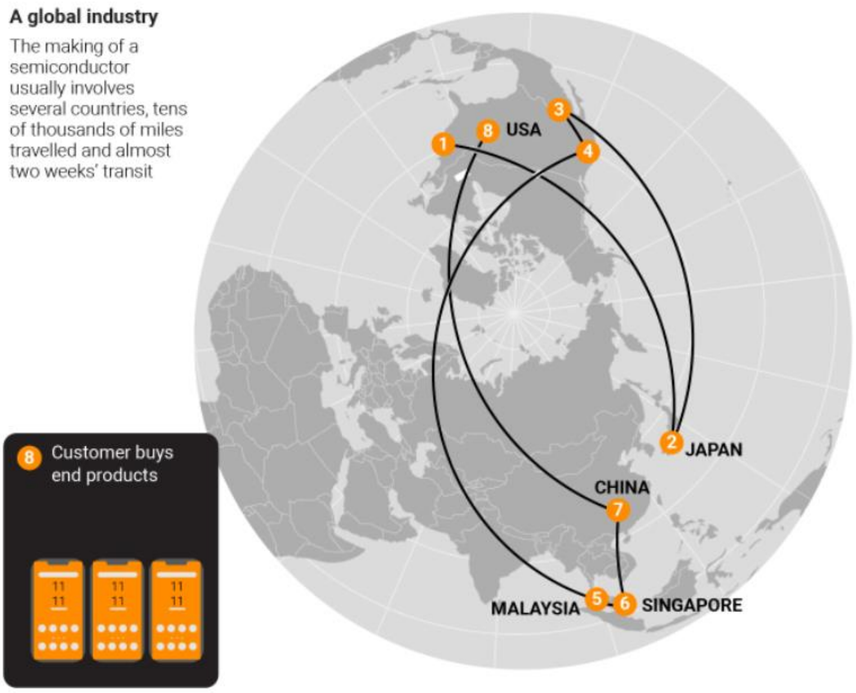


Figure 14 – The semiconductors global industry (Pan & Zhang, 2020)

As a matter of fact, the interdependencies that characterise this supply chain begin from the raw materials supply stage. As far as germanium is concerned, China, Russia, and the United States are its leading providers globally, while the EU domestic production of germanium took place in Finland until 2015. China is the major germanium producer with 80% of the share of global production, followed by the Russian Federation (5% of share), the United States and Japan (2% of global supply each), and minor production from Ukraine (1% of global supply) (European Commission, 2020).

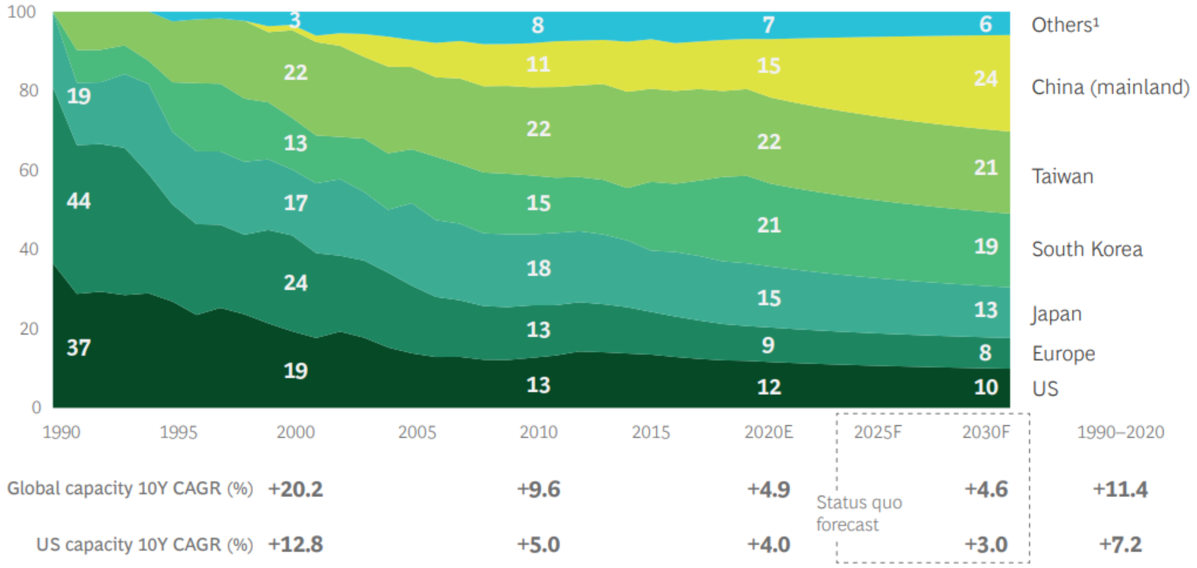
The dangers posed by this kind of centralisation are tangible. Between 2012 and 2016, China, one of the EU's main suppliers of germanium, imposed a 5% export tax on germanium oxide. Initially, the export tax was imposed in 2010, when the Chinese Government attempted to control raw material exports (European Commission, 2014). China has adopted several actions in recent years to preserve germanium resources, including stockpiling and raising taxes, resulting in a significant drop in the export of germanium and its products (British Geological Survey et al., 2017).

Regarding silicon, China has a 66% share in production, followed by the United States (8%), Brazil (7%), and Norway (6%). France, Germany, and Spain produce silicon metal in the EU, accounting for 6% of the global supply (Reichl & Schatz, 2019). China's market share among worldwide producers will continue to grow, following the same trajectory as in previous years. This tendency could be explained by China's production costs remaining at the lowest level in the world, as well as by China's production overcapacity (Euroalliages, 2016). Anti-dumping taxes on silicon metal from China have been imposed by the US, EU, and Canada.

As far as gallium is concerned, it is mainly produced in China, Germany, and United Kingdom with 81% of production in China (Reichl & Schatz, 2019).

Overall, it can be said that China dominates the raw material global market, but the same cannot be said for the production phase.

As it is possible to note from Figure 15, a few main countries define the semiconductors' production value chain: the United States, Taiwan, South Korea, Japan, Europe, and, increasingly, China. For example, fabless enterprises in the United States rely on Taiwanese foundries to produce their chips. The foundries themselves rely on US, European, and Japanese equipment, chemicals, and silicon wafers (Kleinhans & Baisakova, 2020). As a result, such supply chain is extremely vulnerable to external shocks and disruptions because any of the countries mentioned above could enact export controls.



Sources: VLSI Research projection; SEMI second-quarter 2020 update; BCG analysis.

Note: All values shown in 8" equivalents; excludes capacity below 5 kwpm or less than 8".

[1] Includes Israel, Singapore, and the rest of the world.

Figure 15 - Global manufacturing capacity by location (%) (Varas et al., 2020)

Moreover, Figure 15 shows that in recent decades, chip production has shifted away from its traditional strongholds. In 1990, semiconductor manufacturing was controlled by Japan, Europe, and the United States; however, when South Korea, Taiwan, and eventually China entered the market, the three main manufacturing locations were reduced to a combined market share of roughly 35% in 2020, and the downward trend is expected to continue.

As already said in the previous paragraphs, the companies involved in the production of the semiconductor phase are very different from one another, in fact, they have different business models based on whether they are fabless companies (e.g. Qualcomm), foundries (e.g. TSMC), Outsourced Semiconductors Assembly and Test (e.g. ASE Group), Integrated Device Manufacturers (e.g. Intel) or suppliers (e.g. ASML).

In particular, the fabless and IDM markets are dominated by American companies holding a 65% and 51% market share, respectively (Tseng, 2022).

For what concerns foundries, Taiwanese foundries, mainly thanks to TSMC, currently hold a 65% market share, followed by South Korea (16%) and China (6%). The company SMIC ranks first in China and fifth globally, with around 4% of the global foundry market share (Ibid.). In particular, the world's most sophisticated semiconductor production capacity, in nodes below 10 nanometres, is now concentrated in South Korea (8%) and Taiwan (92%). These are single points of failure along the supply chain that can be affected by natural catastrophes, infrastructure outages, or international conflicts, resulting in catastrophic chip supply disruptions (Varas et al., 2021). Moreover, forecasting when capacity will be able to fulfil current demand and if that demand will sustain is a severe challenge for semiconductor companies. End users do not buy semiconductors directly but rather the finished commodities in which semiconductors are contained. This degree of divergence makes forecasting where supply and demand will meet more difficult.

Restrictions are not imposed just on the raw material market but also at the manufacturing level. For example, the US imposed two types of restrictions on China in the context of the US-China trade war. The first one was in 2018 when the United States imposed 25% tariffs on semiconductors imported from China. The second one in 2019, when the US deployed export controls on American semiconductors sales to keep Huawei from accessing inputs, particularly chips, needed to manufacture base stations for 5G (Bown, 2020).

Throughout the semiconductor ecosystem, nationalistic technology and trade policies increase cost pressure and supply chain complexity. Tariffs on imported or exported components raise manufacturing costs, prompting businesses to investigate different tariff mitigation measures. They also pose logistical and regulatory issues. Due to such limitations, access to important end markets could be restricted, potentially leading to a considerable loss of scale.

4.3.1. The Covid-19 pandemic and the semiconductor crunch

The Covid-19 pandemic has led many parts of the world to reconsider how they organise their supply chains, particularly in areas where raw materials and intermediate products and processes are highly concentrated, putting them at greater risk of supply disruption. This was the case for semiconductors.

Demand for consumer electronics increased by 7% during the pandemic's lockdowns (Strategy Analytics, 2021), as everyone needed laptops, webcams, and other items to work from home, limiting supply and resulting in cost-driven price spikes. Covid-19 also caused global supply chains to be interrupted, exacerbating the impact of the shortfall. As the lockdowns eased during the summer 2020, demand for semiconductor chips surged even more as automakers restarted production, resulting in a scarcity across all semiconductor-dependent businesses. In fact, during the Covid-19 pandemic, not only did production plants in Asia, which generate more than half of the world's chips, close, but when they reopened, the rise in chip demand produced protracted supply bottlenecks, creating inflation and weakening Europe's GDP (Bauer et al., 2020).

As a matter of fact, the pandemic shed light on the rigidity of the semiconductors supply chain. Indeed, it is difficult for semiconductor fabs to modify their output in response to external shocks, as the shortage has proved. Building a new fab to satisfy increased demand is not a viable short-term solution due to the enormous expenditure and time necessary. Building a fab and ramping it up to total capacity can take from 24 to 42 months and cost between US$1.7 billion and US$5.4 billion, depending on the quality of the chips produced (Ibid.).

4.3.2. The Ukrainian war and the impact on neon supply

The Ukrainian war is a striking example of an external shock affecting the semiconductor industry. It sheds light on the supply chain interdependencies and shows their weaknesses since if a single piece is lacking, the whole production is affected worldwide.

Neon is a noble gas used in semiconductor photolithography, and according to Reuters calculations, two Ukrainian companies, Ingas and Cryoin, produce 45% and 54% respectively of the world's semiconductor-grade neon, which is vital for the lasers needed to create chips. Both firms shuttered their operations as soon as the Russian invasion began. While estimates vary significantly on how much neon stock chipmakers keep on hand, production could suffer if the conflict carries on. Ingas used to produce 15,000 to 20,000 cubic meters of neon per month for customers in Taiwan, Korea, China, the United States, and Germany, with roughly 75% going to the chip industry. Nevertheless, Taiwan's Economy Ministry, which is home to the world's largest chip maker, TSMC, stated that Taiwanese companies had previously taken advanced preparations and had "safety supplies" of neon, indicating that there would be no supply chain issues in the near future. However, this couldn’t be true for each chip fab, and such a shortage could exacerbate the chip crunch caused by the Covid-19 pandemic (Alper, 2022).

Moreover, Ukraine supplies more than 90% of U.S. semiconductor-grade neon, threatening American manufacturing if stockpiles are not enough, and as a consequence, all the actors relaying on American chips.

4.4. Semiconductors’ Life Cycle Assessment (LCA)

Life Cycle Assessment is a cradle-to-grave analysis technique used to evaluate environmental and human health implications associated with all stages of a product's life, from raw material extraction to processing, manufacturing, distribution, and usage (Muralikrishna & Manickam, 2017).

Regarding semiconductors, the indicators considered are global warming potential, water use, acidification, eutrophication, ground-level ozone (smog) formation, ecotoxicity, possible human cancer and non-cancer health consequences. However, all the studies on semiconductors LCA lack data accuracy and use estimation methods for assessing emissions along the supply chain. Besides, LCA is carried out on representative products of the industry and the technical knowledge that characterises the semiconductors ecosystem makes it more challenging to assess the real impact.

Nevertheless, it is essential to understand the potential impact of such industry from the environmental point of view, a perspective that is mainly left aside. This study will consider three primary parameters: water, resource, and energy consumption. The e-waste and recycling discourse won’t be addressed in this LCA since it falls outside the scope of this analysis.

Moreover, the LCA will focus on the silicon wafer production process, which is very resource-intensive. However, it is important to underline that the LCA of other processes for which silicon is used (e.g. silicon solar cells) could have a lower impact (Schmidt et al., 2012).

As stated in the Semiconductor Review (2020), "*fabricating a small 2g microchip requires 32 kilograms of water, 1.6 kilograms of petroleum and 72 grams of chemical. If we multiply these values by the millions of the chips manufactured in just one factory each year, the result will serve as evidence for large-scale wastage of water along with the generation of toxic chemicals*."

The impact evaluation results carried out by Schmidt et al. (2012) demonstrate that energy consumption is the main cause of the environmental damage when the production of silicon wafers is concerned, followed by upstream chemical production. The use of nitrogen is the most impactful factor among the chemicals used while, in terms of ecosystem quality, wastewater treatment is quite important. In fact, fabs are intensive water users, both in terms of direct water consumption and electricity use, as well as during the lifecycle of the manufactured product. Water is used for cooling equipment, heating, ventilation, and air conditioning systems. Most of the water, in particular ultrapure (deionised) water, is used for rinsing the chips (Frost & Hua, 2017). In fact, Intel believes that 97.26% of its direct water use occurs during manufacture within its own fabs (Intel, 2016). In 2016 the semiconductor industry used 21.8 billion cubic meters of water globally (including water for electric generation) (Frost & Hua, 2017); a quarter of the water used by the global textile industry, the most water-intensive one, which used 79 billion m^3 of water in 2015 (Scott, 2020).

Consumption of chemicals is also relevant for the overall environmental impact; chemicals (in particular, nitrogen consumption in the semiconductor industry is very high) and high purity gases are used. The procedures that turn wafers into hundreds of individual dies (like deposition, selective removal, patterning and cleaning) necessitate the use of materials like acids, bases, and solvents. Indeed, workers in a semiconductor factory are likely to be exposed to carcinogens, and overall, the upstream production of chemicals affects particularly human health (Schmidt et al., 2012).

A significant contribution to the semiconductor environmental footprint is given by electric power. It is required for both production and service activities such as cooling power generation, ultrapure water generation, climate management, etc. More than half of the total electricity demand in the semiconductor industry is accounted for by these service activities (Ibid.). Electric power is also needed to create clean room conditions.

The direct greenhouse gas emissions include NF3, HFCs and PFCs, carbon dioxide, and methane, with the carbon dioxide coming from the oxidation of VOCs, HFCs and PFCs. Overall, energy consumption is responsible for approximately 75% of the total greenhouse gas emissions in the semiconductor sector (Boyd, 2012).

Considering all the inputs needed for wafer production, a total of 28 tonnes of CO2 equivalents is emitted per square meter (Schmidt et al., 2012).

In 2021, the silicon wafer area shipments worldwide amounted to 14.17 billion square inches (Silicon Wafer Global Area Shipments 2010-2021, 2022), about 9.2 million square meters.

*28 tonnes of CO2eq*9.2 million m^2 = 257.6 million tonnes of CO2eq*

This calculation provides a rough estimate of the total emissions caused by the semiconductor industry in a year, considering all the inputs in the production stage, namely the supply chain segment that Europe would like to foster in its territory.

To compare it with the impact of other raw materials, silicon ranks 10th in the global production impact (European Commission & Joint Research Centre, 2020). Overall, such industry does not have the same environmental impact as the others that, as for the case of aluminium, generates more than 1.1 billion tonnes of CO2 equivalents emissions annually – around 2% of global emissions (World Economic Forum, 2020). However, following this logic, the semiconductor industry would account for 0,47% of the total CO2 emissions worldwide. Nevertheless, the desire to make them even smaller and more efficient has complicated their production process: their production process is increasingly energy-intensive and has come to include the use of increasingly harmful chemicals and rare materials (Garcia Bardon & Parvais, 2020). The environmental impact has thus increased, as shown in Figure 15, and become more complex to govern.

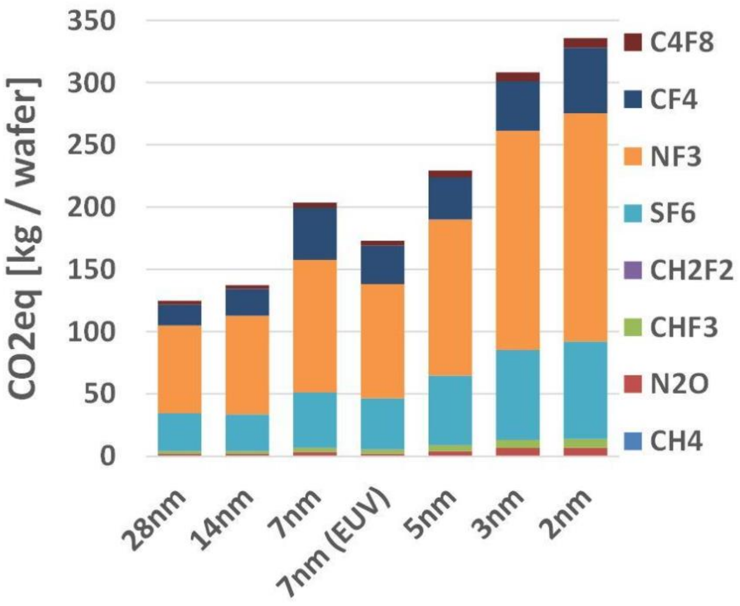


Figure 16 - Estimated equivalent CO2 emissions from greenhouse gases used in process flow across different nodes (Garcia Bardon & Parvais, 2020)

Another relevant factor to the purpose of this LCA is the transportation impact. As has already been said, before making it to the final market, a chip can cross international borders over 70 times (Alam et al., 2020) and so travel across the globe contributes to increasing the semiconductor industry's carbon footprint.

Because energy costs continue to climb and renewable energy sources have yet to become mainstream energy sources, limiting the amount of power required by electronics makes economic and business sense. Energy-efficient semiconductors can help to create products that require less energy. Continued scaling will necessitate the design and fabrication of more energy-efficient semiconductors to improve performance. Chip designers are focusing on lower power architecture to minimise the voltage required and also on improvements in standby power and auto shut-off transistors at the logical design level. At the same time, at the R&D level, new materials have been used to reduce current leakage and the amount of energy consumed by semiconductors. However, the system design and software levels offer the greatest chance to minimise a system's power usage and thus the world's energy consumption (NXP, 2010).

5. The European strategy for semiconductors’ supply

5.1. The European Chips Act

Nearly all the governments of the counties involved in the semiconductor industry took action to address the shortage, from the US to Taiwan to South Korea.

The Chips Act is the perfect example of the communitarian effort to manage and finance the digital and ecological transitions at the European level. At the same time, it is a strategy to address resource criticality that characterises the semiconductor sector. Indeed, it can be seen as a mitigation action since it is a way to secure supply and increase the manufacture of a strategic material through a large investment plan. In particular, the Chips Act is a proposal for a Regulation “*establishing a framework of measures for strengthening Europe’s semiconductor ecosystem*” released by the European Commission in February 2022. It has been conceived as a normative response to the semiconductors supply crunch due to the Covid-19 pandemic, highlighting the strong third-country dependency in manufacturing and chip design.

As can be seen in Figure 17, Europe holds a small share of the semiconductor market (9-10%), and it is not even in expansion. It has become clear, also from figure 15 in paragraph 4.3, that the European semiconductor sector has been in decline for at least 30 years, at the expense of the industry growth in other parts of the world, primarily North America and Asia.

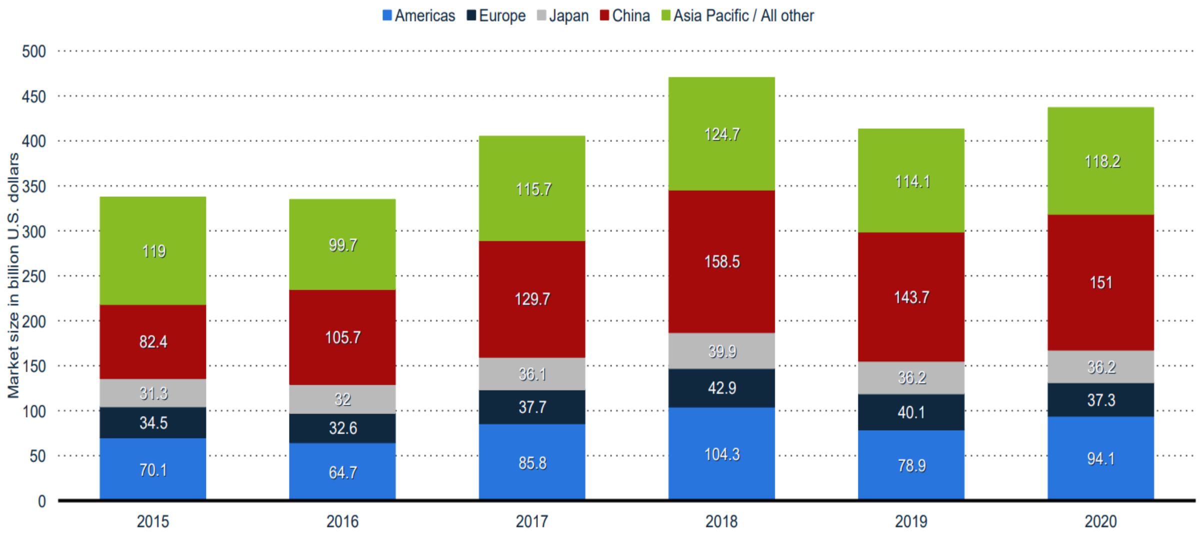


Figure 17 - Semiconductor sales worldwide from 2015 to 2020, by region (in billion U.S. dollars) (SIA, 2021)

However, the Regulation proposal acknowledges that Europe is now strong in research and sectors such as power electronics, industrial automation and equipment manufacture, analogue chips, and low-power technology, but it also recognises that it has vulnerabilities. These include a high reliance on East Asia for chip fabrication, packaging, testing, and assembly, as well as a lack of design and manufacturing capabilities for leading-edge nodes.

The European ambition is, therefore, to double the current market share to 20% by 2030. Public and private investments back such an ambition up to a total amount of 43 billion euros. In particular, the proposal has two objectives.

1. To safeguard the Union's competitiveness and innovation capability, as well as the industry's response to structural changes as a result of fast innovation cycles and the need for sustainability.
2. To strengthen the internal market's functioning by establishing a standard Union legislative framework for increasing the Union's resilience and supply security in semiconductor technology.

To fulfil this plan, the EU has set five strategic objectives:

- Europe should strengthen its research and technology leadership;
- The Union should put in place and reinforce its own capacity to innovate in the design, manufacturing and packaging of advanced chips and turn them into commercial products;
- Europe should set up an appropriate framework to increase its production capacity significantly by 2030;
- The EU should address the skills shortage, attract new talent and support the emergence of a skilled workforce;
- Europe should gain an in-depth understanding of global semiconductor supply chains.

The Chips for Europe Initiative, Security of Supply, and Monitoring and Crisis Response are the three pillars that support the European Chips Act's implementation and achievement of its goals. The funding envisaged will increase Europe's capacity and expertise in areas such as advanced chips below 2 nm, disruptive technologies for AI, ultra-low power energy-efficient processors, etc.

The effort builds on and complements the Digital Europe and Horizon Europe programs; in particular, the former promotes the development of digital capacity in key digital domains where semiconductor technology underpins performance gains, such as High-Performance Computing, AI, and Cybersecurity, as well as skills development and the deployment of digital innovation hubs. In the field of materials and semiconductors, the Horizon Europe (HE) initiative supports rigorous pre-competitive research, technology development, and innovation.

5.1.1. The funding mechanism

The EU budget will contribute up to 3.3 billion euros to the Chips for Europe Initiative, including 1.65 billion euros through Horizon Europe and 1.65 billion euros under the EU's Digital Europe Programme. A new Chips

Joint Undertaking will implement 2.875 billion euros, InvestEU will implement 125 million euros (to be supplemented by another 125 million under InvestEU itself), and the European Innovation Council will implement 300 million euros.

Overall, the public investment comprises 11 billion euros for the 'Chips for Europe Initiative,' which will fund technological leadership in research, design, and manufacturing capacities until 2030. These funds will be raised by pooling investment from the EU and Member States, with the expected participation of the private sector.

The 'Chips Fund' will supplement this budget by providing equity support to start-ups, scale-ups, and other supply-chain enterprises through investment facilitation initiatives. The total investment value is expected to be at least 2 billion euros.

Because government subsidies are prohibited under current EU state aid rules (cf. Article 107 and 108 TFEU), the proposal Regulation establishes a procedural framework to facilitate combined funding from Member States, an investment that is not subject to state aid rules, the Union budget, and private investment without violating EU state aid rules. Moreover, this is in line with the recent communication from the Commission, “A competition policy fit for new challenges”, which states that

> *the Commission may envisage approving public support to fill possible funding gaps in the semiconductor ecosystem for the establishment in particular of European first-of-a-kind facilities in the Union, based on Article 107(3) TFEU. Such aid would have to be subject to strong safeguards to ensure aid is necessary, appropriate and proportionate, undue competition distortions are minimised, and that benefits are shared widely and without discrimination across the European economy.*

5.2.PROs

The EU Chips Act is a government-led effort to bring part of the semiconductor supply chain onshore and, at the same time, create a semiconductor supply chain of politically allied countries.

Support supply chain resiliency through geographic diversification is imperative. It is, in fact, the primary purpose of the Chips Act to foster chip manufacturing in Europe. The 'Chips for Europe Initiative', established under the proposed Chips Act, will help Europe establish large-scale capability by investing in cross-border and publicly accessible research, development, and innovation infrastructure (European Chips Act Proposals in Detail, 2022).

The Chips Act envisages a framework for ensuring supply security and resiliency by attracting new innovative manufacturing facilities and investments within the EU. It will also include modern packaging, testing, and assembly facilities to foster ecosystem spillovers and interactions.

In a field in which hard skills are key for the development of advanced chips, it is necessary to invest in education, training, skilling, and reskilling programs. Indeed, the Chips for Europe Initiative comprises postgraduate microelectronics programs, short-term training courses, employment placements/traineeships/apprenticeships, and advanced laboratory training.

A coordination mechanism between EU Member States and the Commission will be formed to monitor supply chains and avoid shortages. This coordination will include monitoring semiconductor supply, predicting demand, anticipating shortages, and, if necessary, triggering the activation of a crisis stage. Early warning signs of potential bottlenecks and shortages will be developed as part of the efforts.

Finally, aside from these internal measures, the EU would attempt to form solid international alliances with like-minded countries. Its goal is to improve coordination and reduce the likelihood of competing plans. Such collaborations will allow for a thorough examination of third-country policy in the sector, as well as cooperative remedies to supply difficulties, including mutually advantageous diversification options.

If it is true that it makes no sense to replace one dependency with another, at the same time, total self-sufficiency is not a realistic scenario. As counterintuitive as it may seem, to meet current levels of semiconductor consumption, fully "self-sufficient" local supply chains in each region would have required at least $1 trillion in additional upfront investment, resulting in a 35% to 65% overall increase in semiconductor prices and ultimately higher costs of electronic devices for end-users (Varas et al., 2021).

As demonstrated by a survey carried out by KPMG together with the Global Semiconductors Alliance, 53% of the 156 semiconductor CEOs interviewed named territorialism, namely cross-border regulation, tariffs, trade and national security policies, as the most significant industry issue (KPMG & Global semiconductor Alliance, 2021).

5.3. CONs

In 2013 the EU failed with a similar plan, "*A European Industrial Strategic Roadmap for Micro- and Nano-Electronic Components and Systems*", to foster the semiconductor industry. Indeed, the expansion of the European production capacity should be mainly driven by market demand instead of political imperatives. This does not mean that governments should refrain from granting incentives. Governments' role should be to enact policies and investments to enhance the already existing capacities developed in the territory rather than financing from the ground up other supply chain segments that are already strongly developed and consolidated in other parts of the world. Indeed, it will be difficult for EU manufacturers to catch up in an industry that requires significant capital investment and has a long payback period. In fact, during the time needed to catch up, foreign companies would make further technological advances. So, if it is true that long term planning brings with it its advantages as opposed to short term, it is also true that it has to arrive on time. In fact, the EU Chips Act seems not able to address the complexity of the semiconductor environment.

Moreover, the 2nm design goal is quite ambitious in a sector in which production is difficult to adjust over short time frames for several reasons, including the high R&D requirements for chip design. The immense capital and time needed to build efficient semiconductor factories and high entry barriers. Furthermore, the proposal Regulation sets an ambitious strategic target of increasing semiconductor output from 10% of world supply to 20% by 2030. Because the global industry is predicted to double in size by that year, the existing manufacturing capacity would be quadrupled, making the target even more challenging.

Finally, all the new entities envisaged by the Regulation proposal may complicate the already tangled ecosystem and create bureaucratic obstacles to the smooth development of the industry.

5.4.The paradox of the EU Chips Act

To better understand the potential impact of the European investment plan for semiconductors and its ambitions, it is important to place the Chips Act in a broader context of EU strategies that somehow impact the semiconductor ecosystem, particularly the environmental dimension. As it has been said, semiconductors production has a carbon footprint itself but at the same time, they enable the twin transitions. Therefore, weighing the trade-offs and understanding the potential clash between industrial and climate policies is imperative.

5.4.1. Cross-analysis with the EU Emission Trading System

Europe has implemented the Emissions Trading System through Directive 2003/87/EC (revised by EU Directive 2018/410), similar to a European carbon price on energy-intensive industries. The Directive states that major polluting firms in the European Union must have a greenhouse gas emissions permit commencing January 1, 2005. Each installation must annually offset its emissions with permits (European Union Allowances - EUAs, which are equal to 1 tonne of CO2eq) that can be purchased and sold by the individual operators. Allowances are available for purchase or free of charge in European public auctions, or they can be purchased on the market. Each Member State creates a National Quota Allocation Plan and submits it to the European Commission for approval. Following that, the Commission guarantees that the entire ceiling is not exceeded. Such scheme also has an indirect consequence since it implies rising prices, as shown by different macroeconomics analyses (Sager, 2019; Stede et al., 2021).

Article 27 of the Directive 2003/87/EC states that "*Member States may exclude from the Community scheme installations which have reported to the competent authority emissions of less than 25000 tonnes of carbon dioxide equivalent and, where they carry out combustion activities, have a rated thermal input below 35 MW, excluding emissions from biomass*".

A semiconductor plant, like Samsung, emitted 12.9 million tons of CO2 equivalents in 2020 and uses about 100 MW of power each day (Hardison, 2021). Therefore, it is possible to assume that the semiconductor manufacturing industry, that Europe yearn to develop, would not be exempted from the application of such a system.

Figure 18 brings together two rising trends, the amount of CO2 emissions to produce silicon wafers and the ETS price in euros. The process that brought to this graph is fully explained in the Annex at the end of the document.

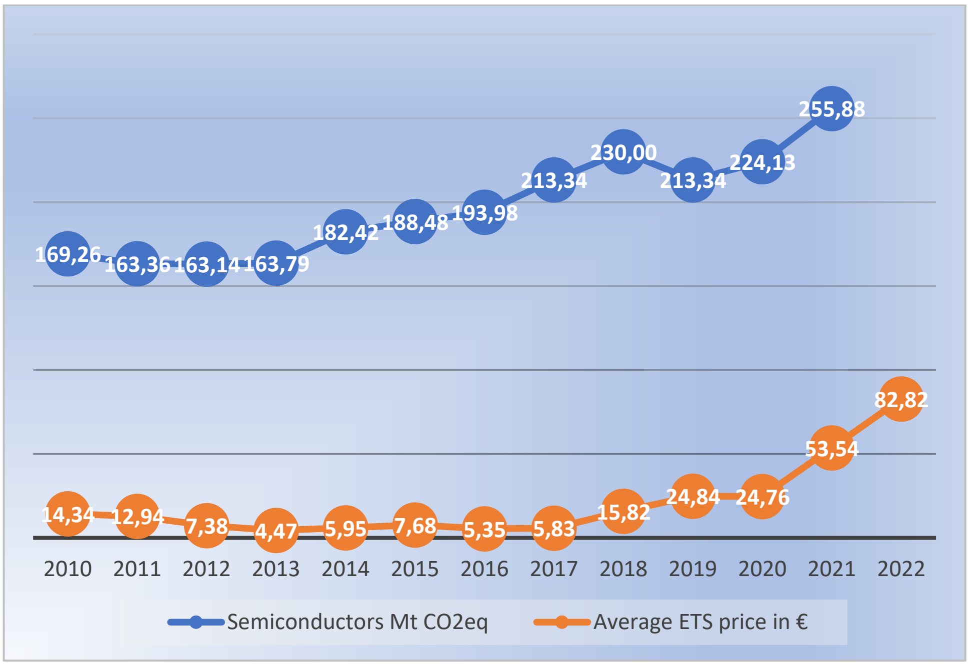


Figure 18 - Semiconductor industry CO2 emissions and ETS price rising trends (own elaboration)

Assuming that semiconductor plants would be subjected to the ETS would entail enormous consequences. In fact, many macroeconomic studies assess that prices of final goods rise when a carbon tax is applied (Känzig, 2022; Baranzini et al., 2000). Therefore, it is possible to say that European chips would be more expensive than the foreign ones. Besides, since the price shown in the chart is an average (the price on May 13th, 2022, was €88.48), the final European product would be much more expensive than its competitors. Plus, the situation is worsened because the price of the European carbon tax on CO2 emissions is rising, which would entail higher costs for companies. Indeed, it is expected to reach €100 by the end of 2022 (Twidale, 2021), which is also the price deemed appropriate to achieve the net-zero target by 2050, together with other decisive mitigation actions (Bhat, 2021).

Moreover, according to a recent Kearney analysis on the future of semiconductors, the total cost of manufacturing chips in Europe is 30-40% higher than in Taiwan or South Korea, two important semiconductor-producing nations (Aurik et al., 2021).

This would give an additional competitive advantage to Asian industries whose products, not being subject to climate policies, have lower costs, thus scuttling the European ambition to be a market leader in the chips manufacturing ecosystem. This would end up with no real emancipation from foreign competitors, and even if Europe would manage to meet the 20% market share target by 2030, the dependence on Asia would not be lessened, as global value chains are too intertwined and too reliant on producers in East Asia.

Nevertheless, the EU is trying to protect the Internal Market, particularly those goods vulnerable to global competition, with an adjustment mechanism such as the Carbon Border tax within the Carbon Border Adjustment Mechanism (CBAM). "*The CBAM will equalise the price of carbon between domestic products and imports and ensure that the EU's climate objectives are not undermined by production relocating to countries with less ambitious policies. It also aims to encourage industry outside the EU and our international* *partners to take steps in the same direction*." (Carbon Border Adjustment Mechanism, 2021). Such mechanism will also reduce the carbon leakage risk and decoupling which have the potential to sabotage any global climate change agreement or even a local carbon tax, as in this case.

It goes without saying that Europe cannot impose environmental standards outside its territory. Nevertheless, it can promote its products within the internal market. However, this measure would fall into the already cited fear of territorialism or nationalism (cf. Par. 5.2) of the semiconductor industry, hence tightening up the complex relations among the supply chain actors and increasing the fear of potential disruptions.

5.4.2. The implications on the net-zero emissions 2050 target

The European Climate Law, proposed and endorsed by the EU Commission in 2021, intends to attain net-zero carbon emissions for EU countries by 2050, primarily by cutting emissions, investing in green technology, and safeguarding the natural environment, as required internationally.

As shown in par. 4.4 most of the CO2 emissions in the semiconductor value chain come from chemical use and electricity consumption during the manufacturing process. Since Europe has not developed its own semiconductor manufacturing industry yet, it is interesting to analyse the American one in such terms. The semiconductor industry consumes 1.3–2.0% of total manufacturing electricity in the United States (Gopalakrishnan et al., 2010). Besides, the study carried out by Kuo et al. (2022) showed that 85% of climate change and particulate matter contributions occurred during the manufacturing stage of semiconductors' life cycle.

In light of these data, it would be normal to wonder whether financing and developing a pollutant industry such as the semiconductor one in Europe would impact the achievement of the net-zero emissions by 2050 targets.

Developing a European semiconductors manufacturing industry would mean more significant effort both to switch to renewables and to foster environmental compensation and mitigation actions.

6. Discussion

The findings of this study result in two main insights that answer the research question.

First the inadequacy of the EU Chips Act as a Regulation by its very nature. In fact, it contains several practical and economic obstacles to achieving the predetermined goal of the 20% semiconductor market share by 2030. There is no European semiconductor firm among the top 10 producers in the world, and in an industry based on economies of scale, this lack of scale among European manufacturers is a major barrier. Furthermore, because of the small size of the European chip market and its fragmentation across different technology nodes, producing at scale for the European market will be problematic. Although EU alliances, incentivised in the EU Chips Act, have the potential to solve the scale issue, first, they must be formed and then sustained over time. However, European companies do succeed in various segments other than fabrication. The Union is currently competing in three relevant markets. One is the development of cutting-edge manufacturing equipment. The other is AI chip design, and a third example is semiconductor research and development in general.

The Union should finance and thus foster these sectors, hence its existing strengths, rather than spending public money on a subsidy war over fabrication capacity with the rest of the world. In fact, the costs may end up outweighing the benefits. Most probably, the EU Chips Act will not bear any tangible results, thus wasting time and, above all money.

The second finding consists in the inadequacy of the EU Chips Act as an example of industrial policy in relation to already-in-force climate policies that could be applied to the European semiconductor industry. In fact, the carbon footprint of the semiconductor industry should not be underestimated, and Europe should embrace a broader view when designing an industrial policy encompassing environmental analysis. The EU Chips Act was born as an expeditious response to an external shock, namely the semiconductor shortage caused by the Covid-19 pandemic, and as such, it lacks long term vision. Europe is thus financing a strategic industry which is at the same time very polluting. Assuming that the ETS would apply, it would result in a less European competitive product. This would not just mean a money waste but also a huge struggle in achieving the 20% market share set by the proposal Regulation in a structured industry where every supply chain segment has its well-established and specialised players while also making it harder to achieve the net-zero emission target by 2050.

Despite climate and industrial policies may seem to have opposite goals, namely the former to foster decarbonisation and the latter to boost economic competitiveness and employment, a new trend in policy which conciliates these two approaches takes shape in the so-called green industrial policies (Rodrik, 2014). At first sight, it is easy to be wary of such a portmanteau since the word “green” is often misused for greenwashing strategies. However, the aim of green industrial policies is to design an industrial strategy in which climate change mitigation becomes a binding constraint in the overall goal of social welfare policy. Their goal is not easy; indeed, policymakers should balance difficult trade-offs and missing the climate change targets would have to come at a cost. Thus, Rodrik (2014) proposes that modern industrial policy should be a "*process of institutionalised collaboration amongst the private sector, government, and civil society*” instead of a top-down strategy. This new approach also entails a much larger objective function, one that includes more long-term sustainable growth in addition to short-term competitiveness and growth.

Although the EU Chips Act claims to be consistent with the European Green Deal because semiconductors will enable the ecological transition, it is possible to argue that it is not a green industrial policy since it does not address the industry’s GHGs externalities.

Therefore, this thesis suggests that the European regulators should adopt the green industrial policy approach. Europe is still a long way from implementing a comprehensive green industrial policy. It has a plethora of green industrial policy efforts at best, the majority of which are uncoordinated, and some are even contradictory. Thus, the European Green Deal's goals could be met if the EU would pursue a green industrial policy in a coordinated way, without fragmenting the EU single market and jeopardizing Europe's level playing field.

7. Conclusions

In conclusion, it is possible to state that the EU Chips act seems an expeditious response to the semiconductor shortage rather than a rigorous industrial policy, thus colluding with some European environmental commitments such as the net-zero emission target by 2050 and the Emissions Trading System. The Union should focus on resource governance and supply chain management, availing the instrument provided by the Commission like the Critical Raw Material list. The EU should, in fact, promote effective green industrial policies encouraging long-term objectives while engaging the entire society and encompassing climate mitigation targets rather than short-term competitiveness of specific sectors and enterprises.

The paradox of the proposal Regulation lies in the fact that the EU is financing a pollutant industry in its territory; given such characteristics, it will potentially be subject to the ETS mechanism. However, the Carbon Border Adjustment Mechanism would be enacted to protect European semiconductor competitiveness at the price level and reduce carbon leakage risk. Thus, sharpening international competition and, at the same time fostering national protectionism, causing disruption along a supply chain which is already fragmented.

To move beyond this concrete example, the goal of the present analysis was to dig into the difficult relationship between industrial and climate policies at the European level in a delicate context such as the digital and ecological transitions. It shows the complex interconnections of these kind of policies and how a thorough ponderation of the global ecosystem and other internal strategies should be accounted for. We live in a world whose complexity is difficult to grasp due to intertwining interests; if we try to regulate it through narrow policy focuses, we will never be able to govern its complexity in a coherent way.

Finally, the European Union was born as an economic entity, specifically as an economic entity to manage two raw materials such as coal and steel (cf. European Coal and Steel Community); in the last years it reset its priorities, namely decarbonisation and digitalisation, but through a cross-analysis of industrial and climate European policies, it is possible to notice that deep down Europe has not betrayed its original essence based on industrial and economic imperatives.

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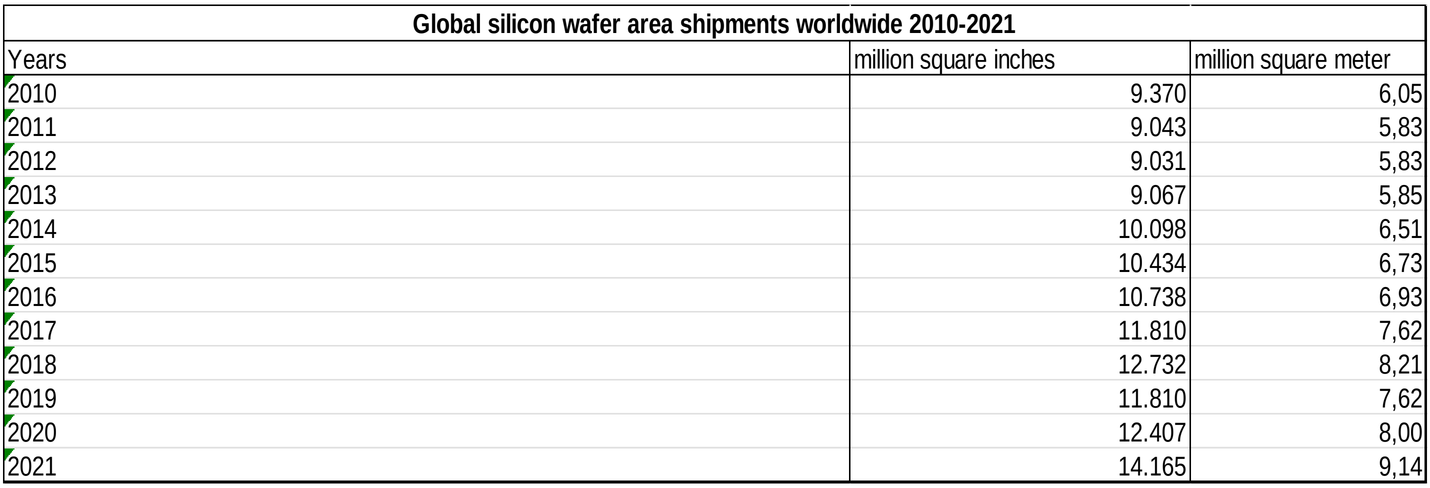
Annex

This section specifies the data elaboration process carried out in Excel to answer the research question.

First, secondary data were gathered. The dataset related to the ETS price over the years was downloaded from the International Carbon Action Partnership (ICAP) database (2022). The European Union Allowances (EUAs) spot price data were provided by the EEX Group. Afterwards, data ware cleaned from missing values, and the annual average price in Euros was calculated for the period 2010-2022, as shown in the tab.

Average ETS price per year (euro)	
Year	Average price
2010	14,34
2011	12,94
2012	7,38
2013	4,47
2014	5,95
2015	7,68
2016	5,35
2017	5,83
2018	15,82
2019	24,84
2020	24,76
2021	53,54
2022	82,82

Two factors were considered for computing the annual tonnes of CO2 equivalents emitted in the period 2010-2021 from the semiconductor industry. First, as stated by Schmidt et al. (2010) in their analysis on the Life Cycle Assessment of silicon wafer processing for microelectronic chips and solar cells, silicon wafer production, including all the inputs, emits a total of 28 t of CO2 equivalents per square meter. Then, I downloaded data on silicon wafer area shipments worldwide from 2010 to 2021 (in million square inches) (Statista, 2022), whose source is the Semiconductor Equipment and Materials International (SEMI) Silicon Manufacturers Group SMG. Since the unit of measure needed was square meter, these data were converted as shown in the tab below.

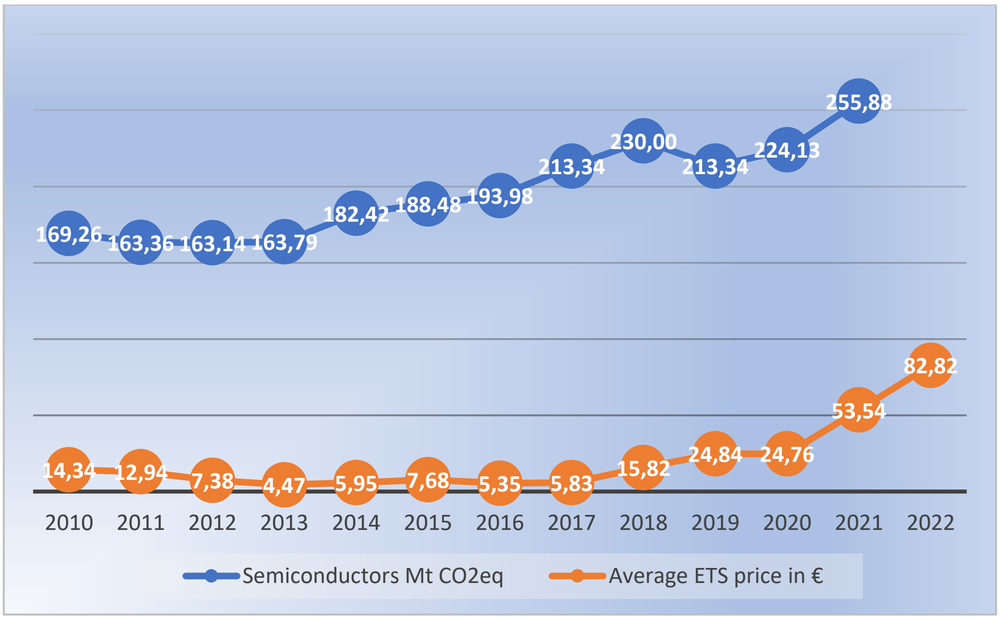


Global silicon wafer area shipments worldwide 2010-2021		
Years	million square inches	million square meter
2010	9.370	6,05
2011	9.043	5,83
2012	9.031	5,83
2013	9.067	5,85
2014	10.098	6,51
2015	10.434	6,73
2016	10.738	6,93
2017	11.810	7,62
2018	12.732	8,21
2019	11.810	7,62
2020	12.407	8,00
2021	14.165	9,14

At that moment, it was possible to compute the amount of annual tonnes of CO2 equivalents emitted in the period 2010-2021 by multiplying the silicon wafer area shipments in million square meters per the amount of CO2 emitted for square meter in the production of silicon wafers (28 t of CO2eq).

Annual tonnes of CO2 equivalents emitted 2010-2021	
Years	Semiconductors Mt CO2eq
2010	169,26
2011	163,36
2012	163,14
2013	163,79
2014	182,42
2015	188,48
2016	193,98
2017	213,34
2018	230,00
2019	213,34
2020	224,13
2021	255,88

The two datasets, the ETS price and the annual tonnes of CO2eq emitted by the semiconductor industry, were then gathered in the same graph to show their rising trend over the years.



Semiconductor industry CO2 emissions and ETS price rising trends (own elaboration)

Summary

Nowadays, a sort of raw materials hierarchy exists for each country, or better, geographic area. The ranking is mainly determined by two variables: economic and strategic importance and security of supply. According to the European Commission, a category worth attention is the one made of the so-called Critical Raw Materials (CRMs), which are gathered in a list published every three years. The raw materials falling inside this class are very strategic and, at the same time, their security of supply is not always guaranteed. The EU Critical Raw Materials list aims to be a functional tool to support an informed decision-making process and in doing so hold up both European and national policymakers when outlining trade agreements and industrial policies. It also points to direct investments in the right direction and to foster and guide innovation through national or European programmes (European Commission, 2020a).

As Hache et al. (2021) write, a strategic material is used in many industrial sectors; it is difficult to find a suitable substitute for industrial applications in the short term; it is employed in a large number of industrial applications; it has limited recycling potential and a high economic value; production and reserves are geographically concentrated, and its production can generate major environmental externalities.

These characteristics make Critical Raw Materials and the regulations related to them worthy of an in-depth analysis.

The European Commission’s communication “*Investing in a smart, innovative and sustainable industry: A renewed EU Industrial Policy Strategy*” (2017) pointed out two major industry trends: digitalisation and decarbonisation. In fact, CRMs’ high strategic rate comes from the fact that they will fuel both the digital and the ecological transition (the so-called twin transitions) and, as such, are vital to delivering both climate and digital ambitions, respectively stated in the European Green Deal (2019) and the Digital Compass (2021). On the other hand, the low security of supply rate is due to the little amount of such resources in European territories and the high dependence on imports from foreign countries.

However, it is important to underline that digitalisation and clean energy technologies can create new raw materials dependencies that can be just as problematic as the reliance on fossil fuels. In fact, price and supply volatility concerns will not disappear in an electrified and renewable energy scenario. While different from the risks associated with hydrocarbons, particularly crude oil characterised by cyclical price spikes, minerals do present some vulnerabilities that need to be addressed. Among them, geographical resource concentration is a significant issue, and, in some cases, a single country alone is responsible for about half of a mineral's global supply. Besides, many sites are subject to significant climatic hazards that could jeopardise the regularity of extraction. For example, more than half of all lithium and copper production today is located in areas with high levels of water stress. Some of the regions among the largest producers, like Australia, China and Africa, are prone to extreme heatwaves and flooding (IEA, 2021). Circular economy strategies such as lifetime extension, servitisation, and recycling can help alleviate these hazards. Still, they may not be enough to offset the increase in resource extraction and their economic, social, and environmental issues.

In fact, effective regulations are needed to address resource impacts, including emissions associated with mining and processing, risks from inadequate waste and water management, and effects on worker safety from human rights violations (such as child labour) and corruption.

Generally speaking, more effective resource governance is imperative. To manage potentially detrimental trade-offs, policymakers should carefully assess the drawbacks (such as severe environmental damage or low economic growth with negative effects on local communities), particularly with extensive knowledge of local circumstances and employing deliberative procedures. As a result, in the absence of effective mitigation measures, politicians and stakeholders may face an ethical dilemma in which a reduction in global carbon emissions is linked to various socio-environmental concerns.

This thesis will thus offer an overview of the CRMs that will enable the digital and ecological transition and the problems related to them, particularly the ones about geopolitical implications, environmental consequences, and supply chain disruption. The mineral and metal demand are expected to grow in the next years (World Bank Group, 2017), and with that, also the just mentioned criticalities will be compounded.

For what concerns geopolitics, at the basis of the CRMs list there is the acknowledgement that access to certain raw materials is an increasing concern in the European Union to be more competitive. Lack of strategic materials may leave a government vulnerable to disruptions along the supply chain of a specific product that require critical resources. At the same time, its industries would lose economic competitiveness in the market.

Because the twin transitions rank so high on the EU policy agenda, they will alter EU-neighbourhood relations and redefine Europe's global policy priorities, with far-reaching geopolitical implications. On 10 March 2020, the European Commission presented ‘A New Industrial Strategy for Europe’. It seeks to strengthen Europe's open strategic autonomy, warning that the transition to climate neutrality could replace Europe's current reliance on fossil fuels with a dependence on raw resources, many of which the Union imports from other countries and for which global competition is intensifying. As a result, the EU's wide strategic autonomy in these sectors will need to be grounded in varied and undistorted access to global raw material markets.

The geopolitical dimension, and in particular the reliability of suppliers, behind raw materials’ criticality cannot be quantified and transposed into an index. Therefore, a qualitative analysis of the complex and dynamic nature of the relations as well as the balance of powers between the client country and the supplier should be deemed more appropriate. In fact, criticality largely depends on the identity of the supplier country vis-à-vis the importer but also on the economic and political interests of a state, of which it is a reflection.

Security of supply is the second issue related to CRMs. Supply chain vulnerabilities concerns arise from a geological factor of resource concentration at a country level resulting then in a series of other issues such as concentration of global production of primary raw materials and sourcing to the EU. Also, the governance of supplier countries is a concern together with their climate polices, which most of the time lack enforceability. Other issues include the contribution of recycling (i.e. secondary raw materials), substitution, EU import reliance and trade restrictions in third countries.

The Covid-19 crisis has highlighted the need for supply security by causing significant international supply chain disruptions and jeopardising critical European industrial ecosystems' competitiveness. Indeed, bottlenecks along a supply chain can lead to high commodity prices and market volatility. In some cases, strategic stockpiling can help governments withstand short-term supply disruptions.

The raw material supply situation has deteriorated significantly in the previous decade, owing to the rapid growth of emerging markets, particularly China, and the increasing diversification of metals and minerals with very specific properties required to enable the twin transitions (Glöser et al., 2015).

The Commission is now focusing on the diversification of suppliers and pursuing international partnerships also implementing digital solutions to get more flexible supply chains.

Finally, even if CRMs will allow the twin transitions and reduce CO2 emissions through renewable technologies and digitalisation, this does not mean that they do not have an environmental impact themselves.

The environmental impact of raw materials is quite difficult to compute due to the complexity of their value chain and the different use they are employed to. Furthermore, data are incomplete, so the most precise way to determine the global environmental impact of one critical raw material in an application is to consider both the environmental impact of producing one tonne of that CRM and the number of tonnes of the same raw material needed for the global production of the application under consideration (Bachér et al., 2020).

It is important to underline that the environmental implications of critical raw materials are both local and global and include both direct and indirect effects as a result of resource utilisation, waste formation, and emissions during the manufacturing process.

A striking example of raw materials subjected to these problems are semiconductors such as silicon, gallium and germanium, all three CRMs which are at the core of the twin transitions. As already said, effective resource governance is vital, especially when it comes to CRMs which are of considerable economic importance and characterised by the potential for global supply disruption, as was the case of the semiconductor crunch due to the Covid-19 pandemic. In particular, this thesis will focus on the proposal Regulation "*EU Chips Act*" (2022) as a European strategy for semiconductors' supply in the digital and ecological transition context.

European industrial policy, promoted by Article 173 of the Treaty on the Functioning of the European Union (TFEU), aims to make European industry more competitive so that it can maintain its role as a driver for sustainable growth and employment in Europe. This is being done in light of the digital transition and the transition to a carbon-neutral economy, as stated by the European Parliament, but this has not always led to the adoption of strategies that have ensured better conditions for the EU industry. In this specific case, it can be assessed not only by analysing the semiconductor ecosystem and its complex global production chain, but also through the study of existing European policies that could negatively affect the success of the target promoted by the EU Chips act. Therefore, this analysis aims to answer the following research question: is the

Regulation proposal "*EU Chips Act*" a successful strategy to secure the supply of semiconductors and ensure Europe the coveted 20% market share? How is it affected by European climate policies?

The EU Chips Act has been designed as a strategy for securing the semiconductors' supply in Europe after the crunch caused by the Covid-19 pandemic and for gaining a significant market share in order to compete with foreign competitors realistically. Still, the environmental impact remains, and it shouldn't be underestimated. Therefore, a Life Cycle Assessment of semiconductors will be provided. Besides, from a cross-analysis of European strategies for Green House Gases (GHG) emissions reduction turns out that the weaknesses of the Chips Act could be greater than its strengths. The main focus will be on the European Emissions Trading System (ETS) but also on the implications on the Net zero targets to be achieved by 2050.

This is a clear example of the latent clash between European climate and industrial policies and their difficult coexistence in a supranational organisation which takes shape in a wide range of both ideological and practical contradictions. Hence, this analysis suggests a type of policy, the green industrial policy, based on an integral and broad approach, a view which is rarely embraced by the regulator. Regulators should, therefore, thoroughly design policies, taking into consideration the correct type of funding and a precise roadmap for implementation when industrial policies potentially conflict with climate policies.

To answer the research question, it is important to understand how the semiconductor industry works and by whom its ecosystem is composed.

Semiconductors are the backbone of the modern economy. They are materials required to operate solar cells, transistors, Internet of Things sensors, self-driving car circuits, etc. Semiconductors are strategic materials thanks to their electrical conductivity characteristics which are unique. Indeed, they are materials whose electrical conductivity value is higher than insulators (such as glass or rubber) and lower than conductors (such as copper or silver). Semiconductors are vital to electrical devices because they govern how, when, and where electricity flows thanks to this hybrid state between conductors and insulators (Encyclopaedia Britannica, n.d.).

Semiconductors are also called chips or Integrated Circuits (IC), but it is important to differentiate. In fact, according to the definitions provided by the EU Chips Act, "*'chip' means an electronic device comprising various functional elements on a single piece of semiconductor material, typically taking the form of memory, logic, processor and analogue devices, also referred to as 'integrated circuit'*".

The most common products and components built with semiconductor materials include, among others, transistors, Light-emitting diodes (LEDs), diodes, integrated circuits, etc. The sectors in which they are used range from Artificial Intelligence (AI) to clean energy technologies and from communication to automotive. As a matter of fact, semiconductors shape how Europe's green and digital revolution will unfold by determining the qualities of the products in which they are incorporated, such as security, privacy, energy efficiency, and performance.

The semiconductor industry is very complex. Its supply chain encompasses Research and Development (R&D), design, manufacturing and assembly, testing, and packaging (ATP) which also comprises input production and end-user distribution. The production phase and its inputs are supported by R&D. Semiconductor manufacturing equipment (SME), materials, design software (called electronic design automation, or EDA), and intellectual property related to chip designs (called core IP) are all inputs used in the production phase. The design and fabrication segments, as well as the SME, are the most valuable and technologically challenging parts of the whole process. EDA and core IP are crucial components that require a lot of expertise and hard skills (Khan et al., 2021).

The three steps underpinning production either occur in a single firm — an integrated device manufacturer (IDM) that sells the chip — or in separate firms, where a fabless firm designs and sells the chip and purchases fabrication services from a foundry and ATP services from an outsourced semiconductor assembly and test (OSAT) firm (Ibid.).

Within the semiconductors supply chain, industries often specialise in particular process steps (design, fabrication, assembly) or technology (memory chips, CPUs, etc.) in pursuit of economic efficiency. No region has the whole manufacturing stack in its own territory; in fact, no country has achieved the so-called "technological sovereignty" or "self-sufficiency." The demand for deep technical expertise and scale has evolved in a highly specialised global supply chain, in which different regions play diverse roles based on their comparative advantages. For example, because of its world-class universities, an enormous pool of technical talent, and market-driven innovation ecosystem, the United States leads in the most R&D-intensive activities, particularly in EDA, core IP, chip design, and SME. On the other hand, East Asia (in particular Taiwan) is a leader in wafer manufacture, and in particular, China is a market leader in ATP (Varas et al., 2021).

Due to this highly geographical specialisation, profound interdependencies and high labour divisions characterise this supply chain, especially across the whole production process. This leads to vulnerabilities across the supply chain that each region needs to address in a specific manner.

A few main countries define the semiconductors’ production value chain: the United States, Taiwan, South Korea, Japan, Europe, and, increasingly, China. For example, fabless enterprises in the United States rely on Taiwanese foundries to produce their chips. The foundries themselves rely on US, European, and Japanese equipment, chemicals, and silicon wafers (Kleinhans & Baisakova, 2020). As a result, such supply chain is extremely vulnerable to external shocks and disruptions because any of the countries mentioned above could enact export controls.

Moreover, in recent decades, chip production has shifted away from its traditional strongholds. In 1990, semiconductor manufacturing was controlled by Japan, Europe, and the United States; however, when South Korea, Taiwan, and eventually China entered the market, the three main manufacturing locations were reduced to a combined market share of roughly 35% in 2020, and the downward trend is expected to continue.

Throughout the semiconductor ecosystem, nationalistic technology and trade policies increase cost pressure and supply chain complexity. Tariffs on imported or exported components raise manufacturing costs, prompting businesses to investigate different tariff mitigation measures. They also pose logistical and regulatory issues. Restriction to access important end markets could result from such limitations, potentially leading to a considerable loss of scale.

The Covid-19 pandemic and the Ukrainian war are two striking and actual examples of the vulnerabilities and external shocks to which the semiconductor supply chain is exposed to.

As a matter of fact, the pandemic shed light on the rigidity of the semiconductors supply chain. Demand for consumer electronics increased by 7% during the pandemic's lockdowns (Strategy Analytics, 2021), as everyone needed laptops, webcams, and other items to work from home, limiting supply and resulting in cost-driven price spikes. Covid-19 also caused global supply chain to be interrupted, exacerbating the impact of the shortfall. As the lockdowns eased during the summer 2020, demand for semiconductor chips surged even more as automakers restarted production, resulting in a scarcity across all semiconductor-dependent businesses. In fact, during the Covid-19 pandemic, not only did production plants in Asia, which generate more than half of the world's chips, close, but when they reopened, the rise in chip demand produced protracted supply bottlenecks, creating inflation, and weakening Europe's GDP (Bauer et al., 2020).

Besides, it is difficult for semiconductor fabs to modify their output in response to external shocks, as the shortage has proved. Building a new fab to satisfy increased demand is not a viable short-term solution due to the enormous expenditure and time necessary. Building a fab and ramping it up to total capacity can take from 24 to 42 months and cost between US$1.7 billion and US$5.4 billion, depending on the type of the chips produced (Ibid.).

On the other hand, the Ukrainian war sheds light on the supply chain interdependencies and shows their weaknesses since it demonstrates that if a single piece is lacking, the whole production is affected worldwide.

Neon is a noble gas used in semiconductor photolithography, and according to Reuters calculations, two Ukrainian companies, Ingas and Cryoin, produce 45% and 54% respectively of the world's semiconductor-grade neon, which is vital for the lasers needed to create chips. Both firms shuttered their operations as soon as the Russian invasion began. Ingas used to produce 15,000 to 20,000 cubic meters of neon per month for customers in Taiwan, Korea, China, the United States, and Germany, with roughly 75% going to the chip industry. Moreover, Ukraine supplies more than 90% of U.S. semiconductor-grade neon, threatening American manufacturing if stockpiles are not enough, and as a consequence, all the actors relaying on American chips (Alper, 2022).

For what concerns the environmental footprint of the semiconductor industry, the indicators considered are global warming potential, water use, acidification, eutrophication, ground-level ozone (smog) formation, ecotoxicity, possible human cancer and non-cancer health consequences. However, all the studies on semiconductors Life Cycle Assessment (LCA) lack data accuracy and use estimation methods for assessing emissions along the supply chain. Besides, LCA is carried out on representative products of the industry and the technical knowledge that characterises the semiconductors ecosystem makes it more challenging to assess the real impact.

Nevertheless, it is essential to understand the potential impact of such industry from the environmental point of view, a perspective that is mainly left aside. This study will consider three primary parameters: water, resource, and energy consumption. The e-waste and recycling discourse won't be addressed in this LCA since it falls outside the scope of this analysis.

A significant contribution to the semiconductor environmental footprint is given by electric power. It is required for both production and service activities such as cooling power generation, ultrapure water generation, climate management, etc. More than half of the total electricity demand in the semiconductor industry is accounted for these activities. Electric power is also needed to create clean room conditions.

The direct greenhouse gas emissions include NF3, HFCs and PFCs, carbon dioxide, and methane, with the carbon dioxide coming from the oxidation of VOCs, HFCs and PFCs. Overall, energy consumption is responsible for approximately 75% of the total greenhouse gas emissions in the semiconductor sector (Boyd, 2012). Approximately, considering all the inputs needed for wafer production, a total of 28 tonnes of CO2 equivalents is emitted per square meter (Schmidt et al., 2012).

In 2021, the silicon wafer area shipments worldwide amounted to 14.17 billion square inches (Silicon Wafer Global Area Shipments 2010-2021, 2022), about 9.2 million square meters.

$$28 \text{ tonnes of } CO2eq * 9.2 \text{ million } m^2 = 257.6 \text{ million tonnes of } CO2eq$$

This calculation provides a rough estimate of the total emissions caused by the semiconductor industry in a year, considering all the inputs in the production stage, namely the supply chain segment that Europe would like to foster in its territory.

The EU Chips Act is a normative answer to secure the supply of CRMs such as semiconductors after the shortage caused by the pandemic, which has highlighted the third-country solid dependency on manufacturing and chip design. Other countries have also adopted mitigation action to respond to the shortage, such as the US, South Korea and Japan.

In particular, the Chips Act is a proposal for a Regulation "*establishing a framework of measures for strengthening Europe's semiconductor ecosystem*" released by the European Commission in February 2022.

Europe holds a small share of the semiconductor market (9-10%), and it is not even in expansion. It has become clear that the European semiconductor sector has been in decline for at least 30 years, at the expense of the industry growth in other parts of the world, primarily North America and Asia.

However, the Regulation proposal acknowledges that Europe is now strong in research and in sectors such as power electronics, industrial automation and equipment manufacture, analogue chips, and low-power technology, but it also recognises that it has vulnerabilities. These include a high reliance on East Asia for chip fabrication, packaging, testing, and assembly, as well as a lack of design and manufacturing capabilities for leading-edge nodes (EU Chips Act, 2022).

The European ambition is to double the current market share to 20% by 2030. Public and private investments back such an ambition up to a total amount of 43 billion euros.

The Chips for Europe Initiative, Security of Supply, and Monitoring and Crisis Response are the three pillars that support the European Chips Act's implementation and achievement of its goals. The funding envisaged will increase Europe's capacity and expertise in areas such as advanced chips below 2 nm, disruptive technologies for AI, ultra-low power energy-efficient processors, etc. (Ibid.).

The effort builds on and complements the Digital Europe and Horizon Europe programs; in particular, the former promotes the development of digital capacity in key digital domains where semiconductor technology underpins performance gains, such as High-Performance Computing, AI, and Cybersecurity, as well as skills development and the deployment of digital innovation hubs. In the field of materials and semiconductors, the Horizon Europe initiative supports rigorous pre-competitive research, technology development, and innovation.

The EU budget will contribute up to 3.3 billion euros to the Chips for Europe Initiative, including 1.65 billion euros through Horizon Europe and 1.65 billion euros under the EU's Digital Europe Programme. A new Chips Joint Undertaking will implement 2.875 billion euros, InvestEU will implement 125 million euros (to be supplemented by another 125 million under InvestEU itself), and the European Innovation Council will implement 300 million euros (Ibid.).

Overall, the public investment comprises 11 billion euros for the 'Chips for Europe Initiative,' which will fund technological leadership in research, design, and manufacturing capacities until 2030. These funds will be raised by pooling investment from the EU and Member States, with the expected participation of the private sector. The 'Chips Fund' will supplement this budget by providing equity support to start-ups, scale-ups, and other supply-chain enterprises through investment facilitation initiatives. (European Chips Act Proposals in Detail, 2022).

Support supply chain resiliency through geographic diversification is imperative. It is, in fact the main purpose of the Chips Act to foster chip manufacturing in Europe. The Chips for Europe Initiative will help Europe establish large-scale capability by investing in cross-border and publicly accessible research, development, and innovation infrastructure (Ibid.). The Chips Act envisages a framework for ensuring supply security and resiliency by attracting new innovative manufacturing facilities and investments within the EU. It will also include modern packaging, testing, and assembly facilities to foster ecosystem spillovers and interactions.

In a field in which hard skills are key for the development of advanced chips, it is necessary to invest in education, training, skilling, and reskilling programs. Indeed, the Chips for Europe Initiative comprises postgraduate microelectronics programs, short-term training courses, employment placements, traineeships, and advanced laboratory training.

Moreover, a coordination mechanism between EU Member States and the Commission will be formed to monitor supply chains and avoid shortages. This coordination will include monitoring semiconductor supply, predicting demand, anticipating shortages, and, if necessary, triggering the activation of a crisis stage. Early warning signs of potential bottlenecks and shortages will be developed as part of the efforts.

Finally, aside from these internal measures, the EU would attempt to form strong international alliances with like-minded countries. Its goal is to improve coordination and reduce the likelihood of competing plans. Such collaborations will allow for a thorough examination of third-country policy in the sector, as well as cooperative remedies to supply difficulties, including mutually advantageous diversification options.

However, the expansion of the European production capacity should be mainly driven by market demand instead of political imperatives. This does not mean that governments should refrain from granting incentives. Governments' role should be to enact policies and investments to enhance the already existing capacities developed in the territory rather than financing from the ground up other supply chain segments that are already strongly developed and consolidated in other parts of the world. Indeed, it will be difficult for EU manufacturers to catch up in an industry that requires significant capital investment and has a long payback period. In fact, during the time needed to catch up, foreign companies would make further technological advances. So, if it is true that long term planning brings with it its advantages as opposed to short term, it is also true that it has to arrive on time. Hence, it seems that the Regulation proposal is not able to address the complexity of the semiconductor environment.

Moreover, the 2nm design goal is quite ambitious in a sector in which production is difficult to adjust over short time frames for several reasons, including the high R&D requirements for chip design, the immense capital and time needed to build efficient semiconductor factories and high entry barriers. Furthermore, the Regulation proposal sets an ambitious strategic target of increasing semiconductor output from 10% of world supply to 20% by 2030. Because the global industry is predicted to double in size by that year, the existing manufacturing capacity would be quadrupled, making the target even more challenging to achieve.

Finally, the new entities envisaged by the Regulation proposal may complicate the already tangled ecosystem and create bureaucratic obstacles to the smooth development of the industry.

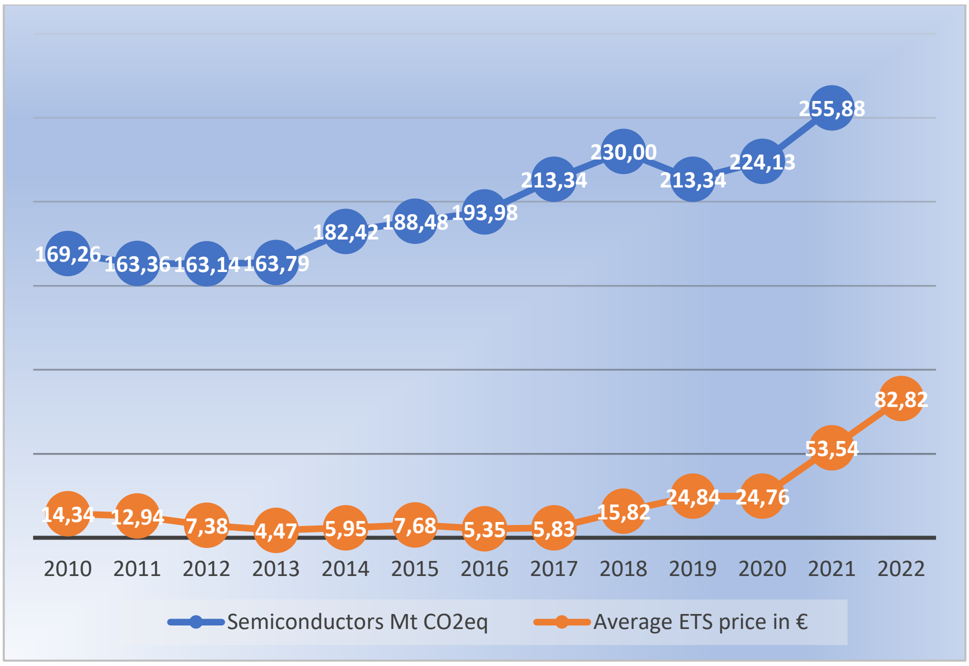
To better understand the potential impact of the European investment plan for semiconductors and its ambitions, it is important to place the Chips Act in a broader context of EU strategies that somehow impact the semiconductor ecosystem, particularly the environmental dimension. As it has been said, semiconductors production has a carbon footprint itself but at the same time, they enable the twin transitions. Therefore, weighing the trade-off and understanding the potential clash between industrial and climate policies is imperative.

In 2003 Europe implemented the Emissions Trading System through Directive 2003/87/EC (revised by EU Directive 2018/410), similar to a European carbon price on energy-intensive industries. The Directive states that major polluting firms in the European Union must have a greenhouse gas emissions permit commencing January 1, 2005. Each installation must annually offset its emissions with permits (European Union Allowances - EUAs, which are equal to 1 tonne of CO2eq) that can be purchased and sold by the individual operators. Allowances are available for purchase or free of charge in European public auctions, or they can be purchased on the market. Each Member State creates a National Quota Allocation Plan and submits it to the European Commission for approval. Following that, the Commission guarantees that the entire ceiling is not exceeded. Such a scheme also has an indirect cost since it implies rising prices, as shown by different macroeconomics analyses (Sager, 2019; Stede et al., 2021).

Article 27 of the Directive 2003/87/EC states that "*Member States may exclude from the Community scheme installations which have reported to the competent authority emissions of less than 25000 tonnes of carbon dioxide equivalent and, where they carry out combustion activities, have a rated thermal input below 35 MW, excluding emissions from biomass*".

A semiconductor plant, like Samsung, emitted 12.9 million tons of CO2 equivalents in 2020, and it uses about 100 MW of power each day (Hardison, 2021). We can therefore assume that the semiconductor manufacturing industry that Europe yearn to develop would not be exempted from the application of such system.

The figure below brings together two rising trends, the annual amount of CO2 emissions to produce silicon wafers and the ETS price in euros.



Semiconductor industry CO2 emissions and ETS price rising trends (own elaboration)

Assuming that semiconductor plants would be subjected to the ETS would entail enormous consequences. In fact, many macroeconomic studies assess prices of final goods rise when a carbon tax is applied (Känzig, 2022; Baranzini et al., 2000). Therefore, it is possible to say that European chips would be more expensive than the foreign ones. Besides, the price shown in the chart is an average (the price on May 13th, 2022 was €88.48), the final European product would be much more expensive than its competitors. Plus, the situation is worsened because the price of the European carbon tax on CO2 emissions is rising, which would entail higher costs for companies. Indeed, it is expected to reach €100 by the end of 2022 (Twidale, 2021), which is also the price deemed appropriate to achieve the net-zero target by 2050, together with other decisive mitigation actions (Bhat, 2021).

Moreover, according to a recent Kearney analysis on the future of semiconductors, the total cost of manufacturing chips in Europe is 30-40% higher than in Taiwan or South Korea, two important semiconductor-producing nations (Aurik et al., 2021).

This would give an additional competitive advantage to Asian industries whose products, not being subject to climate policies, have lower costs, thus scuttling the European ambition to be a market leader in the chips manufacturing ecosystem. This would end up with no real emancipation from foreign competitors, and even if Europe would manage to meet the 20% market share target by 2030, the dependence on Asia would not be lessened, as global value chains are too intertwined and too reliant on producers in East Asia.

Nevertheless, the EU is trying to protect the Internal Market, particularly those goods vulnerable to global competition, with an adjustment mechanism such as the Carbon Border tax within the Carbon Border Adjustment Mechanism (CBAM). "*The CBAM will equalise the price of carbon between domestic products and imports and ensure that the EU's climate objectives are not undermined by production relocating to countries with less ambitious policies. It also aims to encourage industry outside the EU and our international partners to take steps in the same direction*." (Carbon Border Adjustment Mechanism, 2021).

It goes without saying that Europe cannot impose environmental standards outside its territory, nevertheless, it can promote its products within the internal market. However, as demonstrated by a survey carried out by KPMG together with the Global Semiconductors Alliance, 53% of the 156 semiconductor CEOs interviewed named territorialism, namely cross-border regulation, tariffs, trade, and national security policies, as the most significant industry issue (KPMG & Global semiconductor Alliance, 2021). Therefore, the CBAM would fall into the just mentioned fear of territorialism or nationalism of the semiconductor industry, hence, tightening up the complex relations among the supply chain actors and increasing the fear of potential disruptions.

Another consequence of financing the European semiconductor manufacturing industry would be on the European Climate Law, proposed and endorsed by the EU Commission in 2021. It intends to attain net-zero carbon emissions for EU countries by 2050, primarily by cutting emissions, investing in green technology, and safeguarding the natural environment, as required internationally.

Most of the CO2 emissions in the semiconductor value chain come from chemical use and electricity consumption during the manufacturing process. Since Europe has not developed its own semiconductor manufacturing industry yet, it is interesting to analyse the American one in such terms. The semiconductor industry consumes 1.3–2.0% of total manufacturing electricity in the United States (Gopalakrishnan et al., 2010). Besides, the study carried out by Kuo et al. (2022) showed that 85% of climate change and particulate matter contributions occurred during the manufacturing stage of semiconductors' life cycle.

In light of these data, it would be normal to wonder whether financing and developing a pollutant industry such as the semiconductor one in Europe would impact the achievement of the net-zero emissions by 2050 targets. Developing a European semiconductors manufacturing industry would mean greater effort both to switch to renewables and to foster environmental compensation and mitigation actions.

Finally, the findings of this study result in two main insights that answer the research question.

First, the inadequacy of the EU Chips act as a Regulation by its very nature. In fact, it contains several practical and economic obstacles to achieving the predetermined goal of 20% semiconductor market share by 2030. There is no European semiconductor firm among the top 10 producers in the world, and in an industry based on economies of scale, this lack of scale among European manufacturers is a major barrier. Furthermore, because of the small size of the European chip market and its fragmentation across different technology nodes, producing at scale for the European market will be problematic. Although EU alliances, envisaged in the Regulation, have the potential to solve the scale issue, first, they must be formed and then sustained over time. However, European companies do succeed in various segments other than fabrication. The Union is currently competing in three relevant markets. One is the development of cutting-edge manufacturing equipment. The other is AI chip design, and a third example is semiconductor research and development in general. Therefore, the Union should focus on these segments and foster them to reinforce its predominant position in such a fragmented and specialised supply chain.

The Union should finance and thus foster these sectors, hence its existing strengths, rather than spending public money on a subsidy war over manufacturing capacity with the rest of the world. In fact, the costs may end up outweighing the benefits. Most probably, the EU Chips Act will not bear any tangible results, thus wasting time and above all money.

The second finding consists in the inadequacy of the EU Chips Act as an example of industrial policy in relation to already-in-force climate policies that could be applied to the European semiconductor industry. In fact, the carbon footprint of the semiconductor industry should not be underestimated, and Europe should embrace a broader view encompassing climate strategies when designing an industrial policy. The EU Chips Act was born as an expeditious response to the semiconductor shortage caused by the Covid-19 pandemic, and as such, it lacks long-term vision. Europe is thus financing a strategic industry which is at the same time very polluting and assuming that the ETS would apply, it would result in a less competitive product. This would not just mean money waste but also a huge struggle in achieving the 20% market share set by the

Regulation proposal in a structured industry where every supply chain segment has its well-established and specialised players.

However, despite climate and industrial policies may seem to have opposite goals, namely the former to foster decarbonisation and the latter to boost economic competitiveness and employment, a new trend in policy which conciliates these two approaches takes shape in the so-called green industrial policies (Rodrik, 2014). At first sight, it is easy to be wary of such a portmanteau since the word “green” is often misused for greenwashing strategies. Nevertheless, the aim of green industrial policies is to design an industrial strategy in which climate change mitigation becomes a binding constraint in the overall goal of social welfare policy. Their goal is not an easy one, indeed, policymakers should balance difficult trade-offs and missing the climate change targets would have to come at a cost. Thus, Rodrik (2014) proposes that modern industrial policy should be a "*process of institutionalised collaboration amongst the private sector, government, and civil society*” instead of a top-down strategy. This new approach also entails a much larger objective function, one that includes more long-term sustainable growth in addition to short-term competitiveness and growth.

Although the EU Chips Act claims to be consistent with the European Green Deal because semiconductors will enable the ecological transition, it is possible to argue that it is not a green industrial policy since it does not address the industry’s GHG externalities.

Therefore, this thesis suggests that the European regulator should adopt the green industrial policy approach. Europe is still a long way from implementing a comprehensive green industrial policy. It has a plethora of green industrial policy efforts at best, the majority of which are uncoordinated, and some are even contradictory. Thus, the European Green Deal's goals could be met if the EU would pursue a green industrial policy in a coordinated way, without fragmenting the EU single market and jeopardizing Europe's level playing field.

In conclusion, it is possible to state that the EU Chips act seems an expeditious response to the semiconductor shortage rather than a rigorous industrial policy, thus colluding with some European environmental commitments such as the net-zero emission target by 2050 and the Emissions Trading System. The Union should focus on resource governance and supply chain management, availing the instrument provided by the Commission like the Critical Raw Material list. The EU should, in fact, promote effective green industrial policies encouraging long-term objectives while engaging the entire society and encompassing climate mitigation targets rather than short-term competitiveness of specific sectors and enterprises.

The proposal Regulation’s paradox lies in the fact that the EU is financing a pollutant industry in its territory; given such characteristics, it will be ideally subject to the ETS mechanism. However, the Carbon Border Adjustment Mechanism would be enacted to protect the European semiconductor competitiveness at the price level and to reduce the carbon leakage risk (which has the potential to sabotage any global climate change agreement or even a local carbon tax, as in this case). Thus, sharpening international competition and, at the same time fostering national protectionism, causing disruption along a supply chain which is already fragmented.

To move beyond this concrete example, the goal of the present analysis was to dig into the difficult relationship between industrial and climate policies at the European level in a delicate context such as the digital and ecological transitions. It shows the complex interconnections of these kind of policies and how a thorough ponderation of the global ecosystem and other internal strategies should be accounted for. We live in a world whose complexity is difficult to grasp due to intertwining interests; if we try to regulate it through narrow policy focuses, we will never be able to govern its complexity in a coherent way.

Finally, the European Union was born as an economic entity, specifically as an economic entity to manage two raw materials such as coal and steel (cf. European Coal and Steel Community); in the last years it reset its priorities, namely decarbonisation and digitalisation, but through a cross-analysis of industrial and climate European policies, it is possible to notice that deep down Europe has not betrayed its original essence based on industrial and economic imperatives.