HOW TO ENSURE THE RESILIENCE OF SEMICONDUCTOR SUPPLY CHAINS IN THE EUROPEAN UNION?

Ejdys J., Szpilko D.[*]

Abstract: Building resilience in semiconductor supply chains requires continuous analysis of the semiconductor ecosystem, evaluating Europe's strengths and weaknesses in the global market, and the ability to predict unprecedented events. This study aims to identify drivers and barriers to, and the possible scenarios for semiconductor supply chains in European Union (EU) in the 2050 horizon. The authors sought answers to the research questions: What are the drivers for building resilient semiconductor supply chains in EU in the 2050 horizon? What are the limiting factors for building resilient semiconductor supply chains in EU in the 2050 horizon? What are the possible scenarios for semiconductor supply chains in EU in the 2050 horizon? The study was conducted using a four main methods: horizon scanning, TEEPSE analysis, Delphi study, scenario method. Among the most important factors determining supply chain resilience, it is essential to include: Level of investment in STEM talent (science, technology, engineering, mathematics); Level of funding for research, development and innovation in the deployment of advanced semiconductors (e.g., pilot lines for prototyping, testing and experimentation) and – Availability of qualified workers in the semiconductor field.

Key words: semiconductors supply chain, Delphi study, scenario method, resilience

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Introduction

According to a regulation by the European Parliament in 2022, semiconductors (chips) play a crucial role in the digital economy. The global shortage of semiconductors since 2020 has had far-reaching impacts across various industries. Sectors like automotive, energy, communications, healthcare, as well as strategic areas such as defense, security, and space, have been affected by disruptions in semiconductor supply chains. Moreover, the emergence of counterfeit chips poses a serious threat to the security of electronic devices and systems. It is widely agreed that the European Union (EU) needs to enhance its position in the semiconductor industry. This strengthening is necessary not only due to the current

[*] **Joanna Ejdys**, Prof., Faculty of Engineering Management, Bialystok University of Technology, Poland;
✉ e-mail: j.ejdys@pb.edu.pl,
ORCID: 0000-0002-5132-166X
Danuta Szpilko, Ph.D., Faculty of Engineering Management, Bialystok University of Technology, Poland;
✉ corresponding author: d.szpilko@pb.edu.pl,
ORCID: 0000-0002-2866-8059

shortage but also in anticipation of increased semiconductor usage resulting from digitalization. Predictions indicate that the value of semiconductor consumption in Europe, which refers to the value of semiconductors used by EU citizens and industries, is expected to nearly double from €44 billion in 2020 to approximately €80 billion by 2030, as reported by the Kearney Report in 2022 (Kearney Report, 2022). Also the global market for semiconductors is projected to grow from the current value of US$550 billion to over US$1 trillion by 2030 (Kjeld van Wieringen, 2022).

The EU has a strong desire to establish itself as a major player in the global semiconductor ecosystem and ensure its technological sovereignty. To achieve this, the EU plans to combine substantial investments with the goal of doubling its global market share of semiconductors to 20% by 2030, while also striving for equitable distribution of benefits among all member states. However, these ambitions currently face several challenges. Firstly, Ukraine, a major supplier of neon gas essential for semiconductor production, relies on Russia as a leading exporter of this crucial material. Additionally, EU member states exhibit varying capacities, dependencies, needs, and infrastructures concerning semiconductors. The global semiconductor market is also susceptible to unpredictable events, such as the 2021 Taiwan drought that caused significant water supply disruptions affecting the silicon wafer purification process, and the COVID-19 pandemic, which led to reduced production capacities in Chinese factories. To achieve semiconductor independence from Asian suppliers and successfully implement the objectives outlined in the European Chips Act, immediate and comprehensive structural actions are necessary, involving all EU member states and participants in regional supply markets.

As per the Digital Compass, Europe has set ambitious goals for the year 2030. One of these objectives is to increase the production of cutting-edge and sustainable semiconductors within Europe, including processors, to a minimum of 20% of the global production value (compared to a baseline of 10% in 2020) (2030 Digital Compass, 2021). This entails achieving manufacturing capabilities below 5-nanometer nodes, with a target of 2 nanometers, and making the semiconductors 10 times more energy-efficient than current technology. Despite losing ground in the global semiconductor market over the last two decades, the EU still possesses strategic resources within the semiconductor supply chain.

Awareness of facilitating factors and barriers is a key element in the process of building European resilience in semiconductors supply chains. The main aim of the research was to find answers to three research questions.

-What are the drivers for building resilient semiconductor supply chains in EU in the 2050 horizon?

-What are the limiting factors for building resilient semiconductor supply chains in EU in the 2050 horizon?

-What are the possible scenarios for semiconductor supply chains in EU in the 2050 horizon?

The remaining part of the article consists of a literature review highlighting the need for further research, particularly in terms of examining the factors facilitating and hindering the implementation of the adopted strategy, as well as engaging multiple stakeholders. The subsequent section describes the research methodology, specifically the application of the Delphi method for the study. The results of the conducted research are then discussed, and conclusions are drawn, indicating the limitations of the study and suggesting directions for future research.

Literature Review

Chips are ubiquitous and indispensable components of digital and digitized products, devices, and infrastructures (Alam et al., 2020). They are found in a wide range of applications, including smartphones, vehicles, healthcare systems, energy networks, communication devices, and industrial facilities. Some examples of contemporary applications of semiconductors include: smartphones and mobile devices, automotive electronics, automated cars, healthcare technology: the internet of things, AI, cloud-, edge-, and quantum computing, supercomputers, industrial production automation, renewable energy applications, applications in space and defence (Bassot, 2022). The market for semiconductors is projected to experience significant growth, with expectations of doubling from its current value of US$550 million to over US$1 trillion by 2030 (Kjeld van Wieringen, 2022).

The global semiconductor supply chain is characterized by complexity, geographic specialization, and deep and strong interdependence (Kausar et al., 2023; Zhang and Zhu, 2023; Kjeld van Wieringen, 2022; Wai-chung Yeung, 2022; Ciani and Nardo, 2022; Saif et al., 2021). The uncertainty characteristic of the global semiconductor supply chain is caused by low information transparency, short product life cycle, long production cycle, and continuous technological changes (Fu et al., 2023; Mönch et al., 2018).

The current state of semiconductor production in Europe is characterized by a limited share of less advanced chips, known as trailing-edge chips, representing under 10% of global production. These chips are typically at the 22-nanometer node and above. On the other hand, the manufacturing of cutting-edge chips, ranging from 2 to 7 nanometers, is predominantly carried out by two companies in East Asia: TSMC in Taiwan and Samsung in South Korea. Notably, the equipment required for this advanced chip production is exclusively produced by ASML in the Netherlands.

Over time, the EU's global share of chip revenues has declined from 20% in the 1990s to the current 10% (A Chips Act for Europe, 2022).

Without swift and substantial investments, projections indicate that the EU's market share would further decrease to below 5%. This would pose significant risks to Europe's industrial competitiveness and technological autonomy.

The shortages of semiconductors in the global supply chain are primarily caused by:

-a significant increase in demand for IT equipment associated with the digitalization of socio-economic processes. Examples include The number of connected IoT devices worldwide has been growing rapidly and is set to increase from 30.4 billion in 2020 to as many as 200 billion in 2030 (Bassot, 2022; A Chips Act for Europe, 2022),
-the long manufacturing cycle, which contradicts the just-in-time strategy adopted by users (Zhang and Zhu, 2023; Mönch et al., 2018),
-the impact of the pandemic and natural disasters such us: a winter storm in Texas, a severe drought in Taiwan, fires at a factory in Taiwan, fire at a plant in Japan, as well as Covid-19 clusters leading to the closure of factories, e.g. in Malaysia (Bassot, 2022; Fu et al., 2023),
-geopolitical tensions and issues caused by pandemic-related transport restrictions (A Chips Act for Europe, 2022; Ciani and Nardo, 2022).
The goal outlined in the European Chips Act is to mobilize €43 billion in policy-driven investment for the European semiconductor sector by 2030 (European Chips Act, 2022). The implementation of the European Chips Act will only be possible if Europe leverages its strengths and favorable factors while also addressing emerging barriers. Europe possesses several strengths in its pursuit of rebuilding the European semiconductor ecosystem, including: High RandD capacity and advanced-Level STEM graduates; Existing local semiconductor manufacturers such as ASML, Atlas Copro, ATandS, Besi, IMEC, and Zeiss; Strong tradition in Industries and high-quality infrastructure; Demonstrated during COVID-19 efficiency in design, manufacturing, and distribution logistics.
At the same time, significant barriers that slow down the transformation process of the EU as a major player in the global semiconductor market are highlighted by researchers. These barriers include shortage of qualified workers and talent shortage (A Chips Act for Europe, 2022; Semiconductor Industry Outlook 2022); shortages of raw materials for semiconductor manufacturing (Zhang and Zhu, 2023; A Chips Act for Europe, 2022); high demand fluctuations for diverse semiconductors (Wai-chung Yeung, 2022), geographic concentration of semiconductor manufacturing (Wai-chung Yeung, 2022) and strong dependence on non-EU suppliers (Ciani and Nardo, 2022; Kjeld van Wieringen, 2022); the lack of a system to verify the trust, authenticity and integrity of semiconductors (Muñoz et al., 2023; Gandhi et al., 2023; Simchi-Levi et al., 2023). According to the Semiconductor Industry Association (SIA), approximately 15% of all spare and replacement chips in the Pentagon's inventory are reported to be counterfeit (Daniel, 2020).
Taking into account the problems identified, it should be borne in mind that building a resilient supply chain is a time-consuming process (Simchi-Levi et al., 2023; Marzialia et. al., 2022). When considering measures to enhance the resilience of semiconductor supply chains and strengthen Europe's global market standing, it is crucial to acknowledge that the semiconductor sector requires substantial investments in both research and development (RandD) and capital

expenditures. Research indicates that the semiconductor industry allocates significant portions of its investments, approximately 22% for RandD and 26% for capital expenditures (Varas et al., 2021).
This research can potentially provide valuable insights for the future work of the European Parliament in terms of ensuring the technological sovereignty of semiconductor production. By examining the drivers and barriers to building open strategic autonomy at the EU level and addressing supply chain resilience in the semiconductor market, the research can offer recommendations and coordinated solutions to enhance Europe's position in semiconductor production.
In the context of developing a long-term strategy aimed at improving Europe's position in the global semiconductor market, it is essential to examine the factors that facilitate the implementation of the strategy and the barriers that hinder its realization. This process should involve stakeholders representing the business sector, government administration, policymakers, consumers, non-governmental organizations, and the scientific community. Accoroding Kjeld van Wieringen (2022) in future foresight and consultations related to semiconductors, it may be beneficial to involve a broader range of societal stakeholders, such as NGOs, media, environmental groups, and other civil society organizations. This inclusion would provide a more comprehensive public perspective on the EU's chip strategy.
Research foresight and the Delphi method provide valuable tools for conducting studies in this context. By combining foresight research and the Delphi method, a comprehensive understanding of the factors influencing the implementation of Europe's semiconductor strategy can be obtained. These research approaches enable the identification of key factors that support the successful implementation of the strategy, as well as potential barriers that need to be addressed. They also help in generating insights into the priorities, preferences, and concerns of stakeholders, thereby facilitating informed decision-making and the development of effective strategies.

Research Methodology

Research Process

The study was conducted using a 4-phase methodology. Four main methods were used: horizon scanning (phase I), TEEPSE analysis (phase II), Delphi study (phase III), scenario method (phase IV). The survey was conducted as part of the project entitled: A preparedness plan for Europe: Addressing food, energy and technological security, commissioned by the European Parliament. The scope of the study covered issues related to ensuring the resilience of supply chains in 4 areas identified as priorities by the European Parliament: food, energy, semiconductors, satellite communications.
The first phase involved a horizon scanning, in which experts examined the possible effects of destabilising semiconductor supply chains in terms of STEEPED aspects (Van Woensel and Vrščaj, 2015). This first phase of horizon scanning is essential for research on technology and science topics that are

complex and rarely understood without expert knowledge. At this stage, a guiding framework was created using the STEEPED (Social - Technological - Economic - Environmental - Political/Legal - Ethical - Demographic) approach. This approach ensures that the impact of future trends is examined from an interdisciplinary perspective. As part of the STEEPED approach, a team of 7 expert implementers of the study identified a broad catalogue of factors influencing the development of semiconductor supply chains on the basis of literature analysis.

In the second phase, these factors were sorted and aggregated according to the TEEPSE analysis areas (Popper, 2018). They were divided into 6 groups: technological (T), economic (E), environmental (E), political/legal (P), social (S) and ethical (E). This analysis was chosen because the indicated groups of factors play the greatest role in the semiconductor area, which is primarily linked to the economic, technological and political dimensions. As part of the analysis, each expert (described in the research experts section) assessed the selected factors in terms of their importance and uncertainty of development in the 2050 perspective.

In the next phase of the research process, a Delphi research was conducted. The Delphi method is a type of expert research, where the intuitive opinions of experts are treated as legitimate contributions to the formulation of a vision of the future of the research subject. The Delphi method involves surveying a defined group of experts at least twice. Respondents complete a questionnaire in which they make predictions about a problem or situation in a particular area in the long term. In a subsequent round, they complete the same questionnaire, with the aggregated results from the first round of the survey presented to them. The responses are analysed qualitatively and quantitatively, and the information, sent in subsequent rounds to the experts, can be redefined and narrowed down for consistency (Bowles, 1999; Cape, 2004; Szpilko, 2014). The expert may, influenced by the opinion of the general respondents, change his or her opinion on a given topic or maintain it. This procedure allows for more clear opinions. The final step of the procedure is to analyse the collected research material and preparation of the research report (Loo, 2002; Skulmowski et al., 2007).

In the last 4 phase of the research process, possible scenarios for the development of resilient semiconductor supply chains in the EU were developed based on the results of the TEEPSE and Delphi analysis. The scenario method is a logical and formal construction of alternative visions of the desired future based on the involvement of heterogeneous groups of experts, taking into account a thorough knowledge and understanding of the factors shaping the phenomenon under study and enabling rational decisions about the future (Kononiuk, 2012). The scenario-axes technique was used in this study. It consists of identifying two factors that are considered key in the research process. The identified factors are plotted on two axes, resulting in a matrix with the top right field receiving a positive value and the bottom left field receiving a negative value. The other two boxes take the positive and negative values of the first or second factor respectively. In this way, four scenarios are created, representing different perspectives on where the future of the study area might develop (van't Klooster and van Asselt, 2006).

Research Experts

The research within the project entitled: A Preparedness Plan for Europe: Food, Energy and Technology Security, commissioned by the European Parliament, involved a total of 153 experts in the first round and 117 experts in the second round including experts representing various stages of the supply chains in food security, energy security, semiconductors and satellite communication, academics, representatives of government agencies and politicians. With regard to the semiconductor area, 29 people were involved in the study. The characteristics of the semiconductor research sample are shown in Table 1.

Table 1. Characteristics of the research sample

Variable	**Characteristics**
Gender	man – 72.4%; woman – 27.6%
Age	25-34 years – 6.9%; 35-44 years – 37.9%; 45-54 years – 34.5%; 55-64 years – 13.8%; 65 years or older – 6.9%
Education	higher – Professor – 51.7%; higher – PhD – 48.3%
Represented sector	scientists, researchers – 93.1%; companies/industry – 20.7%; regional and local government / policy-makers – 3.5%; special interest groups – 3.5%
Country	Italy – 20.7%; Portugal – 10.3%; Spain – 13.8%; Germany – 10.3%; Greece – 6.9%; Poland – 17.2%; Bulgaria – 3.5%; Austria – 3.5%; Slovakia – 3.5%; Tunisia – 3.5%; Belgium – 3.5%; UAE – 3.5%

The experts of semiconductors area were diverse in terms of gender, age, education, sectors represented and countries. The survey involved 72.4% men and 27.6% women. The respondents aged 35-44 and 45-54 accounted for the highest proportions, with 37.9% and 34.5%, respectively. Those aged 55-64 accounted for 13.8% and those aged 65 or older – for only 6.9%. All of the respondents held either a professor's degree (51.7%) or a doctoral degree (48.3%). The experts participating in the survey represented twelve countries. The highest percentage of respondents in the sample were from Italy (20.7%), Poland (17.2%) and Spain (13.8%).

Research Results

TEEPSE Analysis

Taking STEEPED (Social - Technological - Economic - Environmental - Political/Legal - Ethical - Demographic). aspects into account, the expert team of the study identified a list of factors on the basis of the literature analysis. After sorting and aggregation, they were assigned to the individual TEEPSE analysis groups. As a result, the experts identified 16 main factors, which were included in six groups of the following nature: technological, economic, environmental, political, social and ethical (Table 2).

Table 2. Factors of the TEEPSE analysis

Akronym	Factor type	Name of factor
TEC_01	technological	Level of raw material resources for semiconductor production
TEC_02	technological	Scale of fluctuation in demand for particular types of semiconductors
TEC_03	technological	Dynamics of development of energy-efficient semiconductors
ECN_01	economic	Level of prioritization of semiconductor production for critical sectors e.g. healthcare, medical sector, electronic, automative, army sector (result of dialogue with their manufacturers)
ECN_02	economic	Level of demand for the latest chip technology resulting from developments in artificial intelligence, 5G/6G and autonomous vehicles
ECN_03	economic	Level of funding for research, development and innovation in the deployment of advanced semiconductors (e.g., pilot lines for prototyping, testing and experimentation)
ECN_04	economic	Level of concentration of supply with respect to geographic areas and companies, taking into account network effects and lock-in effects
ENV_01	environmental	Extent of changes in environmental requirements, affecting the reduction of production efficiency
POL_01	political/ legal	Level of willingness to dialogue between semiconductor manufacturers and policy makers
POL_02	political/ legal	Level of ability to implement a centralized purchasing system for semiconductors in the EU
POL_03	political/ legal	Level of opportunity to develop common standards and certification for trustworthy electronics
POL_04	political/ legal	Level of cooperation with relevant third countries (outside the EU)
SOC_01	social	Level of awareness of consumerism
SOC_02	social	Availability of qualified workers in the semiconductor field
SOC_03	social	Level of investment in STEM talent (science, technology, engineering, mathematics)
ETH_01	ethical	Level of preservation of the authenticity and integrity of semiconductors

The presented factors were later rated, according to the school of intuitive logic of scenario construction, on a seven-point scale of importance and uncertainty. With regard to importance, 1 meant that the factor had very low importance and 7 meant that the factor had very high importance. With regard to uncertainty, 1 meant that the factor had very low uncertainty and 7 – very high uncertainty (Figure 1).

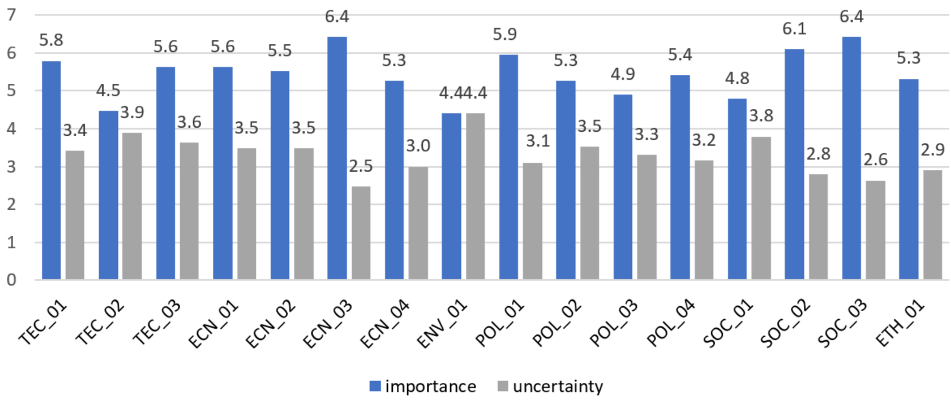

Figure 1: Assessment of the importance and uncertainty of factors for the development of resilient semiconductor supply chains in the EU

Analysing the summary of all factors in terms of their importance, it can be seen that eight of them have a higher uncertainty rating than the average across all factors (of 5.5). The factors that received the highest importance ratings are: SOC_03 – Level of investment in STEM talent (science, technology, engineering, mathematics) (6.4), ECN_03 – Level of funding for research, development and innovation in the deployment of advanced semiconductors (e.g., pilot lines for prototyping, testing and experimentation) (6.4), and SOC_02 – Availability of qualified workers in the semiconductor field (6.1).
In contrast, factors such as the following had the least impact on building resilience in semiconductor supply chains: ENV_01 – Extent of changes in environmental requirements, affecting the reduction of production efficiency (4.4), TEC_02 – Scale of fluctuation in demand for particular types of semiconductors (4.5), SOC_01 – Level of awareness of consumerism (4.8), and POL_03 – Level of opportunity to develop common standards and certification for trustworthy electronics (4.9).
Analysing the ranking of all factors in terms of uncertainty of their development, it can be seen that eight of them have a higher uncertainty score than the average among all factors (of 3.3). According to experts, the most uncertain factors affecting the development of self-sustaining semiconductor supply chains in Europe in the 2030 horizon are: ENV_01 – Extent of changes in environmental requirements, affecting the reduction of production efficiency (4.4), TEC_02 – Scale of fluctuation in demand for particular types of semiconductors (3.9), SOC_01 – Level of awareness of consumerism (3.8), and TEC_03 – Dynamics of development of energy-efficient semiconductors (3.6). These factors with a relatively high level of uncertainty related to changes in environmental requirements that reduce production efficiency can realistically be controlled by EU policy. The other two factors are outside the control of the EU.

Experts considered highly predictable factors (with the lowest uncertainty): POL_04 – Level of cooperation with relevant third countries (outside the EU) (3.2), POL_01 – Level of willingness to dialogue between semiconductor manufacturers and policy makers (3.1), and ECN_04 – Level of concentration of supply with respect to geographic areas and companies, taking into account network effects and lock-in effects (3.0), (Figure 1).

The result of the study is the identification of factors that can be considered as axes of scenarios determining future resilient semiconductors supply chains in EU in the 2050 horizon. Such factors are characterised by both a high degree of importance and high uncertainty (low predictability) - Figure 2.

Among all the factors considered, the experts identified the following as factors of high importance and uncertainty determining the development of resilient semiconductor supply chains in the EU in the run up to 2050: TEC_01 – Level of raw material resources for semiconductor production, TEC_03 – Dynamics of development of energy-efficient semiconductors, ECN_01 – Level of prioritization of semiconductor production for critical sectors e.g. healthcare, medical sector, electronic, automative, army sector (result of dialogue with their manufacturers), and ECN_02 – Level of demand for the latest chip technology resulting from developments in artificial intelligence, 5G/6G and autonomous vehicles.

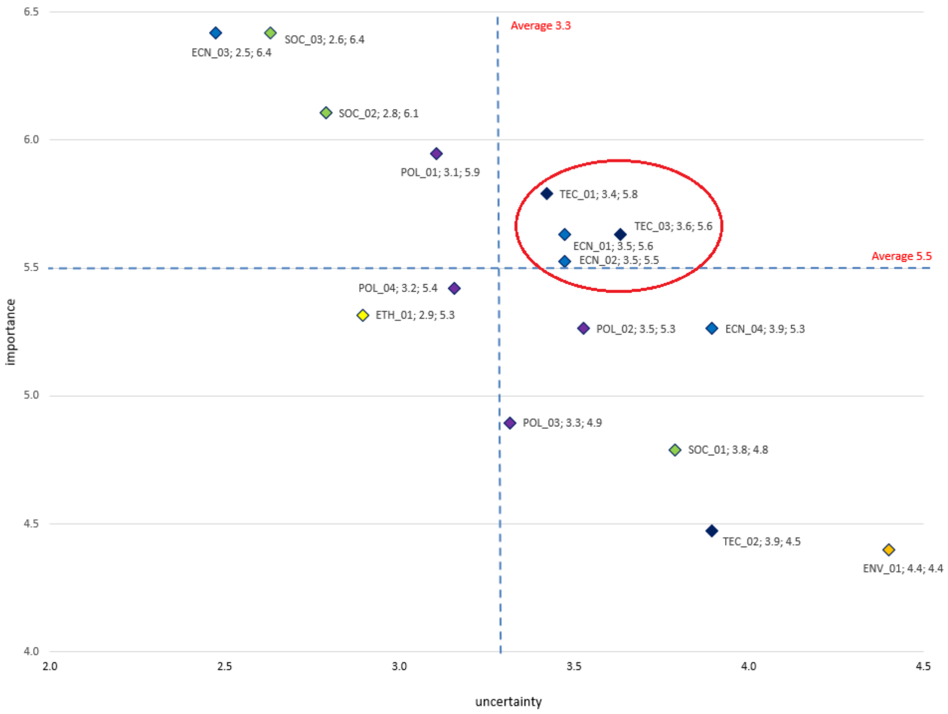

Figure 2: Validity and uncertainty of TEEPSE factors determining the development of resilience semiconductor supply chains in EU in the 2050 horizon

However, it is not possible, on the basis of the results obtained, to unequivocally identify the two factors with the highest values, both in terms of importance and uncertainty. In order to select these, a follow up research process was carried out.

Delphi Research

Based on the literature review, the expert team developed 4 theses for the Delphi study in the semiconductor area. The process of selecting the theses began with analyzing reports, article reviews, statistical data, and input from European experts in the field of semiconductor supply chains, representing various sectors like research, industry, and policy. The shift in policy towards moving away from a global supply chain and focusing on building regional (European) semiconductor supply chains while enhancing their resilience was considered during this selection process.

Within the semiconductors area, four theses were examined:

-Thesis 1. EU share of global cutting-edge, innovative and sustainable semiconductor production will increase from 10 to 20% (T1),

-Thesis 2. Security of supply of semiconductors to strategic sectors of the EU countries will be ensured (T2),

-Thesis 3. Building a dynamic ecosystem across the EU will strengthen Europe's capabilities to achieve its environmental goals and green transitions while improving the Union's security (semiconductors) (T3),

-Thesis 4. EU countries have sufficient resources to produce modern integrated chips (made with the 7-nanometre process) (T4).

Respondents rated all theses highly in terms of their relevance to the study area, as evidenced by the high proportion of 'very significant' and 'significant' responses in both Round 1 and Round 2 of the Delphi survey. Respondents considered the thesis on ensuring the security of supply of semiconductors to strategic sectors of EU countries to be the most important (T2 – 68.4%). They also attributed high relevance to the implementation of activities related to the production in EU countries of modern integrated circuits (made in the 7-nanometer process) (T4 – 52.6%). The detailed distribution of responses in rounds I and II of the survey is presented in Table 3.

Table 3. Significance of theses for building resilient semiconductor supply chains in the EU – results of the first and second rounds of the Delphi study

Thesis	very high significance		high significance		medium significance		very low significance		low significance	
	round I	round II	round I	round II	round I	round II	round I	round II	round I	round II
T1	36.8%	26.3%	42.1%	63.2%	15.8%	10.5%	5.3%	0.0%	0.0%	0.0%
T2	63.2%	68.4%	26.3%	21.1%	10.5%	10.5%	0.0%	0.0%	0.0%	0.0%
T3	36.8%	36.8%	31.6%	31.6%	31.6%	31.6%	0.0%	0.0%	0.0%	0.0%

Thesis	very high significance		high significance		medium significance		very low significance		low significance	
	round I	round II	round I	round II	round I	round II	round I	round II	round I	round II
T4	47.4%	52.6%	42.1%	42.1%	0.0%	0.0%	10.5 %	0.0%	0.0%	0.0%

In order to determine the relevance of the different theses for the development of resilient semiconductor supply chains in the EU, a significance index (Is) was calculated (Ejdys, 2013; Dębkowska, 2013; Nazarko et. al., 2016):

$$I_S = \frac{n_{VHS} \cdot 100 + HS \cdot 75 + MS \cdot 50 + n_{LS} \cdot 25 + n_{VLS} \cdot 0}{n}, \quad (2)$$

where:

- nVHS – number of responses ‘very high significance’,
- nHS – number of responses ‘high significance’,
- nMS – number of responses ‘medium significance’,
- nLS – number of responses ‘very low significance’,
- nVLS – number of responses ‘low significance’,
- n – number of total responses.

The IF indicator takes values ranging from 0 to 100, with a numerical level of the indicator above 50 indicating a high degree of significance of the thesis. Indicators below 50 indicate a low degree of significance of the thesis. The closer the indicator value is to zero, the lower the degree.

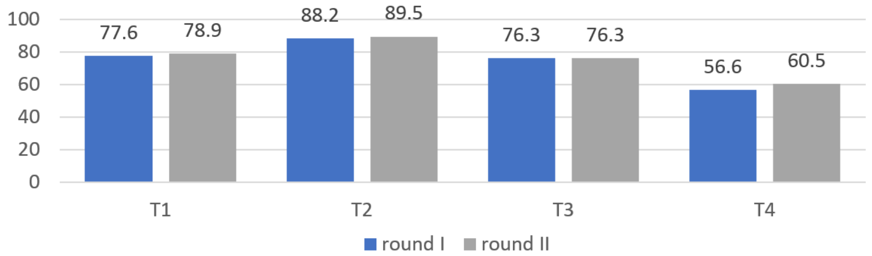

Figure 3: Values of significance indicators for the theses in the semiconductors area

The analyses carried out were presented in the comparative approach. All four theses were rated as being of very high or high importance, as demonstrated by the values of significance indicators (Figure 3).

Among the theses analysed, the highest significance index was noted for thesis T2, which may translate into the very high importance of ensuring security of supply of semiconductors to strategic sectors of EU countries. Slightly lower, but also high significance index values were noted for theses T1 and T3. For thesis T1, this indicates that increasing the EU's share of global cutting-edge, innovative and sustainable semiconductor production from 10 to 20% is also very important. The slightly lower relevance of T3 may be related to the fact that experts attach more importance to the security of supply of semiconductors and that building a dynamic ecosystem across the EU plays a secondary role.

In the Delphi survey, participants were asked to assess the probability of each thesis being realised in the future. They had the option to provide their assessments within four time frames: by the end of 2025, between 2026 and 2030, between 2031 and 2050, or after 2050. Additionally, respondents were given the opportunity to indicate that a particular thesis would not be realized at all. The assessment of the theses' timescale for implementation is characterised by a similar pattern of responses (Figure 4).

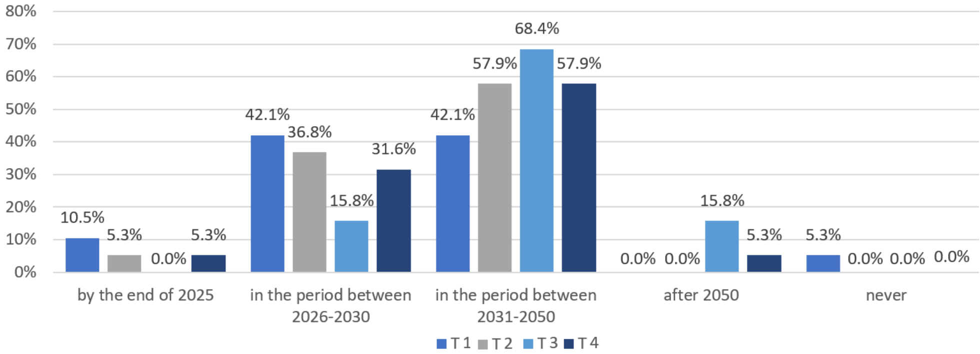

Figure 4: Timescale for implementation of the theses

According to the majority of experts thesis T1 is likely to be realized either during the period 2026-2030 (42.1%) or 2031-2050 (42.1%). Compared to other theses, experts are more optimistic about the EU's chances of increasing its share in the global semiconductor market from 10% to 20% between 2026 and 2030. Only 10.5% of experts believe that T1 will be implemented by the end of 2025, while 5.3% think that the thesis will never come to fruition.

Regarding thesis T2, 57.9% of experts believe that the security of supply of semiconductors to strategic sectors will be ensured in the longer term, specifically during the period 2031-2050. The experts were of a similar opinion with regard to Thesis 4 on the EU's ability to provide sufficient resources for the production of modern integrated chips (made in the 7-nanometre process).

On the other hand, building a dynamic ecosystem across the EU that strengthens Europe's capacity to achieve environmental goals and green transformation (T3), according to experts, requires more time. Over 57% of experts predicted that this event would occur between 2031 and 2050, with 31.6% suggesting that it might even take place beetwen 2026-2030.

The experts participating in the survey were asked to indicate the extent to which the factors (identified in the TEEPSE analysis) were favouring to the implementation of each thesis. The assessment was made using the following scale: to a very high degree, to a high degree, to a medium degree, to a low degree and to a very low degree. In order to assess the factors in terms of their strength in favour of a given thesis, an index of favour was determined for each factor according to the formula (Ejdys, 2013; Dębkowska, 2013; Nazarko et. al., 2016):

$$I_F = \frac{n_{VH} \cdot 100 + H \cdot 75 + M \cdot 50 + n_L \cdot 25 + n_{VL} \cdot 0}{n}, \quad (2)$$

where:

- nVH – number of responses 'very high degree',
- nH – number of responses 'high degree',
- nM – number of responses 'medium degree',
- nL – number of responses 'low degree',
- nVL – number of responses 'very low degree',
- n – number of total responses.

The indicator can take values from 0 to 100. An indicator level above 50 indicates that the factor favours the thesis to a high degree. The closer the indicator value is to 100, the higher the degree of favouritism. An indicator level below 50 indicates a low degree to which the factor favours the thesis. The closer the indicator value is to 0, the lower the degree of influence.

All of the five most important drivers of the theses in the experts' opinion (in both the first and second rounds of the Delphi survey) received index values above 50, meaning that they are highly conducive to the implementation of all theses. The factor 'level of funding for research, development and innovation in the deployment of advanced semiconductors (e.g., pilot lines for prototyping, testing and experimentation)' has the highest average degree of favourability for all theses (89.2). A detailed list of the favouring index values for the individual theses in Round 1 and Round 2 of the Delphi study is presented in Table 4.

Table 4. Values of factor of favouring to the implementation of the theses (drivers for building resilient semiconductor supply chains in EU in the 2050 horizon)

Factor	T1		T2		T3		T4	
	round I	round II	round I	round II	round I	round II	round I	round II
ECN_01	67.1	67.1	82.9	82.9	75.0	75.0	80.6	81.9
ECN_03	93.1	93.1	82.9	82.9	86.1	86.1	94.7	94.7
POL_03	79.2	79.2	68.1	69.4	78.9	80.3	70.8	70.8
POL_04	76.3	76.3	71.1	72.4	81.9	81.9	78.9	78.9
SOC_02	82.9	82.9	76.3	76.3	73.7	73.7	84.2	84.2

The high level of funding for research, development and innovation in the deployment of advanced semiconductors, according to experts, will definitely have a stimulating effect on the implementation of all four theses. An important determinant of the security of semiconductor supply to strategic sectors (T2) will be the intensification of dialogue with semiconductor manufacturers to prioritize production for critical sectors, e.g., healthcare, medical, electronics, automotive, military (ECN_01, 82.9). It is also worth noting that the high availability of qualified workers will strongly support the implementation of theses T1 (82.9) and T4 (84.2). In turn, building a dynamic ecosystem across the EU that will strengthen Europe's ability to achieve environmental goals and green transformation (T3) will definitely stimulate a high level of cooperation with relevant third countries (outside the EU) (POL_04 – 81.9).

In addition to the identification of factors favouring the implementation of the theses, the Delphi study carried out, enabled the analysis and evaluation of barriers. As in the case of the enabling factors, the evaluation was made the following scale was used: to a very high degree, to a high degree, to a medium degree, to a low degree and to a very low degree. In order to assess the factors in terms of their strength in favour of a given thesis, an index of favour was determined for each factor according to the formula (Ejdys, 2013; Dębkowska, 2013; Nazarko, et. al., 2016):

$$I_B = \frac{n_{VH} \cdot 100 + H \cdot 75 + M \cdot 50 + n_L \cdot 25 + n_{VL} \cdot 0}{n} \quad (3)$$

All of the five most important barriers of the theses in the experts' opinion (in both the first and second rounds of the Delphi survey) received index values above 50, meaning that they are highly limiting to the implementation of all theses. The factor 'level of raw material resources for semiconductor production' (TEC_01) has the highest average barrier index value for all theses (77.6), (Table 5).

Table 5. Values of factor of barriers to the implementation of the theses (limiting factors for building resilient semiconductor supply chains in EU in the 2050 horizon)

Factor	T1		T2		T3		T4	
	round I	**round II**	**round I**	**round II**	**round I**	**round II**	**round I**	**round II**
TEC_01	82.9	84.2	76.3	76.3	75.0	73.6	76.3	76.3
ECN_04	68.4	67.1	79.2	79.2	79.2	79.2	77.8	77.8
ENV_01	60.5	60.5	65.3	65.3	75.0	76.3	65.8	65.8
ETH_01	56.6	56.6	69.7	71.1	57.9	57.9	60.5	60.5
SOC_02	80.3	81.6	72.4	73.7	65.3	63.9	82.9	82.9

The low level of raw material resources for semiconductor production (TEC_01) will be a barrier to the implementation of all theses, especially T1 (84.2) and T2 (76.3). The low level of availability of qualified workers (SOC_02) will definitely limit the implementation of theses T1 (81.6) and T4 (82.9). In contrast, the low level of concentration of supply with respect to geographic areas and companies, taking into account network effects and lock-in effects (ECN_04) will be a significant constraint on the implementation of theses T2 (79.2), T3 (79.2) and T4 (77.8). Building a dynamic ecosystem across the EU will strengthen Europe's capabilities to achieve its environmental goals and green transitions (T3, 76.3) will destimulate the extent of changes in environmental requirements, affecting the reduction of production efficiency (ENV_01).

Scenarios

Confronting the results of the two analyses (TEEPSE analysis and Delphi) led to the selection of two factors – the axes of scenarios for the development of resilient semiconductor supply chains (Figure 5).

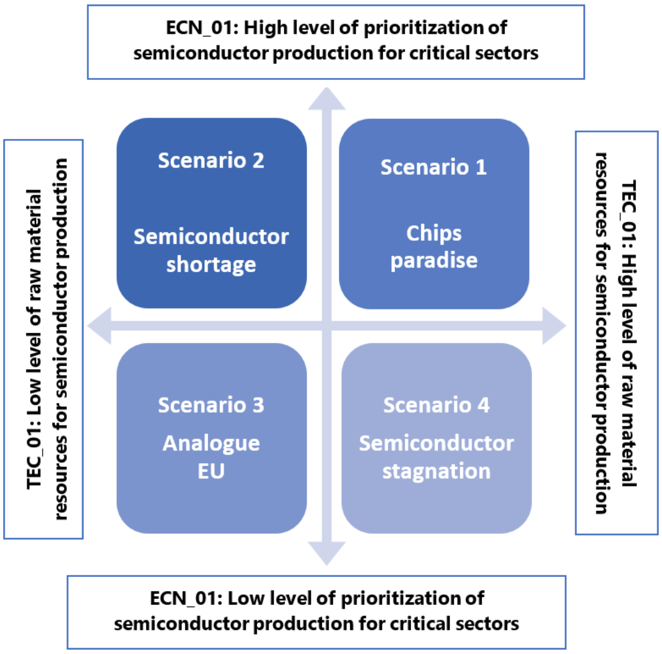

Figure 5: Axis configuration of scenarios for the development of resilient semiconductor supply chains in the EU up to 2050

Two factors were used as axes (driving forces) for the scenarios: TEC_01 – Level of raw material resources for semiconductor production and ECN_01 – Level of prioritization of semiconductor production for critical sectors e.g. healthcare, medical sector, electronic, automative, army sector (result of dialogue with their manufacturers). The experts conducting the study proposed the following names for the different scenarios: S1 – Chips paradise, S2 – Semiconductor shortage, S3 – Analogue EU, S4 – Semiconductor stagnation (Figure 5). The experts also assessed the other factors of the TEEPSE analysis in each scenario. Based on the assessment, four scenarios for the development of resilient semiconductor supply chains in the EU up to 2050 were characterised.

Scenario 1 – Chips paradise. The EU has finally achieved its long-desired goal of attaining self-sufficiency in semiconductor production. The availability of raw materials has been effectively secured. Through constructive dialogues between decision-makers and manufacturers, the production of semiconductors is being prioritized for critical sectors, such as healthcare, medicine, electronics, automation, and the military. Moreover, the manufacturing processes have become highly efficient, enabling the industry to meet the demand for cutting-edge chip technology driven by advancements in artificial intelligence, 5G/6G, and autonomous vehicles. This remarkable state of affairs owes its success to substantial funding in research, development, and innovation for advanced semiconductors. The investment is not only focused on technology but also on nurturing STEM (science, technology, engineering, mathematics) talent. As a result, several prototyping, testing, and experimentation pilot lines have been established in EU countries. These countries boast a skilled workforce that has implemented manufacturing technologies, thus ensuring the stability of supply chains within the EU semiconductor industry. Additionally, the EU has developed common standards and certifications for trustworthy electronics. There is a strong emphasis on maintaining a high level of protection for the authenticity and integrity of semiconductors. These measures contribute to bolstering the overall reliability and trustworthiness of electronic devices. Overall, this success story in achieving self-sufficiency in semiconductor production stands as a testament to the EU's commitment to cutting-edge technology, robust research and development, and a skilled workforce. Through these endeavors, the EU has not only secured its semiconductor industry but also strengthened its position as a global player in the tech landscape.

Scenario 2 – Semiconductor shortage. The EU is facing a significant shortage of raw materials for semiconductor production. With limited manufacturing capacity, priority is given to fulfilling the needs of critical sectors such as healthcare, the medical industry, electronics, automation, and the military. The scarcity of semiconductors has led to substantial financial investments in research, development, and innovation, especially concerning breakthrough manufacturing technologies. Efforts are also being made to invest in STEM (science, technology, engineering, mathematics) talent development, aiming to increase the number of skilled workers. Due to the semiconductor shortage, there are extensive collaborations with third countries (outside the EU) to maintain supply chain continuity. However, relying on imports sometimes results in materials of lower quality, posing significant challenges in ensuring a high level of authenticity and integrity for the semiconductors. Overall, the current situation underscores the urgency for the EU to address the semiconductor shortage by bolstering domestic production capabilities and strengthening collaborations with external partners. The focus on research, development, and nurturing a skilled workforce remains crucial in mitigating the impact of the shortage and ensuring the steady supply of high-quality semiconductors for critical industries within the EU.

Scenario 3 – Analogue EU. The EU has been plunged into an economic collapse as a result of various crises (financial, armed conflicts, health-related). The low level of semiconductor production, stemming from the scarcity of raw materials, has significantly rendered the EU dependent on supplies from third countries (outside the EU). Unfortunately, the critical sectors' needs, such as healthcare, the medical industry, electronics, automation, and the military, are not given priority due to the lack of dialogue between EU decision-makers and semiconductor manufacturers.

Consequently, semiconductor manufacturers are primarily focused on meeting the demands arising from the developments in artificial intelligence, 5G/6G, and autonomous vehicles. The prevailing crisis in the EU has led to chronic financial constraints, affecting research, development, and innovation in the deployment of advanced semiconductors. Moreover, the lack of investment in STEM (science, technology, engineering, mathematics) talent development has resulted in a shortage of qualified workers in the semiconductor industry in the European job market. In the midst of this chaos, little attention is given to the crucial matter of safeguarding the authenticity and integrity of semiconductors. As a result, the EU faces significant challenges in ensuring the reliability and security of semiconductor components. To overcome these difficulties and restore stability, the EU must prioritize dialogue with semiconductor manufacturers, allocate adequate funding for research and development, and invest in STEM education to foster a skilled workforce. Emphasizing the protection of semiconductor authenticity and integrity is vital to rebuilding the semiconductor industry's reputation and securing resilient supply chains in the EU.
Scenario 4 – Semiconductor stagnation. In the EU, the availability of raw materials for semiconductor production is at a high level. However, due to a lack of consensus between decision-makers and semiconductor manufacturers, especially concerning pricing for critical sectors, there has been a broad-scale collaboration with third countries (outside the EU) to import these components. As a result, the European semiconductor market is experiencing stagnation, with the focus primarily on meeting the demands arising from advancements in artificial intelligence, 5G/6G, and autonomous vehicles. Despite this, efforts are made to maintain a high level of authenticity and integrity protection for these components. The lack of dialogue between semiconductor manufacturers and EU decision-makers is leading to limited funding for research, development, and innovation in the implementation of advanced semiconductors. Consequently, investments in STEM talent development are proving to be insufficient, and as a consequence, skilled workers are seeking opportunities beyond the EU's borders, where the semiconductor industry is rapidly flourishing. To overcome this stagnation, it is imperative for the EU to establish constructive dialogues with semiconductor manufacturers, addressing concerns related to critical sectors and pricing. Increased funding for research and development is essential to drive innovation and advancements in semiconductor technology. Additionally, investing in STEM education and talent development within the EU will help retain qualified workers and revitalize the semiconductor industry, making it more competitive on the global stage.

Conclusion

The analysis conducted on the determinants of building resilience in semiconductor supply chains of the EU using the TEEPSE method resulted in identifying four factors characterized by the highest level of importance and a high degree of uncertainty. These factors include: TEC_01 – Level of raw material resources for semiconductor production, TEC_03 – Dynamics of development of energy-efficient semiconductors, ECN_01 – Level of prioritization of semiconductor production for critical sectors e.g. healthcare, medical sector, electronic, automative, army sector (result of dialogue with their manufacturers), and ECN_02 – Level of demand for the latest chip technology resulting from developments in artificial intelligence, 5G/6G and autonomous vehicles.

Analyzing the identified factors that are both important and uncertain will enable decision-makers and entrepreneurs to construct more flexible and adaptive scenarios for development and action strategies.

The four development scenarios for enhancing resilience in semiconductor supply chains in the EU by the year 20250, proposed as a result of the conducted research, were built upon two key factors. These factors constitute the axes of the scenarios and include: TEC_01 – Level of raw material resources for semiconductor production and ECN_01 – Level of prioritization of semiconductor production for critical sectors e.g. healthcare, medical sector, electronic, automative, army sector (result of dialogue with their manufacturers).

The proposed four scenarios: S1 – Chips paradise, S2 – Semiconductor shortage, S3 – Analogue EU, S4 – Semiconductor stagnation will enable the EU and individual countries to determine their existing situation as well as the desired situation in the future concerning the resilience of semiconductor supply chains. Defining a desired scenario allows EU countries to establish appropriate actions and strategies today, ensuring the realization of the scenario and thus achieving resilience against disruptions in semiconductor supply chains.

Building a resilient supply chain will be achievable through the support of four policy options: (i) Facilitating international collaborations to endorse state-of-the-art semiconductor mega factories; (ii) Fostering indigenous semiconductor ecosystems and the contemporary semiconductor industry; (iii) Focusing on STEM education and research and development orientation and (iv) Enhancing safeguards for the EU market against security and safety vulnerabilities.

Among the necessary actions ensuring the resilience of European semiconductor supply chains, it is essential to include:

-developing strategic alliances: the EU could collaborate with other nations and organizations to exchange resources and expertise within the semiconductor industry,

-enhancing competitiveness and bolstering resilience,

-forming partnerships with major corporations to establish manufacturing facilities within the EU (such as Samsung TSMC, Wolfspeed fab in Ensdorfl, or Intel in Magdeburg),

-providing financial backing for pilot lines and design infrastructures geared towards cutting-edge semiconductor technologies,

-implementing investment tax incentives for capital expenditures involved in cutting-edge semiconductor production and associated equipment,

-offering exclusive access to research and development services for manufacturers situated in Europe,
-encouraging companies to boost their semiconductor production within its borders, thereby decreasing reliance on imports from foreign nations,
-supporting startups engaged in chip design and development, funding pilot series for new technologies, a collaborative effort between research and development, industry, and central financial agencies,
-ensuring a stable supply of raw materials might involve the development of mining and refining endeavors within Europe, and notably, through partnerships with non-EU countries.
The authors are aware of the limitations of the conducted research, which include the consideration of the European context within the global semiconductor supply chain and the limited number of experts involved in the Delphi study. Future research directions should focus on analyzing and assessing the effectiveness of actions taken to improve Europe's resilience and security within the global semiconductor supply chain. There is also a need for comprehensive awareness-building among society regarding the role that Europe should play in the global semiconductor supply chain. Only comprehensive and engaging solutions involving all stakeholders (business, academia, suppliers) have a chance of success.

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JAK ZAPEWNIĆ ODPORNOŚĆ ŁAŃCUCHÓW DOSTAW PÓŁPRZEWODNIKÓW W UNII EUROPEJSKIEJ?

Streszczenie: Budowanie odporności łańcuchów dostaw półprzewodników wymaga ciągłej analizy ekosystemu półprzewodników, oceny mocnych i słabych stron Europy na rynku globalnym oraz zdolności przewidywania bezprecedensowych wydarzeń. Niniejsze badanie ma na celu zidentyfikowanie sił napędowych i barier oraz możliwych scenariuszy dla łańcuchów dostaw półprzewodników w Unii Europejskiej (UE) w perspektywie 2050 roku. Autorzy szukali odpowiedzi na pytania badawcze: Jakie są czynniki sprzyjające budowaniu odpornych łańcuchów dostaw półprzewodników w UE w perspektywie 2050 roku? Jakie są czynniki ograniczające budowanie odpornych łańcuchów dostaw półprzewodników w UE w perspektywie 2050 roku? Jakie są możliwe scenariusze kształtowania się łańcuchów dostaw półprzewodników w UE w perspektywie roku 2050? Badanie zostało przeprowadzone przy użyciu czterech głównych metod: skanowania horyzontu, analizy TEEPSE, metody Delphi, metody scenariuszowej. Do najważniejszych czynników determinujących odporność łańcuchów dostaw należy zaliczyć: Poziom inwestycji w talenty STEM (nauka, technologia, inżynieria, matematyka); Poziom finansowania badań, rozwoju i innowacji w zakresie wdrażania zaawansowanych półprzewodników (np. linie pilotażowe do prototypowania, testowania i eksperymentowania) oraz - dostępność wykwalifikowanych pracowników w dziedzinie półprzewodników.

Słowa kluczowe: łańcuch dostaw półprzewodników, metoda Delphi, metoda scenariuszowa, odporność