From Waste to Worth: A Comprehensive Market Analysis of ICARUS Consortium's Recycled Silicon in 5 Key Sectors

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Report objectives

The objective of this report is to provide a comprehensive analysis of the silicon industry and its applications, including the markets for the recycled silicon kerf losses from PV production in the same photovoltaic (PV), semiconductor, and electronic industries. Through the analysis framework of the market structure, conduct, and performance model, the report aims to identify potential opportunities and challenges for companies operating primarily in the kerf recycling/processing industry, who are members of the EU ICARUS project consortium. By exploring the market shares of competing companies, distribution strategies, pricing mechanisms, and financial measures, the report will first provide insights into the structure, operations, profitability, and efficiency of the industry. Additionally, the report will analyse the implications of this information for the development of a go-to-market strategy for the secondary raw materials (in particular kerf) produced by ICARUS, with a focus on silicon. The positive outcomes of this research will likely include a better understanding of the global supply and demand scheme by targeted sector, nation and company, as well as concrete market research into the development of potential clients' relationships, partnerships and joint ventures. Ultimately, the report will conclude with a general market outline and offer recommendations for future action for the different consortium partners.

ICARUS project description

Silicon is a widely used material in electronic devices, solar panels, and other industries, having become an essential component of modern life. With a growing demand for electronic devices and renewable energy sources, the use of silicon has significantly increased over the past few decades. However, this increased demand has also led to an increase in waste generated from discarded electronic devices and solar panels, which contain silicon. As a result of the material scarcity, the high energy intensiveness of its production, and strategic sourcing in China in particular, the need for effective and sustainable recycling technologies for silicon has become more critical than ever. Indeed, the production of (e.g.) photovoltaic (PV) panels generates a large waste stream originated from different steps of the value chain.

Important European industries depend on the upstream processing of silicon, which currently relies on primarily Asian supply. This dependence poses a significant risk, as the COVID-19 pandemic has shown. The ICARUS consortium is formed by 17 companies spread all over Europe. It aims to secure this process by turning the upstream process wastes into a secondary raw material, enabling the recovery of high-value material from ingots and wafers manufacturing. ICARUS will develop an industrial 'symbiosis', providing re-processed and refined material for high-end applications. The project will be a driver for a renewed start of a new element of the European PV industry, demonstrating innovative industrial pilots producing silicon, silica, and graphite raw materials, as well as converting silicon waste into full-value industrial commodities.

The Consortium identified different steps of the process in which, through the development of pilot plants and procedures, it will be possible to recycle primary raw material. From this low-purity and highly polluted waste material called Silicon-Kerf (Si-Kerf), the pilot plants can extract high and medium-purity silicon. This regenerated silicon can be re-introduced into the silicon supply chain for solar panels, utilized for other high-end applications that have to be developed on basis of the new source of supply, like silicon for semiconductors, silicon-based anodes for Lithium-Ion batteries (LIB), or even reused at lower purity levels for producing Silicon-Aluminium alloys and SiC fines.

Upon examining Figure 1, sourced from the ICARUS proposal, it is possible to look into the different steps of waste generation during the production of wafers for PV panels. The waste streams generated are detailed in the following list:

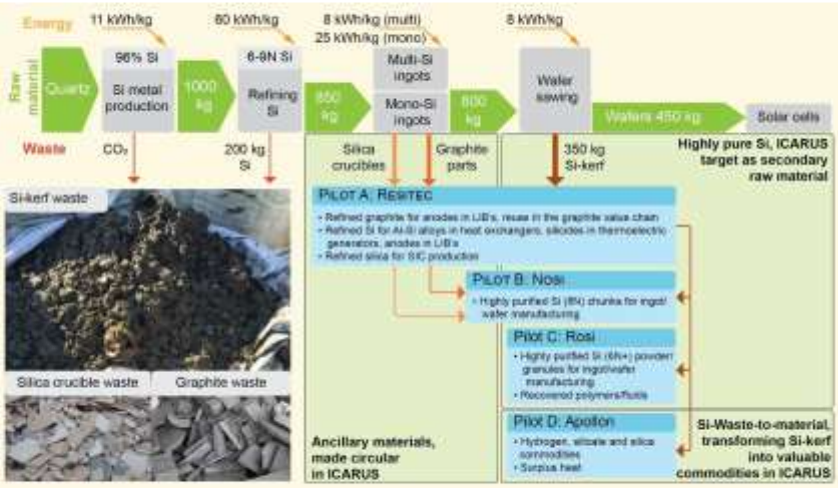


Figure 1. Waste streams from PV production.
Source: ICARUS proposal

1. CO_2 in the step of Si metal production
2. Si (200kg) in the refining step
3. Silica crucibles and graphite parts in the ingots-formation step.
4. Si-Kerf (250kg) in the wafer sawing step.

The ICARUS Consortium aims to utilize the silicon present in the waste streams and recycle it as a secondary raw material, which will unlock significant volumes of newly available recycled materials such as 9.6 million tonnes of Si (about 80% of the current annual production of 12M tons) (51), 1.165 million tonnes of silica, and 490,000 tonnes of graphite (about 47% of the current annual production of 1 Mt) by 2050. To provide a better understanding of the Consortium's project structure, we have defined the four main objectives as outlined in the proposal:

Objective 1: Enable the recovery of >95% of high value material from ingots and wafers manufacturing.

Objective 2: Scale-up modular solutions to process, recycle and refine Si-kerf, and alternatively transform Si-kerf into valuable raw materials.

Objective 3: Develop industrial symbiosis by providing processed and refined material to further high-end applications.

Objective 4: Ensure the actual implementation of the project�s outcomes in the real world.

ICARUS pilots' activities

Upon reviewing Figure 1, it is evident that the depicted companies, referred to as Pilots, will be responsible for converting the aforementioned waste streams into secondary raw materials, thereby promoting the establishment of a circular economy in Europe and the transformation of the previously unused material into valuable commodities. Let us proceed with a systematic examination of each company in a sequential manner.

PILOT A

RESITEC is a Norwegian company from Kristiansand created with the purpose of producing and refining metals and minerals. It will gather all the waste from the different value chain waste streams and treat them according to pre-defined standards, so that it will be able to deliver either for final high-end applications to other companies part of the consortium (GRANGES, MMEX, CIDETEC, SGL, FIVEN)or for further refining to the other pilots (NOSI (pilot B) and ROSI (pilot C)), or also to produce green hydrogen (LUXCHEMTECH (Pilot D)).

PILOT B

NOSI owns a process formed by the combination of two pre-existing processes, inherited from its two parent companies (Fesil Sunergy and N.E.D. Silicon Srl.). The procedure developed has the potential to regenerate silicon at a much better quality than the conventional processes, like Siemens and FBR.

PILOT C

The technologies developed by ROSI Solar, a French company from Grenoble that recycles solar panels, allow for the revalorization of the Si- kerf. This company is owner of the core proprietary technology CCS (Controlled Conditioning of Silicon) that will scale up the silicon treatment to 500 t/yr.

PILOT D

LUXCHEMTECH is the former Solar World, a German pioneer in the solar sector and the owner of the core proprietary technology SiW2M "Si-Waste-to-Material" and it will scale up the actual laboratory-scale pilot reactor of silicon to green hydrogen gas to semi-industrial scale.

MY AND CHEMCONSERVE ROLE

ChemConserve BV, an innovative Dutch SME, operates within the realm of recycling and critical raw materials commercialization, utilizing industrial waste and end-of-life products. Founded in 2012 and stemming from the technological knowledge developed by its predecessor, Deka Holding, ChemConserve is Exploitation Manager in the ICARUS project. Its involvement is limited to 2 work packages. In Work Package 6 it identifies and develops the potential for the recycling technologies created throughout the Consortium, establishing a suitable commercialization structure, and, in the future, negotiating exploitation agreements. Concerning the Work Package 7 ChemConserve contributes to the industry stakeholder workshop, assists in developing project dissemination material, and helps to create a project-focused documentary.

As an intern working with ChemConserve at the ICARUS project, my role involves numerous of tasks related to venture development. I am responsible for 1. researching patented silicon-kerf-related recycling techniques and creating a "patent landscape" out of it, and 2. conducting market research on the possible high-end applications of the recycled silicon in different potential high-end application markets, such as the PV industry and in the Lithium-Ion Batteries market. The two latter duties have led to the redaction of this report.

Other relevant ICARUS activities

It is important for the scope of this report to list the activities of the other companies inside the consortium, as the suggestions and strategies contained in this text, are aimed to be helpful throughout all the Consortium network.

SINTEF AS

Sintef is expected to develop methods for:

- ✓ the separation of silica and silicon through thermal treatment of kerf
- ✓ the use of graphite and silicon in LIBs
- ✓ graphite purification and granulation

- ✓ the development of a technology for the injection of Si-powders into the melt for Si-Al alloys

NORSUN AS

Norsun AS is expected to:

- ✓ Increase the value and the market of the Kerf by reducing the contamination.
- ✓ Develop a process for pot-scrap suction.

INSITUUT POLYTECHNIQUE DE GRENOBLE (IPG)

IPG is expected to:

- ✓ Share the ownership for the development of ROSI's technology.

COMMISSARIAT À L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (CEA)

CEA is expected to:

- ✓ Develop a system for the decontamination of organic materials from silicon The purified silicon can then be separated into different parts and used to make various products, such as solar panels.

BIFA UMWELTINSTITUT GMBH

BIFA is expected to:

- ✓ Develop and LCA of the recycling Si-Kerf in the upstream of the PV value chain to the downstream application.

FUNDACION CIDETEC

CIDETEC is expected to:

- ✓ Be responsible for the evaluation of recycled graphite and Si-Kerf as active materials in LIBs and the estimation of the benefits of these technologies once industrialized.

UNIVERSITY OF CYPRUS

UCY is expected to:

- ✓ Develop a methodology for the development of highly efficient thermoelectric modules based on Si-Kerf.

MARELLI EUROPE S.P.A.

MARELLI is expected to:

- ✓ Develop thermoelectric modules based on silicide.

GRÄNGES SWEDEN AB

GRANGES is expected to:

- ✓ Demonstrate the process to manufacture Si-Al alloys from Si-Kerf.

SGL CARBON GMBH

SGL is expected to:

- ✓ Demonstrate the process of recycling Graphite form Si ingots and wafering process.
- ✓ Develop a method to use recovered graphite and silicon in LIBs.

AYMING

AYMING is expected to:

- ✓ Take care of the communication with EU and the respect of the guidelines.
- ✓ Take care of dissemination and outreach activities.

FIVEN Norge AS

FIVEN is expected to:

- ✓ Demonstrate the process to recycle silico into SiC for technical glass and semiconductors.

Introduction to silicon

Silicon metal (Si), in its original shape, is a grey metalloid element. It is the second most abundant element in the earth's crust after oxygen and the eighth-most common element in the universe. According to publicly available sources (1), nearly 30 percent of the earth's crust by weight can be attributed to silicon.

The element “Silicon” has an atomic number of 14 and naturally occurs in silicate minerals, such as silica, feldspar, and mica, which are major components of common rocks like quartz and sandstone. Being a metalloid, Silicon holds properties from both the metal and non-metal world. It has relatively high melting and boiling points, making it suitable for various industrial operations, and, when crystallized, forms a diamond cubic crystal structure. The atomic structure of silicon, which includes four valence electrons, is critical to its role as a semiconductor and its use in electronic and solar industry.

Silicon forms and purity grades

When it comes to the silicon utilized in the production of solar panels, it can be categorized into various groups based on the arrangement of its atomic structure:

- **Polycrystalline (poly-Si).** It is also called polysilicon and it is a high purity, polycrystalline form of silicon (2). The solar cells made from this type of silicon are blue-coloured and made of multiple silicon crystals melted together. The panels created this way are often a bit less efficient, but are more affordable (4).
- **Monocrystalline (mono-Si).** It is also called single-crystal silicon and it is a high purity form of silicon (2). Its crystal lattice is continuous, unbroken to its edges and free of any grain problems (unlike polysilicon). The solar cells made from this type of silicon are black-coloured and made of a single silicon crystal, assuring a higher efficiency rating, but also a higher price (4).
- **Amorphous.** Silicon that has a disordered atomic structure. Because it can be vapor deposited onto large substrates, amorphous silicon is used to create thin film transistors on almost all active-matrix LCD screens as well as thin film photovoltaic cells on solar panels manufactured in long sheets.

Depending on the final product, silicon can present different grades of purity:

- **Metallurgical grade** (**MG**). To define silicon as of metallurgical grade-silicon (MG-Si), the silicon material needs a purity equal or higher than 98%.
- **Solar Grade** (**SoG**). To define silicon as of Solar grade-silicon (SoG-Si), the silicon material needs a purity equal or higher than 99,9999% (a 6N+ purity).
- **Electronic Grade** (**EG**). To define silicon as of Electronic grade-silicon (EG-Si), the silicon material needs a purity equal or higher than 99,9999999% (a 9N+ purity).

Solar panels production process (Error! Reference source not found.) (9) (Error! Reference source not found.)

Figure 2. The production process of PV modules

High-purity silicon is a vital material in the production of solar panels and semiconductors, and it is derived from high-purity quartz. The process begins with the crushing of quartz to obtain silica (SiO_2) and the reduction of silica, resulting in metallurgical grade silicon (MG-Si) with 98% purity. To achieve the desired 99.9999% (6N) minimum purity for PV applications, several purification steps must be taken, leading to the formation of polysilicon. There are three main processes for producing polysilicon: Siemens process, Fluidized Bed Reactor (FBR) technology, and Upgraded Metallurgical-Grade (UMG) silicon.

The Siemens process remains the dominant technology for creating high-purity silicon. Developed by Siemens and Wacker in the 1950s, this process starts by creating trichlorosilane (TCS) as an intermediate product with a low boiling point. Silicon is then deposited on slim, high-purity silicon filaments, which are electrically heated in a steel bell-jar to grow polysilicon rods of 15-20 cm in diameter.

The FBR technology is more energy-efficient, consuming only one-tenth of the electricity used by the Siemens process. It begins with the injection of a silicon-containing gas and oxygen through nozzles, creating a fluidized bed capable of carrying tiny silicon particles. The temperature is increased to the reaction zone, and silicon deposits on seed particles to form larger granules. However, obstacles such as patents, complex fluid dynamics, high costs, and large amounts of silicon dust have limited its widespread adoption.

The UMG technique does not purify the raw MG-Si but instead uses physical methods like vacuum melting and directional solidification to extract impurities directly from the silicon metal. Despite consuming less energy than the Siemens process, the UMG technique produces lower purities and has lost its cost advantages due to improvements in the Siemens process. Consequently, commercial production of UMG silicon ceased in 2020.

Polysilicon chunks or rods are melted in a crucible, and silicon ingots needed for wafer production are obtained through crystallization. Monocrystalline silicon production is more complex and energy-consuming than polycrystalline silicon production. Two methods are used for monocrystalline silicon production: the Czochralski (CZ) method and the floating zone (FZ) method. The CZ method is widely used for its better resistance to thermal stress, production speed, and lower cost, while the FZ method eliminates the risk of contamination from crucible material and crystal defects.

Silicon ingots are then cut into wafers using wire saw cutting, which includes two main types: slurry cutting and diamond wire cutting. Diamond wire cutting is more popular due to its environmental friendliness, ease of cleaning, speed, and use of an aqueous coolant, while slurry cutting is slower and produces more waste.

Finally, silicon wafers are transformed into solar cells through several steps, including pre-check, texturing, acid cleaning, diffusion, etching, washing, anti-reflective coating deposition, contact printing, drying, testing, and cell sorting. The solar cells are then used in the assembly of solar PV modules. The quality of solar cells is graded based on the smoothness of the production process and the quality of the silicon wafer material.

METHODOLOGY:

THE SCP PARADIGM

In this market analysis of silicon and its high-end applications, with the purpose of identifying markets for recycled kerf we have opted to utilize the Structure-Conduct-Performance (SCP) paradigm. This decision results from the recognition of how such a paradigm can be effective in providing a complete view of market dynamics. It describes with a good level of detail the interaction between the market's structure, the behaviour of firms within that market, and the overall market performance.

The structural elements of the market, such as the number and size of firms, the market concentration at the supply and demand side and the degree of product differentiation will be helpful in forming an understanding of the competitive landscape in the silicon market, allowing to identify the degree of competition within it.

The conduct component of the SCP paradigm enables to examine the strategic decisions made by firms, such as pricing, research and development, and marketing strategies. This analysis will aid in understanding how companies in the silicon market are behaving and responding to the existing market structure and competition.

Lastly, the performance aspect of the SCP paradigm offers insights into the efficiency and welfare implications of the market. Indeed, it assesses the overall performance enabling to evaluate the effectiveness and productivity of the market and it facilitates the development of a more informed go-to-market strategy.

By adopting the SCP paradigm, it is possible to create a comprehensive and detailed market analysis, thereby ensuring that the strategies are effectively aligned and will deliver a competitive edge in the high-end applications of silicon.

In order to give a more clear and defined organization to the text, the text will be divided in the types of silicon-related markets, drafting an SCP paradigm for each of them. The topics' division proposed will be:

1. Polysilicon industry
2. Photovoltaic (PV) industry.
3. Semiconductors.
4. Lithium-Ion Batteries (LIB) with silicon-based anode.
5. Silicon-Aluminium (Si-Al) alloys.

PORTER'S 5 FORCES MODEL

After analysing these 5 markets through the SCP, we will include a "conclusion and implications" section to assess the potential market dynamics and challenges that the ICARUS consortium may encounter in the lithium-ion battery sector. The analytical framework chosen for this purpose is Porter's Five Forces, a widely acclaimed model that enables a comprehensive review of the current state of the market while also offering valuable insights into possible future trends within the lithium-ion battery industry.

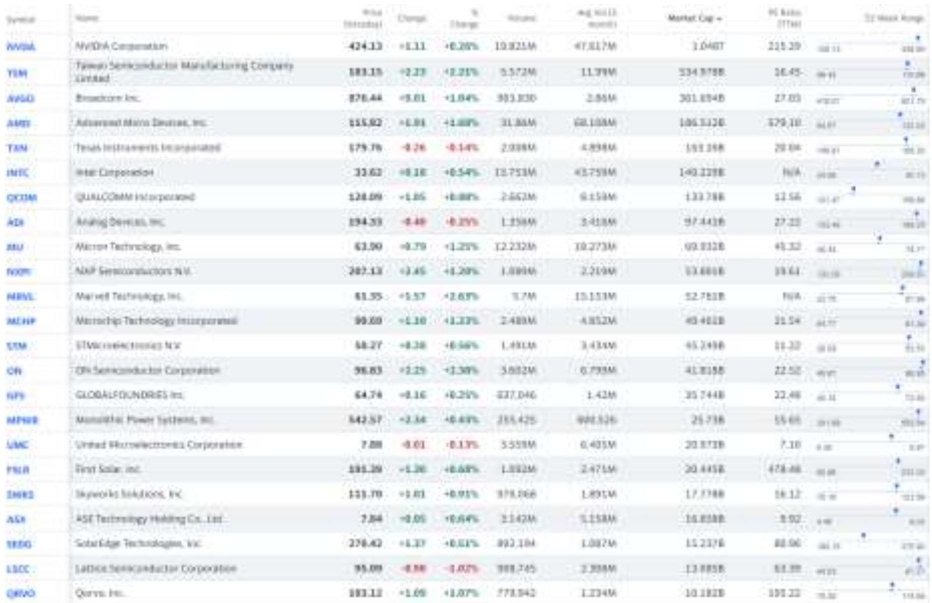
The selection of Porter's Five Forces stems from its relevance and effectiveness in analysing competitive dynamics within an industry. Developed by Michael E. Porter, a renowned economist and strategist, this framework has proven to be instrumental in evaluating the overall attractiveness and competitiveness of a market, identifying potential barriers to entry, and assessing the relative power of various market forces on the Consortium's business operations. Moreover, this model helps in understanding the underlying economic structure and key driving forces in the different sectors in which ICARUS is involved.

Definition of the Silicon Market

The silicon market is a complex and dynamic industry that encompasses the production and sale of silicon-based materials, devices, and integrated circuits (ICs) used in a wide range of electronic devices, including computers, smartphones, TVs, and automobiles. The silicon market is made up of several segments, including silicon wafers, photovoltaic (PV) cells, and integrated circuits. Silicon wafers are thin slices of silicon that are used as the foundation for building electronic devices, such as solar panels, while integrated circuits are used to make microprocessors, memory chips, and other electronic components. The demand for silicon-based materials and devices has increased exponentially in recent years, driven by the growth of the electronics industry and the rise of new technologies such as the Internet of Things (IoT), artificial intelligence (AI), and 5G networks (Error! Reference source not found.). The silicon market is also influenced by macroeconomic factors, such as changes in global GDP, interest rates, and trade policies. It is highly competitive, with many players operating across the entire value chain, from silicon production to the design and manufacturing of electronic devices. The industry is characterized by high levels of innovation, with companies investing heavily in research and development to stay ahead of their competitors.

Geographically, the silicon market is dominated by Asia, particularly China, followed by Japan, South Korea, and Taiwan, which account for a significant portion of global silicon production and consumption. However, the industry also has a strong presence in North America and Europe. Despite its rapid growth and technological innovation, the silicon market faces several challenges, including rising production costs, supply chain disruptions, and environmental concerns related to large waste streams that end up in landfills and energy-intensive manufacturing processes. As a result, companies in the industry are increasingly focusing on sustainability and green manufacturing practices to reduce their environmental footprint and ensure long-term profitability.

In conclusion, the silicon market is a complex and dynamic industry that plays a critical role in powering the global economy and driving technological innovation. From the production of silicon wafers to the design and manufacture of integrated circuits, the industry is characterized by high levels of competition, innovation, and investment in research and development.



Symbol	Name	Price (Intraday)	Change	% Change	Volume	Avg Vol (3 month)	Market Cap	PE Ratio (TTM)	52 Week Range
NVDA	NVIDIA Corporation	424.13	+1.11	+0.26%	10.821M	47.817M	1.048T	215.29	[illegible]
TSM	Taiwan Semiconductor Manufacturing Company Limited	103.15	+2.23	+2.21%	5.572M	11.79M	534.978B	16.45	[illegible]
AVGO	Broadcom Inc.	876.44	+9.01	+1.04%	393.830	2.86M	361.894B	27.03	[illegible]
AMD	Advanced Micro Devices, Inc.	115.82	+1.81	+1.08%	31.86M	68.108M	186.512B	579.10	[illegible]
TXN	Texas Instruments Incorporated	179.76	-0.26	-0.14%	2.008M	4.898M	163.16B	20.04	[illegible]
INTC	Intel Corporation	33.62	+0.18	+0.54%	13.753M	43.759M	140.228B	N/A	[illegible]
QCOM	QUALCOMM Incorporated	128.09	+1.05	+0.88%	2.662M	8.159M	133.78B	12.56	[illegible]
ADI	Analog Devices, Inc.	194.33	-0.48	-0.25%	1.258M	3.418M	97.443B	27.22	[illegible]
MU	Micron Technology, Inc.	63.90	+0.79	+1.25%	12.232M	19.273M	69.832B	45.32	[illegible]
NXPI	NXP Semiconductors N.V.	207.13	+2.45	+1.20%	1.889M	2.219M	53.885B	19.61	[illegible]
MRVL	Marvell Technology, Inc.	61.35	+1.57	+2.63%	5.7M	15.153M	52.781B	N/A	[illegible]
MCHP	Microchip Technology Incorporated	90.60	+1.10	+1.23%	2.489M	4.852M	49.402B	21.54	[illegible]
STM	STMicroelectronics N.V.	50.27	+0.28	+0.56%	1.491M	3.434M	45.249B	11.22	[illegible]
ON	ON Semiconductor Corporation	96.83	+2.25	+2.38%	3.802M	6.799M	41.815B	22.52	[illegible]
GFS	GLOBALFOUNDRIES Inc.	64.74	+0.16	+0.25%	837.046	1.42M	35.744B	22.48	[illegible]
MPWR	Monolithic Power Systems, Inc.	542.57	+2.34	+0.43%	255.425	600.526	25.73B	55.65	[illegible]
UMC	United Microelectronics Corporation	7.88	-0.01	-0.13%	3.559M	6.405M	20.873B	7.10	[illegible]
FSLR	First Solar, Inc.	191.29	+1.26	+0.68%	1.892M	2.471M	20.445B	478.48	[illegible]
SWKS	Skyworks Solutions, Inc.	111.70	+1.01	+0.91%	979.068	1.891M	17.778B	16.12	[illegible]
ASX	ASE Technology Holding Co., Ltd.	7.84	+0.05	+0.64%	3.142M	5.158M	16.858B	8.92	[illegible]
SEDG	SolarEdge Technologies, Inc.	276.42	+1.37	+0.61%	892.184	1.087M	15.237B	88.96	[illegible]
LSCC	Lattice Semiconductor Corporation	95.09	-0.98	-1.02%	988.745	2.308M	13.885B	61.39	[illegible]
QRVO	Qorvo, Inc.	103.12	+1.09	+1.07%	773.942	1.234M	10.182B	100.22	[illegible]

Figure 3. Stocks representing semiconductors and solar companies in July 2023 (Source: Yahoo Finance) (52)

The aim of the following paragraphs is to outline the structure of the silicon market in more detail to make it available for the ICARUS Consortium. Through the means of different applicable frameworks, we will explore the different segments, the key players for each of these and understand the level of competitiveness. We will first prioritize the segments having a direct impact on the members of the Consortium, like PV, semiconductors, LIBs and so on. Completed this task a brief analysis of possible new uses and technologies will be performed to give an overview of other possible output products of interest. By examining these issues, the ICARUS members will gain a deeper understanding of the key drivers and trends shaping the silicon market today and in the future.

POLYSILICON

MARKET STRUCTURE – POLYSILICON

Before diving into the structure, conducts and performance of high-end polysilicon applications, it is fundamental to take a look at the industry that produces the key raw materials for such applications: the polysilicon manufacturers.

Here a list of the top 10 players for Polysilicon production worldwide is provided. This list has been compiled based on the Market Cap of each of these companies, which, according to Bernreuter Research, are top polysilicon producers (14).

	Company Name	Country of origin	Market Cap (bn)...	EBITDA (bn)	Revenue (ttm) (bn)	Forward P/E	Trailing P/E	ROA (ttm)	ROE (ttm)	EBITDA Margin
1.	OCI Company Ltd.	South Korea/ Malaysia	1 168	null	null	null	null	null	null	null
2.	Tongwei Co.,Ltd	China	153,2	33,32	100,98	8,64	5,56	22,39%	56,05%	39%
3.	National Silicon Industr...	China	56,27	0,77	3,62	103	128,75	0,47%	2,8%	21%
4.	GCL Technology Holdin...	China	43,73	16,05	35,93	3,24	2,49	11,92%	42,19%	44%
5.	Corning Incorporated	China	28,56	3,03	0,08	13,94	31,7	3,4%	7,84%	83%
6.	Xinte Energy Co., Ltd.	China	21,77	19,76	37,54	3,61	1,52	16,28%	48,47%	52%
7.	Wacker Chemie AG	Germany/USA	8,76	1,46	7,88	12,64	5,3	7,54%	22,72%	18%
8.	REC Silicon ASA	China	7,16	-0,07	0,14	21,54	null	14,89%	134,69%	-45%
9.	Daqo New Energy Corp.	China	3,01	2,81	4,04	4,53	2,03	26,85%	42,76%	69%

TBALE 1 - Top 10 polysilicon companies by Market CAP with heatmap. Source: Yahoo Finance

Upon examining Table 1, it is possible to already draw some conclusion on the polysilicon market characteristics. It is readily apparent that it displays a high degree of market concentration, focused mainly in China. Indeed, 70% of the polysilicon production leaders are situated in China, confirming once more the country's preeminent role in the global polysilicon sector. This dominance can be attributed to a confluence of factors, such as China's abundant resources, well-established manufacturing infrastructure, and government policies that actively endorse the development of the solar industry.

Furthermore, it is important to recognize that several companies have operations extending across multiple countries. For instance, Wacker Chemie AG maintains operations in both Germany and the United States, while OCI Company Ltd. has a presence in South Korea and Malaysia. This international footprint could afford these companies the flexibility to manage risks associated with regulatory changes, market volatility disruptions in the supply chain. Nonetheless, upon examining Figure 4, it is possible to observe how the supremacy of China in the polysilicon production, and, discussing this graph, in the PV production, is so overwhelming that a change in the market dynamics for this sector is not going to happen soon, unless a big technological breakthrough will emerge.

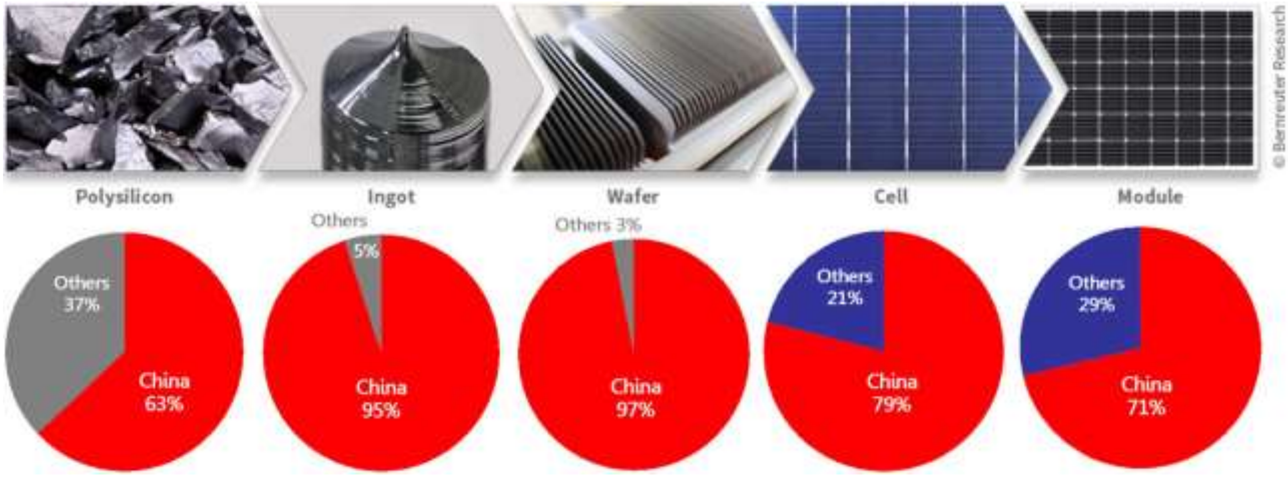


Figure 4. China's share in production volumes along the solar value chain in 2019. Source: Bernreuter Research

Thanks to the data provided in this chart and other data retrieved on Internet (Error! Reference source not found.), it is possible to say that China showed an increase of 29% in the production volumes along the solar value chain throughout the last 12 years. Indeed, it moved from an already significative 55% in 2010, to 84% in 2022. IEA in a special report (21) highlights the importance of distributing the manufacturing capacity for these processes worldwide, as unforeseen events can happen which can hinder the flawless solar supply chain. This is demonstrated by recent manufacturing halts in China, due to COVID in 2020, which caused a 10-year high rise in the price of polysilicon globally.

MARKET CONDUCT – POLYSILICON

The market structure then guides the firms' conduct in the industry. The oligopolistic nature and geographical concentration of the polysilicon industry influence the competition level and strategies that firms will adopt.

In the polysilicon market, companies are engaged in intense competition due to the high demand in the manufacturing of semiconductors and photovoltaic (PV) cells for solar panels. This market is characterized by a moderate level of competition, as only few key players such as Tongwei Co. Ltd, Wacker Chemie AG and OCI Company Ltd dominate the market. These companies, together with few others, have substantial market share and have established strong relationships with downstream manufacturers. New entrants face significant barriers due to the high capital costs associated with setting up polysilicon production facilities and the technical know-how required to produce high-quality polysilicon.

Pricing is heavily influenced by the balance of supply and demand. Most firms adopt cost-based pricing strategies, where the price of polysilicon is determined based on production costs and desired profit margins. Companies engage in price competition during periods of oversupply. However, long-term contracts between producers and customers are also common in this type of industry, helping to stabilize prices. This also influences the marketing strategies put in place by the companies in the sector. Indeed, being mainly a B2B market, these schemes are more imprinted to focus on establishing and maintaining strong customer relationships. As a consequence, they normally aim to show the superior quality of their polysilicon, often highlighting, for example, the low impurities content or the level of environmental friendliness of the techniques used to produce or recover polysilicon from the production line.

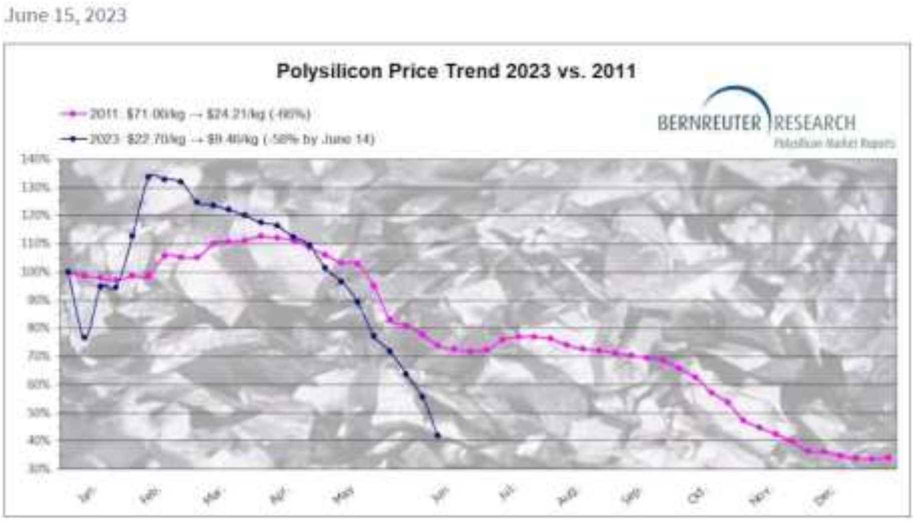


Figure 5. Polysilicon price trends 2023 vs 2011

Furthermore, the price trends in polysilicon are renown to look a bit like a roller-coaster especially in the past decade with periods of oversupply and shortage alternating. According to the latest analysis by Bernreuter Research and as we can see from Figure 5 (40), we know that the price of polysilicon plummeted during 2023 after a period of shortage between 2021-2022, to which companies worldwide answered by increasing the production. They did so while ignoring the advice of the Silicon Branch of the China Nonferrous Metals Industry Association, which warned about the dangers of pursuing only short-term interests. This was already forecasted to happen as we saw a similar price trend behaviour in 2011, when, again, the plummeting price was preceded by a shortage from 2004 to 2008. This is reported in the graph and compared to the current price reduction, that is to be considered even heavier than the previous one.

Talking about the product design, as aforementioned, polysilicon is a highly standardized product as its product design is quite undifferentiated. Nonetheless, it is possible to make a clear differentiation relatively to its purity. Indeed, the prices at which company sell polysilicon highly depends on the final product the material is intended for. Showing higher prices for silicon of electronic grade (9N purity) when compared to the metallurgical grade (4N purity), as the processes behind the production of these two types of material is different. High-purity polysilicon is required for semiconductors and high-efficiency solar cells, and firms that can consistently produce high-quality polysilicon can achieve a competitive advantage. Some firms are also exploring ways to reduce the environmental impact of polysilicon production, by creating recycling system for different steps and parts of the process.

MARKET PERFORMANCE – POLYSILICON

The firms' conduct in the industry, which is a consequence of the market structure, determines the market's performance. The competitive strategies and adjustments made by firms in response to market signals have implications for production efficiency, pricing, and the quality and variety of polysilicon products. Therefore, when analysing the performance of a market the first thing to do is to define the metrics that will be used to study it. In the case of polysilicon, we decided to use the production efficiency and the quality and variety of polysilicon products.

As previously analysed in Table 1, it is possible to say that the production of polysilicon in the last 10 years has been shifting from a U.S.-European superiority in the markets to a Chinese superiority. Indeed, in 2011 (41) U.S. based Hemlock semiconductors occupied the top position, but not later than the next year, it was losing it to a Chinese company. At the time, China had a share of only the 30% in the global polysilicon production, while in 2022 they reached 76%. Therefore, when talking about production efficiency, it results fundamental to talk about China. Indeed, only the production capacity of the top-three firms (Chinese) put together is higher than the sum of the other 7 put together. This surprising data should be a warning for the

European and American economies. As we recently saw happening with the war in Ukraine, energetically depending on a dictatorial regime is not convenient as it can put at risk the energy security of entire nations. Consequently, since the polysilicon is the main raw material used for the production of solar panels, considered the future of renewable energy, the Western countries should start working on their own solar supply chain, in order to reduce the dependence from a country, which international relations are not so stable, as shown by the China-Taiwan situation. This whole set of analysis is confirmed by looking at Figure 6, retrieved from Statista (42), where we can see the major countries in silicon production worldwide in 2022, with China producing almost 10-times more silicon than Russia, classified as second.

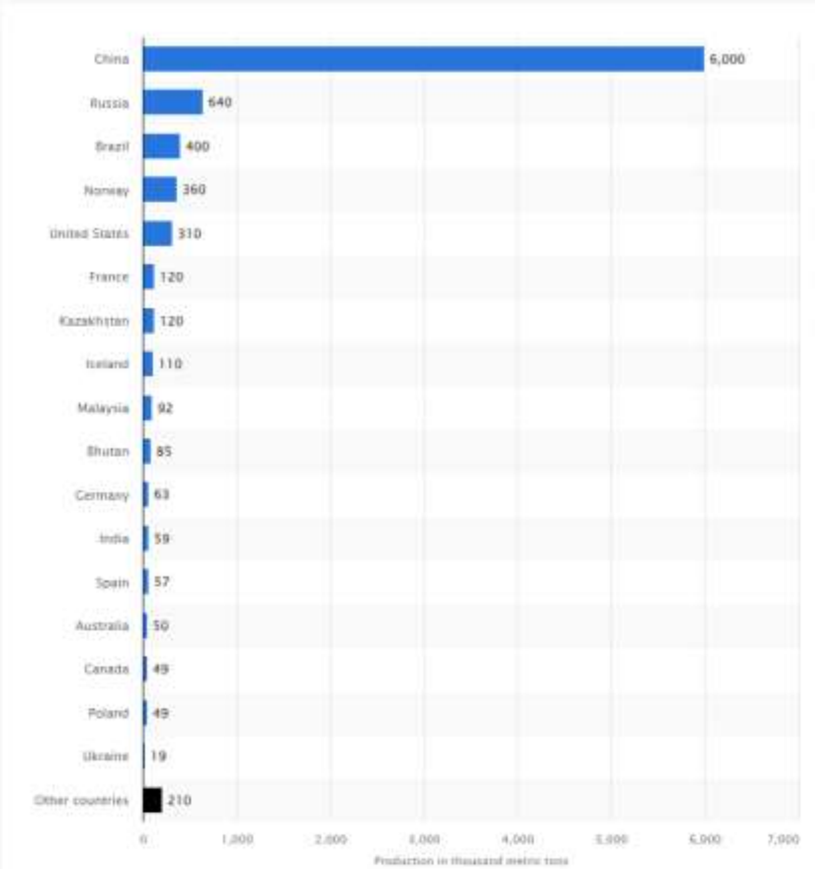


Figure 6. Major countries in silicon production worldwide in 2022

Concerning the quality and variety of polysilicon production, it is important to make a first distinction. There are two main varieties of silicon produced with two associated quality grades. These are the solar-grade and the electronic-grade silicon. As explained in the previous chapter "silicon forms and purity grades", the first is used to produce solar panels and shows a purity of at least 6N, the latter is used as semiconductors' material and shows a purity of at least 9N.

When talking about solar grade polysilicon we see, once again, a marked Chinese superiority. Indeed, Bernreuter Research reports (41) that China is now producing more than 80% of the solar-grade polysilicon worldwide and is forecasted to grow even further reaching an amount equal to the 90% of the total production. This suggests that China is likely to control this market, potentially making Western countries entirely dependent on Chinese businesses.

Considering the electronic-grade polysilicon market, the Asian advantage is again clear and linked to multiple reasons. First of all, upon examining Figure 7 (43) we see how, already in 2021, the region with the highest market share was East Asia, as they hold about the 70% of total semiconductors exports. The main reason behind this dominance is the presence in the region of the biggest semiconductors producer: TSMC, which holds 60% share of the global foundry revenue. This makes the world market dependent, once again, on this part of the world.

Figure 7. Global electronic grade silicon market forecast, 2022-2032

As mentioned earlier, given the political and economic uncertainty in the region, these situations (for both polysilicon grades- markets) could have serious effects on global economic trends. For instance, if China were to invade Taiwan, the US, which is known for supporting Taiwan's government, would be forced to halt its purchases of polysilicon from China. The same reaction would be expected from other Western countries who oppose such actions, similar to the response, on natural gas purchases, following Russia's invasion of Ukraine.

In order to give more detailed information about the performance of the polysilicon market, we will analyse the performance of the top 10 firms according to different financial metrics. We will focus on the comparison of the EBITDA margin with both the Revenue (ttm) and the Trailing P/E of the top companies of this sector. Indeed, comparing the EBITDA margin with Revenue (ttm) assesses operational efficiency and cost management, while comparing it with Trailing P/E helps assess investor perceptions of growth potential. This comparison sets good benchmarks for the industry performance. The data are retrieved from Table 1 and possible implications are discussed.

Revenue and EBITDA Margin:

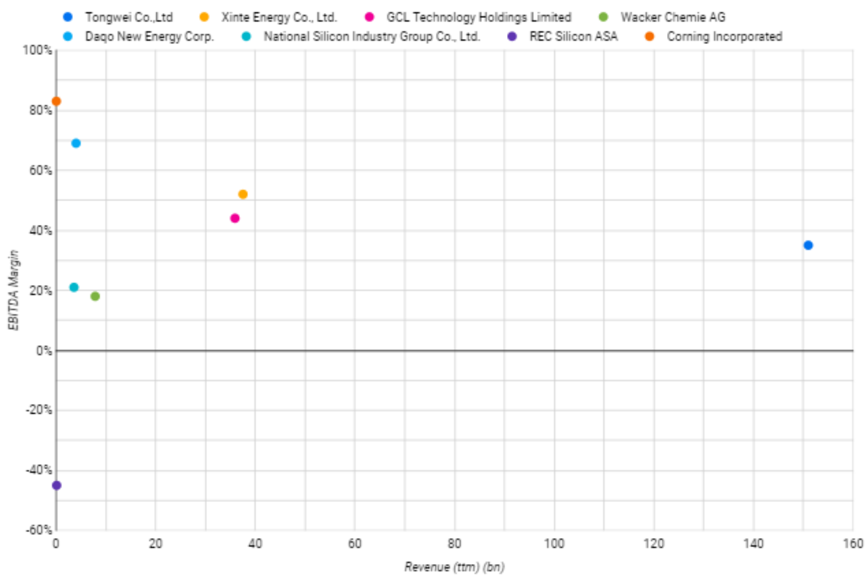


Figure 8. Scatter plot Revenue VS EBITDA margin top polysilicon companies

- For instance, Tongwei has the highest revenue and a relatively high EBITDA margin. This shows that the company not only generates significant sales but also efficiently converts a portion of those sales into profits, demonstrating effective cost management.
- On the contrary, REC Silicon ASA is operating at a negative EBITDA margin, indicating that the company is currently not able to convert sales into profits effectively, possibly due to high operating expenses or lower sales prices.
- Xinte Energy and Daqo New Energy have impressive EBITDA margins but comparatively lower revenue. This suggests that these companies might be operating in a niche or premium segment of the market where they can charge higher prices or maintain lower costs, resulting in higher profit margins despite lower sales volumes.
- Corning Incorporated, instead, has one of the highest EBITDA margins among these companies at 83%, which suggests excellent operational efficiency. It means that a significant portion of the revenue generated by the company is retained as EBITDA, indicating effective cost management. However, in terms of revenue, Corning Incorporated's revenue is considerably lower compared to some other companies like Tongwei, Xinte Energy and GCL Technology Holdings. Despite this, the high EBITDA margin demonstrates that the company is able to convert a substantial portion of that revenue into operational profit.

Trailing P/E and EBITDA Margin:

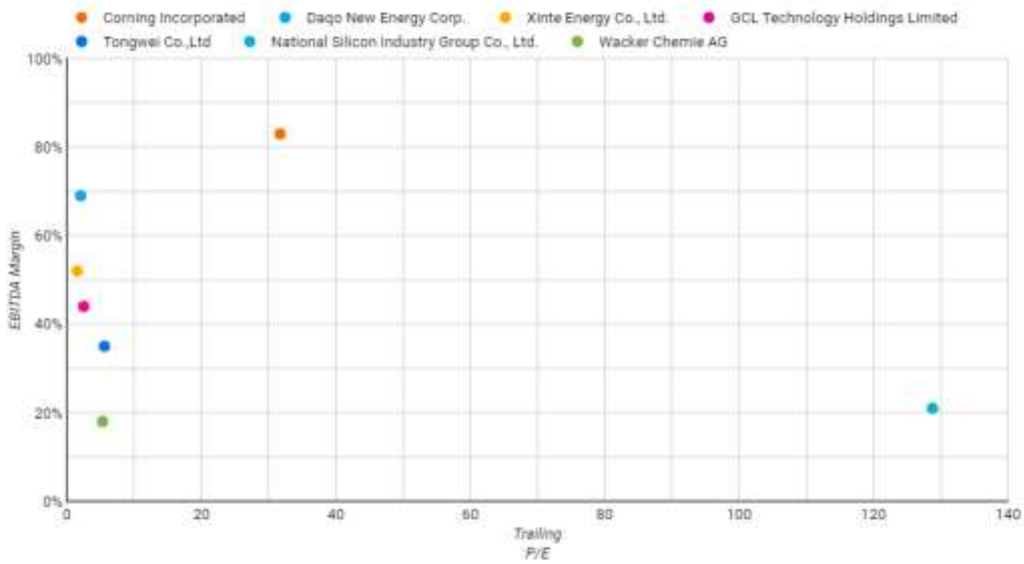


Figure 9. Scatter plot Revenue VS EBITDA margin top polysilicon companies

- National Silicon Industry, for example, has a moderate trailing P/E and a moderate EBITDA margin. This could indicate that the market expects this company to follow its current profitability path in the future, making it a safer investment for interested parties, showing an average operational profitability.
- Conversely, Wacker Chemie AG has a relatively low trailing P/E and a low EBITDA margin, implying that the market may be undervaluing its earnings or that it expects slower growth for this company.
- Companies like Xinte Energy and Daqo New Energy, with low trailing P/E ratios but high EBITDA margins, may suggest that these companies are undervalued by the market, or there might be some risks associated with these companies that affect their P/E ratios.

- Concerning Corning Incorporated, the combination of a quite high Trailing P/E and a high EBITDA margin suggests a company that is highly efficient and profitable and is expected to grow significantly in the future. This may be due to:
    a) The company's successful cost management strategies and operational efficiencies that have led to high profitability.
    b) The company's strong positioning in its market, leading to investor confidence in its ability to maintain or increase its earnings.
    c) The company may be benefiting from positive industry trends or growth opportunities that are expected to drive its future earnings.

Based on the gathered data, it is possible to make the following general observations about the polysilicon sector:

1. **High Growth Expectations**: Despite the diversity in performance, there's an apparent high growth expectation in the sector, as suggested by the P/E ratios of several companies. High P/E ratios, such as those of National Silicon Industry, typically indicate that investors expect high earnings growth in the future. This suggests a general feeling of optimism about the future of this sector.
2. **Operational Efficiency**: High EBITDA margins for many companies indicate that the polysilicon sector, in general, has strong operational efficiency. Companies like Daqo New Energy, Xinte Energy, and GCL Technology Holdings are able to maintain high EBITDA margins, implying they effectively control their operating costs and run efficient operations.
3. **Sector's Profitability**: Apart from some outliers, the profitability of the sector seems good given the EBITDA margins, ROA, and ROE. This profitability, together with the high growth expectations reflected in the P/E ratios, may attract more investments into the sector, stimulating further growth and competition.

To circle back, the performance analysis feeds back into the market structure. To improve performance and ensure the stability of the supply chain, there may be a need for market changes, such as incentivizing polysilicon production in other regions or implementing policies to reduce the barriers to entry. This could, in turn, reshape the market structure, prompting changes in firms' conduct, and further affecting market performance.

CONCLUSIONS AND IMPLICATIONS FOR ICARUS- POLYSILICON

In the complex and rapidly evolving landscape of the global polysilicon industry, it is crucial to understand the competitive dynamics that underpin its market structure. Porter's Five Forces Analysis, a strategic tool developed by Harvard Business School Professor Michael E. Porter, offers a comprehensive framework for evaluating these dynamics. The analysis explores five key forces, assigning them a level from low to high, that influence industry competition: the threat of new entrants, the bargaining power of buyers, the bargaining power of suppliers, the threat of substitute products or services, and the intensity of competitive rivalry. Collectively, these forces dictate the profit potential of an industry by influencing prices, costs, and required investments.

In this section, we apply Porter's Five Forces Analysis to the polysilicon market, a critical sector with implications for various high-end applications, including semiconductor and photovoltaic cell manufacturing. The aim is to gather insights about the future trajectory of the industry, providing strategic implications for the ICARUS consortium. This detailed analysis will guide the understanding of the industry's competitive dynamics, setting a strategic foundation to navigate the upcoming challenges and opportunities.

1. Threat of New Entrants: Low

The barrier to entry in the polysilicon industry is high, largely due to substantial upfront capital investment required for establishing polysilicon production facilities. The significant technical know-how required to produce high-quality polysilicon further heightens this barrier. Indeed, according to a patent landscape developed for the Consortium, the total Asian patent ownership concentration is equal to 94% of the listed patents, compared to a meagre 3,4% and 3% of USA and Europe respectively. Additionally, the top four Chinese companies control a significant share of global production, with the leading Chinese company, Tongwei Co., Ltd., having a production capacity nearly 18 times larger than the lower ranking producers. This scale, coupled with China's abundant resources and supportive government policies, provides the Chinese with a competitive advantage that would be challenging for new entrants to replicate.

ICARUS's efforts to recycle and repurpose waste materials could effectively lower the barrier to entry for European companies in the polysilicon industry. Notably, the life cycle assessment (LCA) of recycled material shows it to be highly favourable when compared to virgin material. This means that recycled silicon not only minimizes environmental impact but also enhances its economic position due to potentially lower costs associated with resource extraction and processing. Consequently, using recycled silicon can be a cost-effective and environmentally friendly alternative that could further disrupt the current market dynamics. By offering an alternative source of raw materials that bypasses the need for large-scale mining and refining operations, ICARUS could help facilitate the emergence of new market participants.

This increased competition could help break the dominant position of Chinese companies and stimulate innovation within the industry. Nonetheless, ICARUS' stakeholders should always be advised of the possibility to trade with these Chinese companies, exchanging knowledge or materials.

2. Bargaining Power of Suppliers: Moderate to High

The fact that 70% of the top polysilicon producers are based in China and collectively hold a significant portion of global production capacity gives these suppliers considerable market power. This dominance is further amplified by the existing manufacturing infrastructure and supportive governmental policies. Suppliers' power is also reflected in their ability to set prices based on production costs and desired profit margins, particularly during periods of oversupply. However, the presence of international companies like Wacker Chemie AG, that operates in multiple countries might balance the power to some extent, leading to moderate to high bargaining power overall.

The goals set by ICARUS, aiming to retrieve 95% of high-value raw materials from the losses in silicon ingot and wafer manufacturing, have the potential to shift power dynamics significantly within the polysilicon market. If achieved, European companies can expect to have access to a more diversified supply chain, reducing their dependence on Chinese suppliers. This reduced dependency on a few, key, predominantly Chinese, suppliers will lead to a decrease in suppliers' bargaining power. Suppliers will face increased competition from the recycled materials, challenging their ability to dictate prices and terms. Additionally, a more diversified supply chain will likely result in more stability in prices and a lower risk of supply disruptions due to geopolitical tensions or trade policies. This shift can contribute to a more resilient and robust polysilicon market in the long run.

3. Bargaining Power of Buyers: Moderate

The prices of polysilicon highly depend on the final product the material is intended for, with higher prices for higher purity polysilicon. Together with this, the significant market concentration among producers reduces the bargaining power of buyers and long-term contracts between producers and customers are also common in this industry, further stabilizing prices and limiting purchasers' negotiation power. However, the presence of some internationally operating companies with operations in different countries provides some diversification of supply, potentially increasing the bargaining power of buyers to a moderate level.

With ICARUS's processing solutions, an increase in the available supply of raw materials is anticipated. This expansion in supply will proportionally increase the bargaining power of buyers, who will have more options to choose from when sourcing polysilicon. Buyers can leverage this enhanced position to negotiate better terms and prices, fostering a more competitive and fair market environment. Furthermore, if ICARUS can consistently produce high-quality materials at competitive prices, a substantial shift in the market's power dynamics may occur. This shift could potentially provide buyers with an even stronger position, causing a lasting change in how the polysilicon market operates.

4. Threat of Substitutes: Low

Polysilicon is an integral raw material for the production of semiconductors and photovoltaic (PV) cells, with no known direct substitutes that currently can match its performance characteristics and cost-effectiveness. Therefore, the threat of substitutes is low. Nonetheless, the continued search for alternative renewable energy sources and advances in technology may pose future substitution threats. Indeed, the work being done by ICARUS may indirectly increase this threat over time. By developing and advancing modular processing and recycling technologies, ICARUS could pave the way for material innovations. These new materials, originating from recycling and refining waste streams, may possess unique properties that could serve as substitutes for polysilicon in certain applications. If successful, these materials could provide an alternative to polysilicon, especially if they prove to be more sustainable or cost-effective. While the impact on the threat of substitutes remains speculative at this point, the possibility represents a long-term market dynamic that warrants close attention.

5. Competitive Rivalry within the Industry: High

The polysilicon industry is characterized by high competition, particularly among the top producers, as evidenced by the vast differences in Market Cap and production capacities. Firms are driven to increase their production efficiency to maintain or improve their market positions. The competition is further heightened by price wars during periods of oversupply, with firms aiming to offer the most competitive pricing to secure contracts.

ICARUS's efforts align with the global trend towards sustainability and circular economies. The consortium's closed-loop systems would reduce waste and make the industry more sustainable, enhancing the international interest for such products.

PV INDUSTRY

MARKET STRUCTURE – PV INDUSTRY

In 2021, the global market size of solar photovoltaic (PV) panels reached USD 167.83 billion (11). When studying the growth rate and market size of an industry, it is valuable to check whether they are balanced worldwide or if some regions are having more influence than the others in the industry. When observing the numbers representing the market size of the PV industry, the supremacy of China on all the other countries and regions stands out clearly. Indeed, when comparing different market measures and ratios, we noticed how the Chinese dominate this market.

First thing, we looked at the PV- related trade in the main PV producing regions worldwide, taking in consideration the US, Europe, and the Asian pacific countries. To give a clearer overview of the situation we created a graph that shows the value of PV – related trades in these three regions. In this graph the value relates to the sales completed in the regions and expressed in billion US dollars.

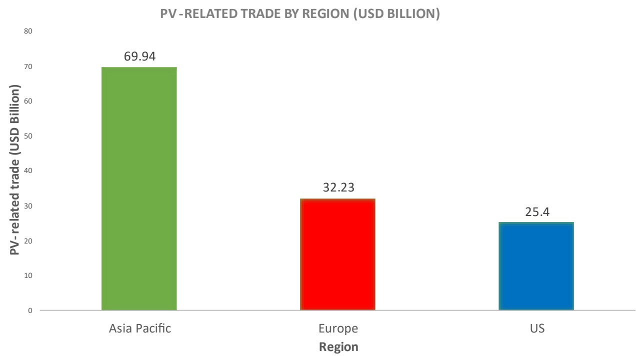


Figure 10. PV- related trade by region

Upon examining Figure 10, it is clear how the Asian pacific area is the main driver of PV production and trade showing a value that is equivalent to more than the double of the trades happened in Europe (which used to be a top PV producer). What is surprising when looking at the Asian-pacific number of 69.94 USD Billion is that China, with its 40 USD Billion in PV-related trades in 2021, makes up more than the 57% of the whole trades in the region and almost the 25% in the world.

Another interesting metric to be considered is the compound annual growth rate (CAGR), a measure for annual increase. The PV industry showcases an anticipated compound annual growth rate (CAGR) between 7.8% and 8.3%, depending on the source of reference, from 2022 to 2030, which is conceivable when taking in consideration that its CAGR from 2011 to 2021 was 30%.

When analysing the market share of the top 10 PV producers worldwide, we noticed that the data vary according to the source found. In this document you will find a classification based on the market capitalization (Market CAP), which refers to the value of a company that is traded on the stock market (15).

	Company Name	Country of Operation	Market CAP (bn)	EBITDA (bn)	Revenue (ttm) (bn)	Forward P/E	Trailing P/E	ROA (ttm)	ROE (ttm)	EBITDA Margin
1.	LONGi Green Technol...	China	339,37	13,81	138	12,38	13,87	5,07%	26,9%	9,9%
2.	Enphase energy Inc	USA	28,65	0,62	2	29,5	46,42	12,4%	75,6%	31%
3.	Kyocera Solar	Japan	20,71	278,12	2,030	16,81	21,55	20,1%	4,4%	13%
4.	First Solar Inc	USA	17,71	0,13	2,8	0,98	460,02	-1,14%	0,71%	4,6%
5.	Solaredge technologie...	Israel	17,61	0,43	3,4	25,77	75,09	5,72%	9,1%	12%
6.	Sharp Solar	Japan	4,86	64,08	[illegible]	null	null	-0,86%	-75,6%	2,5%
7.	JinkoSolar Holding Co.	China	2,64	4,84	91	6,17	11,66	-1,2%	10,7%	5,3%
8.	SunPower Corporation	USA	2,6	0,36	1,8	22,17	31,1	-1%	13,6%	20%
9.	SMA Solar Technology	Germany	2,53	0,08	1,8	null	35,22	3,38%	22,5%	4,4%
10.	Canadian Solar Inc	Canada	2,52	0,78	1,2	7,53	8,22	3,73%	17,3%	65%

TABLE 2 - Top 10 Solar companies by Market CAP with heatmap. Source: Yahoo Finance

Differing from the list of the top 10 polysilicon players, the list presented for the PV industry does not show the same presence of Chinese companies. Indeed, according to this list the PV industry shows a high degree of internationalism as we can find companies representing almost every continent. This shows that the level of competition is high in this specific industry, in particular when focusing on the companies from number 2 to number 10, where we can see similar values relatively to the market capitalization and, as a consequence, of market share. Another interesting information detectable from the companies listed, is that different companies involved in the PV market, tend to vertically integrate the whole process of development, production and market introduction of the solar modules and products, so that they can ensure a faster, cheaper, and more organized manufacturing process.

Concerning LONGI Green Technology Co. Ltd, its dominance in the field is undisputed, as shown by its market cap being 12 times higher than the one of number 2 (Enphase energy Inc). Such a high value in this metric, often reflect a larger scale of operations, meaning that LONGI has a larger market share relatively to the other 9 companies listed. Furthermore, the supremacy of this Chinese company in the market means it can have a stronger influence in the industry, by setting prices, standards, and innovation. LONGI was founded in the year 2000, but it was not before 2012 that it started building such a strong presence in the market. Indeed, through the last years, it was able to increase its revenue from $243 million to $11,378 billion, an increase of 47 times. This shows once again how the Chinese government incentives, which began around 2012, have helped domestic companies to invest more easily in research and development of solar technologies and to improve their equipment in order to establish a world supremacy that, to date, is difficult to reverse.

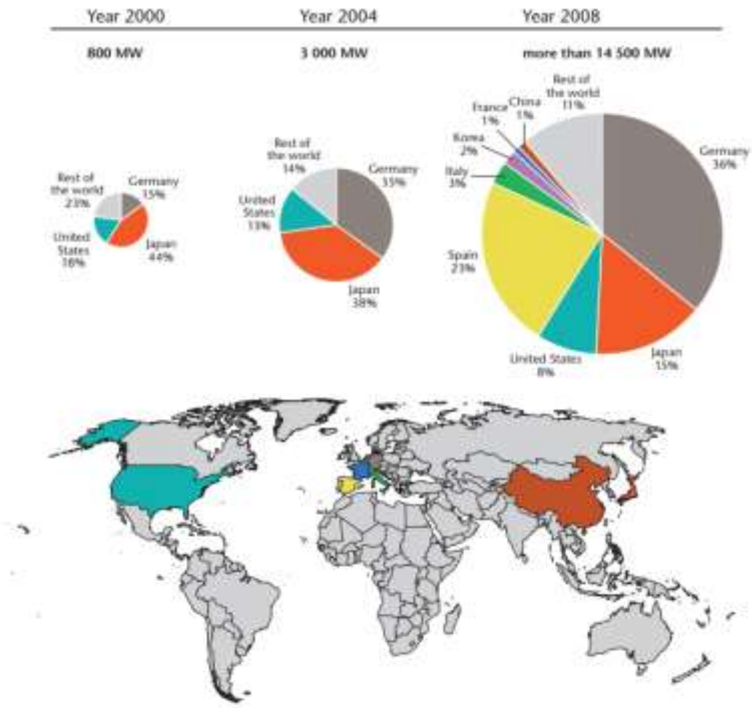


Figure 11. Solar PV installed capacities in leading countries between 2000 and 2008. Source: IEA.

We know how this supremacy in the silicon industry was not present if we turn the clock back of about 15 years, and this can be clearly reflected by an analysis of the current PV market, which is tightly linked to the silicon production and refinement. Indeed, upon examining Figure 11 (**Error! Reference source not found.**) which analyses the PV installed capacities worldwide between 2000 and 2008, we notice how, when this technology was at its starting point, its development was proceeding at a faster pace in the European region. In fact, three countries (Germany, Spain and Italy), in 2008, were making up for the 62% of the entire PV installed capacities on a global level. China, instead, was only at the beginning of its run for carbon fuels-independency and it was making up only for 1% of the world PV installed capacity, showing an incredible increase up to 2022 (16; Error! Reference source not found.), when they reached a capacity of 392.6 GW, that compared to the 3372 GW installed worldwide, make up for the 11.6% worldwide. This huge increase for China is again related to their surplus of resources and to the policies put in place. Other reasons that could have influenced such a growth can be related to two possible causes: (1) the development of new technologies for the sawing of silicon wafers and (2) the rise of Xi Jinping, at the top of the Chinese communist party. Indeed, the latest president of the country, seems to have clearly understood the direction China should take in the next decades to maintain its supremacy of the global solar markets', drafting numerous policies imprinted to the development of the solar market such as lowering the interest loans for the purchase of equipment, stipulating land transfer price refunds, electricity price refunds and multiple-year corporate tax reductions (18; 19).

MARKET CONDUCT – PV INDUSTRY

The asymmetrical market structure of the PV industry, as demonstrated above, heavily influences the conduct within this sector. The international presence of key players has resulted in a high degree of competition. Yet, the dominance of few companies, supported by governmental policies, suggests a potential for significant influence on pricing and innovation. This influence is particularly crucial considering the ongoing technological advancements in the field, where leading companies compete for supremacy, constantly innovating to stay ahead. Let's further examine how these structural elements translate into specific market conduct in the PV industry.

The photovoltaic market is generally characterized by a high level of competition with numerous manufacturers, particularly from a global perspective. There are some large and influential companies, such as LONGI, Enphase and Jinko Solar, which could lead to the idea that such a market shows an oligopolistic structure, but this is not the case. Indeed, it is not possible to find a small group of firms that exclusively can dominate the market. Instead, the market dynamics are in constant change, so that the leading companies can often vary. One reason for such structure is also linked to the continuous development of new technologies that are capable of better efficiency relatively to production and energy consumption. In the solar energy field, there is moderate barrier to entry, when compared to other industries like semiconductors or Lithium-Ion batteries. Nonetheless, the high investments related to the production plants and the training of expert human resources bring the barriers still quite high for small to medium businesses, making up for a threat of new entrants set at a moderate level.

In the PV market, prices have followed a general downward trend over the years due to technological advances and economies of scale. Most companies use a cost-based pricing strategy, in which a company adds a profit over the cost related to production and manufacturing. The objective linked to this strategy is to stay competitive, as there are many players in the market. This kind of pricing possesses the main advantage of allowing the company to be price transparent, as it can provide a logical explanation to the customers on an eventual increase in the prices, justifying it with the cost of materials, labour, and shipping (33)

As aforementioned, the photovoltaic market is in constant transformation. Indeed, solar is now in the mind of investors worldwide, as it is considered crucial for the energy transition and thanks to this common effort spread all over the world, it is gathering a faster pace, which allowed this technology to be used also in other industries.

Taking in consideration all the information collected until now, it is clear how the main conduct driver for this specific market is: **technological advancement.** Indeed, the endless cycle of innovation within this industry is driven by the persistent efforts of all the competing firms trying to outperform each other by discovering or adopting new technologies. This ongoing pursuit is fuelled by the potential for temporary competitive advantage, despite its transient nature. As reported in "Global market outlook for Solar Power 2022-2026" by the magazine Solar Power Europe (34), this behaviour brings to a constant innovation. It can be showcased with some practical examples.

The main product features on which the companies are focusing nowadays to increase their competitivity are associated with different qualities possessed by the instrumentation. First of all, they want to improve the efficiency, which refers to the part of energy in the shape of sunlight that the panels can convert into electricity. One example of improved efficiency is the introduction of alternative technologies to PERC (Passivated Emitter Rear Contact), which still represent the state of the art, like:

- HJT (Heterojunction Technology),
- TOPCon (Tunnel Oxide Passivated Contact) created by Fraunhofer in Germany, and
- IBC (Interdigitated Back Contact) from the Maxeon Solar.

These technologies are currently being evaluated for having a better cost and performance balance, features that will probably influence their establishment as new State of the Art technologies in this field. Examples of firms that focus their R&D on improving efficiencies are the American SunPower Corporation and the German ISC-Konstanz.

Another feature that represents a focus point of this industry is the wafer size. Indeed, around 2018 (34), the majority of the companies around the world started converging to bigger module sizes, as this can enhance the power of the cells or modules produced per unit time, reducing the equipment needed, the manpower and various other costs. Companies who focalized their R&D on this specific characteristic are, for example, LONGI and NexWafe. Finally, this continuous evolution brings with it the need to adapt the existing production lines to the latest technology, creating another focus area for these companies. A clear example of the improvement of this step is the adaptation of PERC modules production lines to production lines used for IBC cells (newer and more efficient) created by a joint effort of ISC-Konstanz in Germany and SPIC in China.

The photovoltaic (PV) industry has seen many joint ventures (JTs) and mergers and acquisitions (M&A) as companies seek to strengthen their positions, access new technologies, and gain efficiency. In fact, a multitude of examples exist for both modalities. Joint ventures are established for different purposes, such as to expand a company portfolio, improve existing technologies and reduce production costs. Interesting examples are the JTs between: Total and SunPower in 2011, which aimed to create a world leader for the solar industry and the more recent Duke Energy and REC Solar, which aim was to expand Duke's renewable energy portfolio and create more solar solutions for the customers. M&A, instead, are created for other scopes, such as vertical integration of specific processes or expanding a company's operations and production capabilities. Examples of M&A in the solar industry are: Canadian Solar and Recurrent Energy in 2020, which increased Canadian Solar's project development and construction capabilities, and Jinko Solar and Swelect Energy in 2017, which helped Jinko Solar to expand its operations in the Indian market. A fact worth noting is related to China and the establishments of joint ventures. Indeed, as China stops many foreign companies from getting part in its markets, the firms need to find other means to access them. There are two possible ways: the set-up of a Wholly Foreign-Owned Enterprise (WFOE) or forming a joint venture with a Chinese business partner. These can be complicated agreements because of the different laws and policies in China.

Another tool used by companies to gain a competitive advantage on their rivals is the vertical integration. Vertical integration means controlling multiple stages of the supply chain, from raw material sourcing to the finished product and, sometimes, even distribution. Numerous companies are known to have performed vertical integration in the solar energy industry. First Solar, for example, thanks to this tool owns the whole process, from the manufacturing phase to the installation of the finished module. Another example is Jinko Solar, a Chinese company, which is fully vertically integrated and offers products form all the different levels of the production line, from the solar wafers to a complete photovoltaic power system.

MARKET PERFORMANCE – PV INDUSTRY

Given the detailed review of the market conduct within the photovoltaic industry, we can see how the actions and strategies of firms significantly shape the overall performance of the industry. From the evolution of new technologies to strategic mergers and acquisitions, the industry's conduct paints a picture of a highly competitive and innovative environment. These market dynamics, in turn, impact the performance metrics, such as production efficiency, profitability, and societal impact, among others. Let's further delve into these facets to understand how the market conduct translates into the overall performance of the PV industry.

To analyse the performance of the photovoltaic market, we decided to focus on the production efficiency. As aforementioned, the Asian market, China in particular, is moving towards complete dominance of the photovoltaic industry. This is true for both, the raw material (polysilicon) and the PV module production. We already saw how China controls all the production steps of the solar supply chain (Figure 3). Together with this data, a report from Fraunhofer ISE (44) shows how, throughout the last decade Asia kept the supremacy also in PV module production. Indeed, upon examining Figure 12, we can see how already at the beginning of the “run for photovoltaics” Asia was producing around 82% of the modules, increasing to an impressive 93% of the yearly production in 2021.

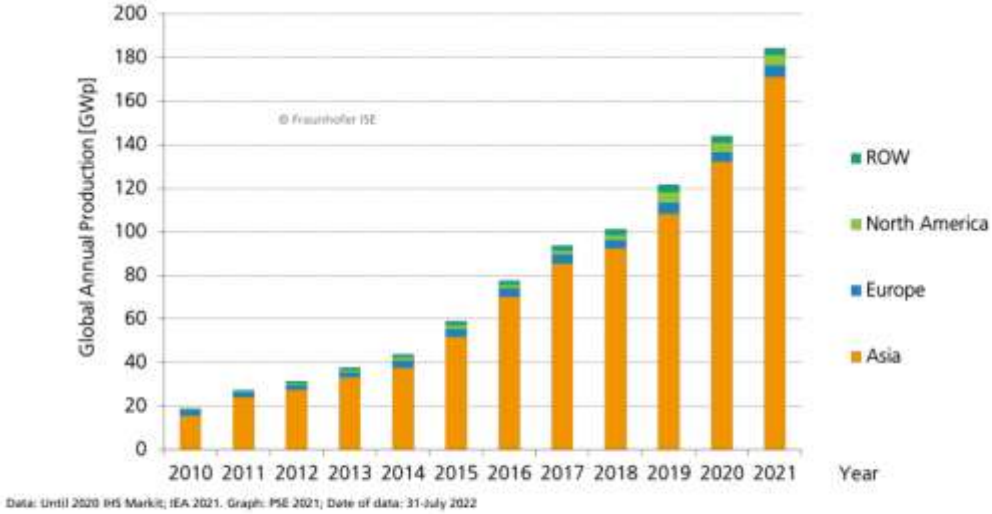


Figure 12. PV Module Production by Region

These data, alongside showing the almost total Asian control of the market, show a steady growth in the photovoltaic industry. Consequently, also its profit margins showed the same pattern. This trend is driven by the increasing demand for photovoltaic worldwide, as the modules are seen as one of the main futures of renewable energy production sources (45% according to EIA by 2050) (53). Moreover, this growth is guided by a constant progress in technological advancements relatively to this specific technology (as previously showed in Market Conduct-PV industry).

Therefore, these photovoltaic industry's performance patterns demonstrate a strong correlation between market structure, firm conduct, and industry performance. Such a competitive market, in junction with government incentives to adopt renewable energy, has urged firms to continuously innovate and strive for increased production efficiency. Leading firms that can efficiently produce high-quality, durable, and efficient panels at competitive prices to have higher profit margins and a larger market share. These same firms are also the ones investing more in R&D, pushing the technological frontier of the industry, which in turn drives competition, leading to an improved product quality and innovation.

As this technology is becoming a central part in the life of different countries and types of consumers, it is important to discuss its societal impact, as part of the performance of this industry. Without question, the PV production generates a significant number of jobs across the globe, ranging from research and development to manufacturing, sales, and installation. Each phase creates a tidal wave effect of economic growth, boosting local and national economies.

The shift towards renewable energy driven by photovoltaic technology also reduces the reliance on fossil fuels, even if, for now, the production still involves the formation of polluting waste. This partially alleviates the environmental issues associated with their extraction and use, including air and water pollution, habitat destruction, and global warming. As photovoltaic technology becomes more efficient and affordable, more communities gain access to clean, sustainable energy, enhancing their quality of life and promoting sustainable development.

In order to give more detailed information about the economic performance of the photovoltaic market, we will analyse the performance of the top 10 firms according to different financial metrics. We will focus on the comparison of the EBITDA margin with both the Revenue (ttm) and the Trailing P/E of the top companies of this sector. Indeed, comparing the EBITDA margin with Revenue (ttm) assesses operational efficiency and cost management, while comparing it with Trailing P/E helps assess investor perceptions of growth potential. This comparison sets good benchmarks for the industry performance. The data are retrieved from Table 2 and possible implications are discussed.

Revenue & EBITDA Margin

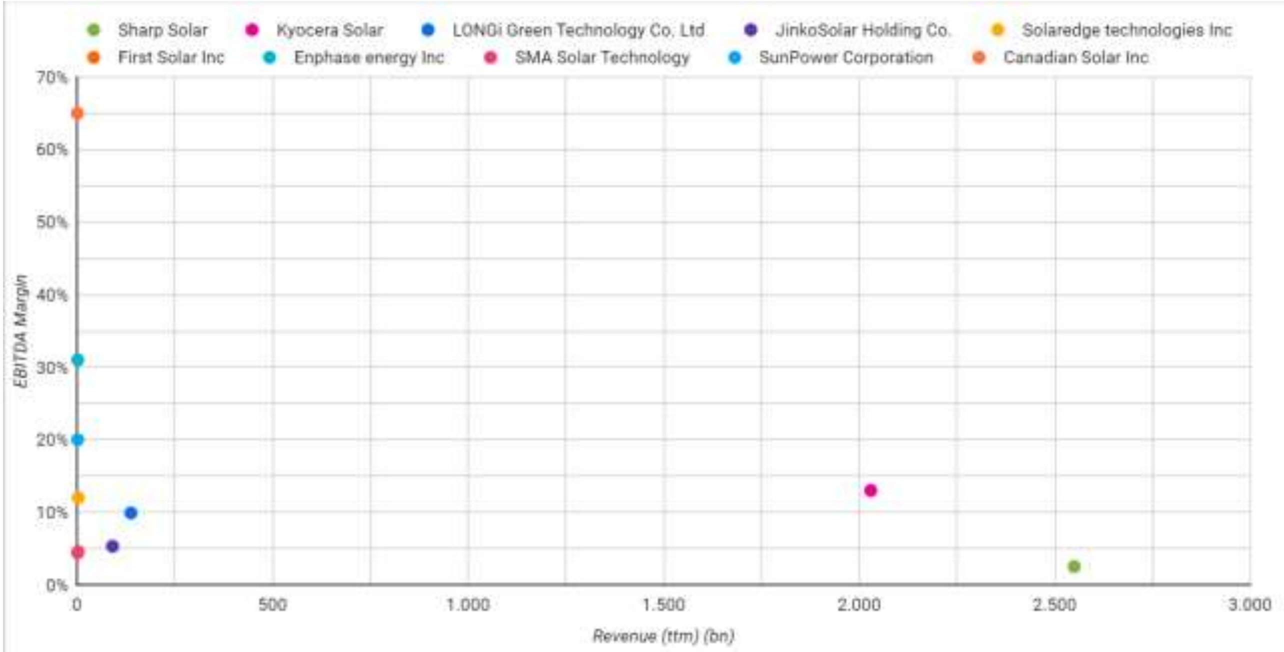


Figure 13. Scatter plot Revenue VS EBITDA margin top PV companies

- High revenue and high EBITDA margin suggest a company is not only generating significant sales but is also managing its costs effectively. Kyocera Solar and Sharp Solar have notably high revenues, but their EBITDA margins are only at 13% and 2.5%, respectively. This could indicate that while these companies have a large market presence, their operational costs may be relatively high, impacting their profit margins.
- On the other hand, Canadian Solar Inc. has a lower revenue of 1.2 billion but a high EBITDA margin of 65%. This suggests the company is excellent at converting revenue into operating profit, indicating efficient cost management.
- Enphase Energy Inc. shows a balance of a good EBITDA margin (31%) and decent revenue (2.00 billion), highlighting both operational efficiency and reasonable sales volume.

Trailing P/E & EBITDA Margin

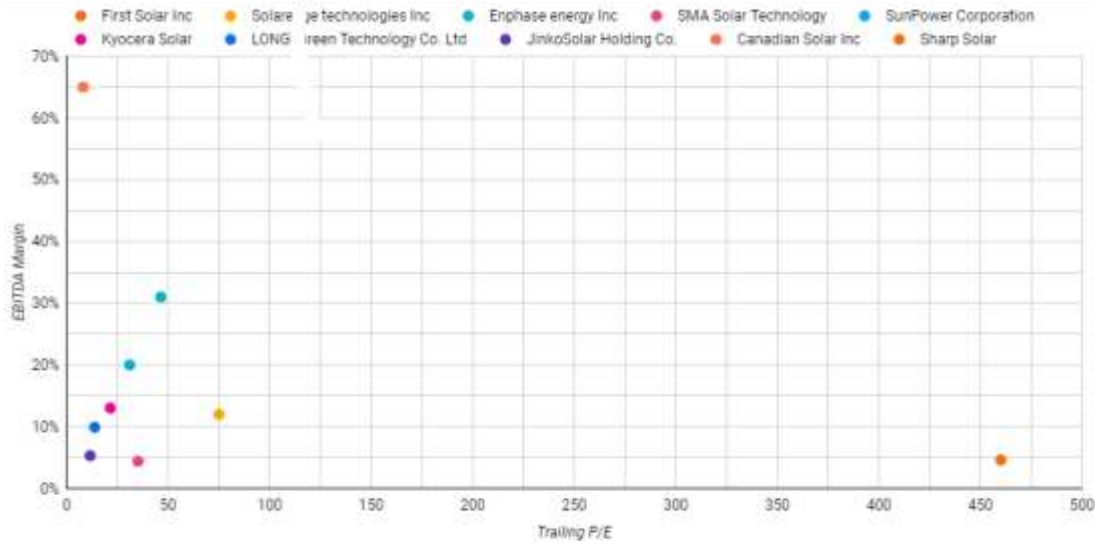


Figure 14. Scatter plot Trailing P/E VS EBITDA margin top PV companies

- A lower P/E ratio can suggest the company is undervalued or generates strong earnings relative to its market valuation. When coupled with a high EBITDA margin, it implies the firm is efficiently producing earnings and is possibly undervalued by the market.
- Canadian Solar Inc. stands out with a trailing P/E of 8.22 and an impressive EBITDA margin of 65%. This combination indicates a strong earnings capacity and efficient operations, which the market might not have fully priced in.
- Conversely, companies with high P/E ratios and low EBITDA margins could be seen as overvalued or less efficient. First Solar Inc., with its extremely high trailing P/E ratio of 460.02 and a low EBITDA margin of 4.6%, could be an example of this, indicating potential overvaluation and operational inefficiency.
- Enphase Energy Inc., despite its good trailing P/E, appears to be operationally efficient and profitable, as shown by its high EBITDA margin. The substantial trailing P/E ratio could reflect the market's positive expectations for the company's future earnings growth. This combination could be interesting to investors who are interested in growth stocks in the photovoltaic industry.

Based on the gathered data, it is possible to make the following general observations about the photovoltaic (PV) industry:

1. **Profitability Potential**: If a company follows the right cost management and operational practices, it can achieve high levels of profitability, as demonstrated by Canadian Solar Inc. and Enphase Energy Inc., showing that the photovoltaic industry can offer substantial returns.
2. **Growth Opportunities**: The market expectation for some companies, like Canadian Solar Inc. and JinkoSolar Holding Co., indicates that there is a potential for growth within the industry. This could be caused by global trends such as the increasing interest in renewable energy and the definition of numerous climate change mitigation policies.
3. **Risks**: Like in any other industry, there are some risks. High P/E ratios in some cases could signal overvaluation, while negative ROA or ROE could reflect operational or financial issues. Some companies might be facing unique challenges that need to be overcome to improve their market position and financial health.
4. **Global Market**: The photovoltaic industry is a truly global market, with leading companies operating from various countries like China, USA, Japan, Israel, Germany, and Canada. This international

presence indicates a widespread demand for photovoltaic solutions and brings unique opportunities and challenges related to geographic diversity.

In conclusion, successful firms in the photovoltaic industry, driven by technological advancement and favourable policies, reinvest profits into further innovation. This continuous innovation alters conduct, pressuring all firms to evolve or risk becoming uncompetitive. The growth and profits can attract new entrants, changing the market structure by increasing competition. Additionally, the industry's success may influence government policies to be more favourable, again impacting conduct. In essence, the performance of the PV industry feeds back into both its structure and conduct, leading to continual market evolution.

CONCLUSIONS AND IMPLICATIONS FOR ICARUS – PV INDUSTRY

As previously explained in the methodology of this report, to draw the conclusion and implications for the different markets ICARUS intends to target, we will utilize the Porter's 5 Forces analysis. Indeed, this model clearly depicts the current situation and organization of the industry, allowing to gather insights on the future developments within the specific market and provide strategic implications for the consortium.

1. **Threat of New Entrants - Moderate**

The solar PV industry is characterized by significant capital investment, complex technology, and economies of scale and this all together generates high entry barriers. However, as the global interest for renewable energy increases, it is probable that we will start seeing a growth in governments' support plans all over the globe, accompanied by policy incentives, which could, reversely, encourage new entrants. As a consequence, we can define the threat of new entrants as being at a moderate level.

ICARUS, given their unique position in the recycling and refining of silicon waste, could potentially provide the pilots and the other member-companies with a significant competitive advantage. The consortium should try to protect this advantage by securing patents or trade secrets on their recycling technology, improving the amounts of material produced at their facilities and upscaling them enough to be considered competitors of the major market players. Indeed, if not well protected, the new technologies developed by ICARUS could allow other companies to access the market without the need of a big starting investment, as the technologies would be already readily available for them to exploit. By doing so, the companies can further raise the barriers for potential new entrants in the niche of recycled silicon.

2. **Bargaining Power of Suppliers - High**

The solar PV industry is largely dependent on Asian, primarily Chinese, suppliers for raw materials, particularly silicon. This dependency amplifies the bargaining power of these suppliers, posing a risk for the industry forced to rely on them. ICARUS, with its focus on silicon recycling, is positioned to mitigate this risk. Indeed, as part of the main objectives drafted by the consortium, there is the idea of improving the European positioning in the PV industry. By turning waste into a valuable resource, they are reducing dependency on external suppliers, moving in the direction of the creation of a circular economy within the European borders, which will be able to both convert the materials into a final product and reutilize the waste by repurifying and making it readily available. Still, they should continue to diversify their supply chains and build strategic relationships with different established industry players all across the globe, sourcing the material to be repurified directly from them, further decreasing their vulnerability to supply chain disruptions.

3. **Bargaining Power of Buyers – Moderate**

The end-users of solar PV modules, such as utilities, businesses, and homeowners, need the final product to be efficient, affordable, and environmentally responsible, in accord with the direction taken by the whole planet towards a more sustainable future. ICARUS, by recycling silicon waste, offers an environmentally friendly alternative to traditional silicon, which could appeal to this constantly growing segment. To strengthen their position, the companies' part of ICARUS should communicate their sustainability credentials effectively, exploring all the possible high-end applications for their recycled silicon as they are doing with semiconductors, lithium-ion batteries, silicon aluminium alloys and thermoelectric. Moreover, they should emphasize the societal impact that their cutting-edge technologies will have in the longer term, discussing points such as job creation and CO_2 emissions reduction. Considering all these factors, the overall bargaining power of buyers is likely to be high, as the companies need to adapt to the newest market's green expectations.

4. **Threat of Substitute Products or Services - Low**

While there are currently no direct substitutes for silicon in PV production, ongoing research and development efforts in the renewable energy sector may result in the emergence of new technologies or alternative materials. The Consortium must stay abreast of these developments and adapt their strategy accordingly. Their unique recycling process and focus on high-end applications for silicon offer a certain degree of protection against substitution, but continuous innovation and strategic partnerships with research institutions are essential to maintain their competitive edge. In this light, ICARUS should strive to create a strong network for the passage of information inside European borders, involving knowledge institutions like university and research centres, and all the key industry player who work on European soil.

5. **Intensity of Competitive Rivalry - High**

The solar PV industry is marked by intense competition, dominated by a major Chinese player which shows a higher market cap when compared to the competitors. ICARUS, with its unique niche in silicon waste recycling, stands apart from the majority of the competition. However, this doesn't protect them from the aggressive competitive dynamics in the industry. Indeed, the use of recycled materials is not new to the PV sector, with numerous companies and institutions around the globe focusing their R&Ds on sustainable developments. Therefore, it's crucial for the consortium to focus on enhancing their operational efficiency, continuing with a constant investment in research and development, and maintaining a robust financial structure. By demonstrating the value and potential of their recycled silicon, they can not only stay competitive but also attract potential investments, partnerships, and possibly drive industry valuation norms by setting the new standards for such technologies.

In conclusion, ICARUS operates within a challenging, but dynamic industry. With its unique recycling technology and sustainability-driven mission, it has the potential to transform and lead this developing market. To navigate the industry successfully, the consortium must continue its commitment to innovation, operational excellence, policy advocacy, and sustainable practices while strategically managing industry forces.

SEMICONDUCTORS

MARKET STRUCTURE – SEMICONDUCTORS (23; 24)

Semiconductors, alternatively called integrated circuits (ICs), are fundamental constituents of electronic devices, serving as enablers for progress across a multitude of sectors. Their influence spans artificial intelligence, transportation, healthcare, communications, military systems, and more. Typically, semiconductors are made from pure elements such as silicon or germanium, compounds like gallium arsenide, or from a controlled mixture of these. Specific amounts of impurities are carefully introduced to manipulate the material's conductivity. Rare gases, notably neon, also play a role in the manufacturing process. The criticality of microchips in today's technology-centric world has led some analysts to call them the "new oil" of the 21st century.

Integrated circuits, accounting for 4% of total world trade, reign as the world's most traded product. Semiconductors' landscape is formed by multiple companies spread across the globe. Indeed, depending on the metrics used to analyse them, some differences will be observed in the list of companies resulting from the search. Nonetheless, when looking at their country of origin, three main regions will appear: Taiwan, South Korea, and the USA.

- ***Taiwan**:* Taiwan stands as a titan in the global semiconductor market, producing more than 60% of the world's semiconductors, primarily thanks to companies like TSMC. Taiwan's substantial grip on the semiconductor industry underscores its geopolitical expertise, earning it the nickname of "Taiwan's Silicon Shield."
- ***South Korea**:* For South Korea, semiconductors are a major export product, with Samsung as a leading figure in the production scene.
- ***United States**:* Despite semiconductor manufacturing no longer being a dominant sector, the United States continues to command a significant portion of the global semiconductor market share.

Table 3 shows a possible classification of the top 10 players of the semiconductors' industry. This division is based on the Market Cap.

	Company Name	Country ...	Market Cap	EBITDA (bn)	Revenue (ttm) (bn)	Forward P/E	Trailing P/E	ROA (ttm)	ROE (ttm)	EBITDA margin
1.	Samsung Electronics ...	South Korea	[illegible]	[illegible]	[illegible]	null	null	4,15%	13,6%	23%
2.	Taiwan Semiconducto...	Taiwan	13.032	1.567	2.280	null	84,89	15,61%	37,71%	68%
3.	NVIDIA Corporation	USA	1.148	6,09	25,88	42,42	243,25	6,27%	18,85%	23%
4.	Broadcom Inc.	USA	375,69	20,29	35,04	20,17	28,54	13,84%	63,67%	57%
5.	ASML Holding N.V.	Netherlands	297,71	8,46	24,39	30,16	39,09	15,14%	74,09%	34%
6.	Advanced Micro Devi...	USA	190,54	3,98	23,07	27,97	522,74	0,16%	0,72%	17%
7.	Texas Instruments Inc...	USA	166,46	10,39	19,5	22,73	20,56	21,88%	56,43%	53%
8.	Intel Corporation	USA	143,36	9,86	56,42	19,75	null	-0,76%	-2,81%	17%
9.	QUALCOMM Incorpor...	USA	137,47	14,49	41,07	12,79	13,16	17,12%	64,36%	35%
10.	Applied Materials, Inc.	USA	122,18	8,32	26,64	20,55	19,2	17,96%	50,48%	31%

TABLE 3 - Top 10 semiconductors companies by Market CAP with heatmap. Source: Yahoo Finance.

Interestingly, the fifth place in the list is occupied by a Dutch company: ASML. This company is a producer of lithography systems used to manufacture the ICs (equipment suppliers in the Figure below), which is considered as an integral part of the production process, therefore putting them in a prominent position as, if ASML faces supply chain or technological hindrances, the entire sector will face shortages in the machines or pieces needed to produce the circuits. This can be easily deducted from Figure 15, representing the semiconductor supply chain.

Figure 15. Supply Chain of semiconductor with input and output. Source: AWS.

The semiconductor industry is growing rapidly, with sales reaching $ 574.1 billion in 2022 (25). The market is projected to continue growing at an average rate of 6-8% per annum until 2030, potentially reaching a value of $1 trillion. As previously mentioned, this market seems to be fairly concentrated within three regions, but it also results concentrated in three different types of IC's applications: automotive, industrial electronics, and computation and data storage. These three clusters made up for around 70 % of the trade value in this sector.

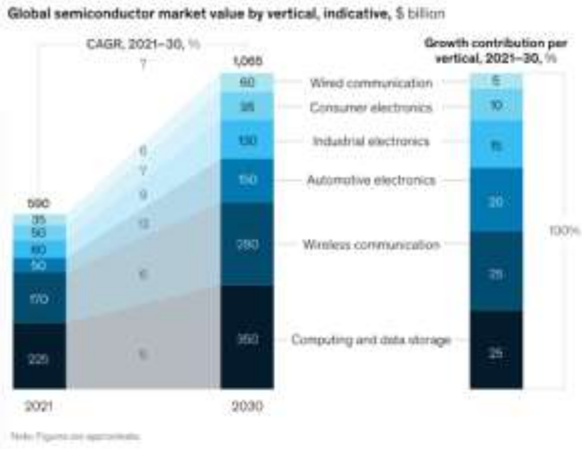


Figure 16. Global semiconductor market value by vertical ($ billion). Source: MarketsandMarkets

Figure 16 clearly shows which sub-sectors of the semiconductor market are forecasted to dominate the industry in the following years (up to 2030). Once again, these data confirm the currently existing trends in this field. Definitely, according to this prediction, two of the three aforementioned sub-categories, which are dominating the current scenario, will also lead the future run. Indeed, wireless communications and data storage, alone, are forecasted to give a growth contribution of 50%, when combined, to the semiconductor market, with the automotive sector substituting the industrial electronics in the top three, with a significant 20% growth contribution and a CAGR of 13%, making it the highest in this area. This change in the future structure of this industry can be related to the current situation where there is strong investment in the development of electric vehicles (EVs) and related products. Furthermore, the latest developments in the battery sector are also interesting for the recycling and recovery of silicon as, according to recent studies, silicon has been found to be a rather perfect substitute of Graphite for the anodes of Lithium-Ion Batteries (LIBs), making the EVs world attractive also for this sector.

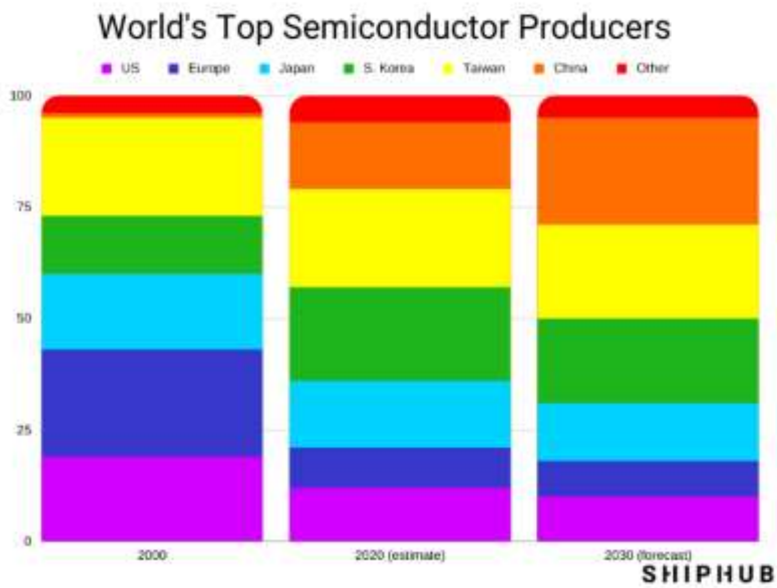


Figure 17. World's top semiconductor producers. Source: SHIPHUB.

When evaluating the future changes in the market structure for ICs, it is needed to note the particular position of China. Once more, this country and its economic dynamics have to be taken in consideration when looking at the future of this industry. Indeed, from the forecast shown in Figure 17 (23), it is clear that China will take up one of the most, if not the most, important place in this market by 2030. According to the same graph the USA, despite having eight companies in the top 10 players of 2022, are seeing their advantage reducing at an incredibly fast pace, as reported by the charts when comparing data from the year 2000 and 2020. The causes of such a consistent growth by the Chinese industry is, once again, due to the favourable policies established by Xi Jinping's communist party and by the size of China population as well as geographical area, which allows it to have bigger and easily expandable material and human resources.

MARKET CONDUCT – SEMICONDUCTORS

The structure of the semiconductor industry, marked by dominant players like NVIDIA, TSMC, and Samsung Electronics, is a foundation for its conduct. High barriers to entry, heavy investments requirements in R&D, and anticipated shifts in global dynamics (notably China's growing influence) set the stage for understanding the industry's behaviour. As we move to examine the market conduct, we'll see how the aforementioned structural aspects shape firms' strategic decisions, competitive dynamics, and responsiveness to technological innovation and price competition.

Unlike the PV industry, the semiconductor market is generally considered oligopolistic. This specific structure entails different consequences. To begin with, as the true top players are represented by few companies, it is likely that they are not competing on prices, but more on other elements like technology advancements and product differentiation, making this kind of industry heavily prone to innovation. Secondly, oligopolistic industries normally show high entry barriers. This is caused, in the semiconductor case, by two main factors: high startup costs, related to the costs of the materials and the technologies, and the presence of several proprietary technologies, protected by IPRs. Finally, this market structure normally reflects a high level of interdependence between the major firms. Indeed, changes in prices or the launch of a new product, from one of these top players, can significantly impact the actions and performance of the others.

Indeed, as shown previously in Table 3, in the semiconductor industry, the top is occupied by few firms, which record the highest revenue and/or show the highest market caps. According to the latest news and the data gathered, three companies are showing a clear supremacy. These are Samsung, NVIDIA and TSMC, which with their higher market caps are the dominant players. These firms not only produce a large volume of semiconductors, but they also invest heavily in research and development, further solidifying their positions. When analysing the ICs industry, it is important to underline, how, despite its oligopolistic structure, this market still shows a strong dependency on technological innovation. The perfect example of this idea is the company NVIDIA, whose latest incredible results are driven by the increase in demand for processors used to power artificial intelligence applications. Indeed, even if it has always been a pre-eminent company in the sector, only since the advent of AI technologies it improved its market position so exceptionally.

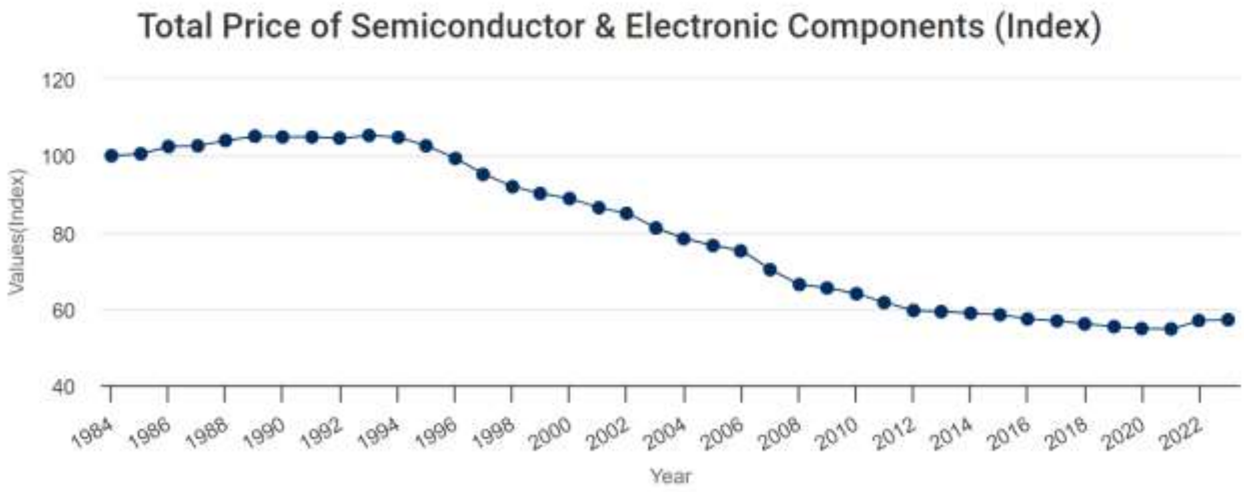


Figure 18. Total price of semiconductor & electronic components (Index). Source: IBISworld.

Upon examining Figure 18 (36), we see how the price of semiconductors has fallen steadily over the past 20 years. This specific trend of falling prices is caused indirectly by Moore's Law, which observed how the number of transistors that can be placed on an IC without further expenses doubles every two years. With the increase of the computing capacity year by year, manufacturers are able to produce chips more and more powerful using less and less expensive silicon. Because of this decrease in the prices of raw material, the industry has become more competitive, shaking its oligopolistic structure, and bringing previously smaller companies to fight with the established ones. Therefore, the industry giants are pressed to offer their own products at lower prices to be able to stay in the game.

When looking at the graph showed in Figure 8, we see how, during the recession that characterized the last years of the 2010s, the price declined heavily, as consumers were putting off the computer's purchases and waiting for the economy to turn around. Indeed, what happened is that the demand drop caused a domino effect along the supply chain, leading to this price reduction. We see how, after a year of apparent stabilization the prices dropped again 0.5% during 2013, with a further decline that continued until 2016. After that, the demand increased significantly giving a glimpse of hope to the industry, but numerous semiconductor suppliers overproduced in 2019 leading to a further decrease.

When in 2020 the COVID-19 Pandemic happened, this industry saw a further decrease in demand, due to economic uncertainty caused by worldwide disruptions in supply and manufacturing chains. Nonetheless, the market recovered faster than expected causing the opposite problem: a shortage in semiconductor raw materials and production. Indeed, after the manufacturing plants were stopped by the pandemic, the demand surged again rapidly both in the personal electronic and the automotive sectors, straying the suppliers. Furthermore, another important factor influencing the price trend is of political nature. In fact, trade tensions and restrictions, particularly between the United States and China, started to play a significant part in the shortage, with numerous U.S. sanctions on Chinese technology companies, that led to hoarding of chips and an overall increase in demand. Lastly, the geographical distribution of the main semiconductor manufacturers plays an important role in the price performance as a significant amount of ICs' production is located in a small number of regions, particularly in East Asia. As a matter of fact, Taiwan and South Korea are the most notable centres of chip manufacturing, hosting major companies such as TSMC (Taiwan Semiconductor Manufacturing Company) and Samsung Electronics. The concentration of the semiconductors production in specific regions can pose risks to the global supply chain because of possible local disruptions. These can be political, like the growing tensions between the Chinese and the Taiwanese governments which could cause trade restrictions or other measures, and they can be natural, such as floods or earthquakes, which, for example, characterize this region. In response to all these challenges, TSMC, announced, at the end of 2021, plans to increase chip prices by 20%, contributing to a late, but strong, effect on the semiconductors prices that year. Even if they kept being lower than the previous year, this delayed surge in prices headed by Taiwan contributed to the blunting of price declines, bringing to a small decline in the year of only 0.2%, showing the beginning of a recovering trend. In 2022, the beginning of the inflation wave, raised the costs in many markets, while it prolonged the chip shortages, as manufacturers intensified their production to fulfil the rising consumer demand. However, this acceleration came at a higher cost, resulting in a 4% surge in semiconductor prices in 2022. Concerning 2023, TSMC further announced an increase in prices, but growing fears regarding a potential recession will result in consumers trying to spend slowly over the year, keeping tempered the price increase when compared to 2022.

Ultimately, the conduct of companies in the semiconductor market, including their high levels of innovation, strategic pricing, and their responses to market fluctuations and external factors such as geopolitical tensions or supply chain disruptions, directly impacts their performance and the industry's performance as a whole. Let's examine how these factors have manifested in the industry's performance metrics.

MARKET PERFORMANCE – SEMICONDUCTORS

One of the best metrics to be used for the analysis of the performance of the semiconductors (ICs) market is the sales growth.

Sales growth is a vital measure because it serves as an indicator of the overall condition, expansion, and potential opportunities within the industry. Indeed, when we see strong sales growth across the entire market, this implies that the industry as a whole is thriving. It could be a result of a variety of factors. It might indicate an expanding customer base, which can happen as new technology sectors emerge and require semiconductors, such as the growth of electric vehicles, Internet of Things (IoT) devices and AI applications. The latter is confirmed by the surge of NVIDIA as a top semiconductor producer as they specialize in AI ICs, a market niche which is growing day by day, particularly since the introduction of the AI assistance working with a GPT code. Moreover, robust sales growth might suggest that businesses and consumers alike are investing more in technology, which could be due to economic prosperity or shifts in societal behaviours. For instance, the push towards digital transformation in businesses and the increase in remote work or schooling have strengthened the demand for personal computers and other digital devices. This was particularly true during and immediately after the Covid-19 pandemic, when the different companies across the globe realized that they could spare a big amount of funds, by keeping their employees in a home-office working situation. They reduced all the overheads related to them moving to and working at an office. On the other hand, if the semiconductor market's sales growth is sluggish or declining, it might indicate potential issues. This could be due to market saturation, economic downturn, or technological stagnation, among other reasons.

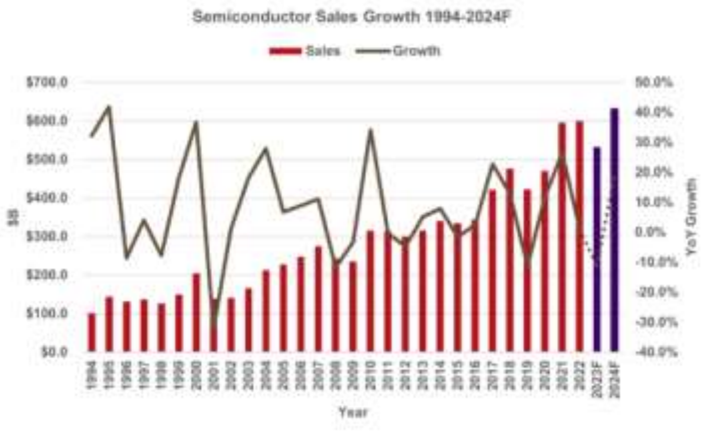


Figure 19. Semiconductors sales growth 1994 -2024 (forecasted). Source: GSAglobal.

Upon examining Figure 19 (45), the first thing to be noticed is how the market of semiconductors reacted to the events of the last two decades, starting from the steep decrease in 2001, when the U.S. experienced the 9/11 attack. The market crash in 2008 and the Tsunami in Japan in 2011 (headquarter of many semiconductors companies) are two other significant moments. Together with numerous steep declines, the growth in semiconductors sales show also different peaks. One of the most interesting is the aforementioned peak of 2020-2021, when during the pandemic sales grew almost exponentially.

Looking to the future, an analysis made by World Semiconductors Trade Statistics (46) shows how in 2023 a decline is expected of about the 10% in the sales of ICs. This is due in response to an increasing inflation and a weakening of the demand in the end-markets, in particular those relying on customer spendings. During this year, the regional markets forecasted to decline the most are the Americas (-9.1%) and the Asia Pacific one (-15.1%). Owing this decrease to the big presence on their territories of multiple world-class players in the semiconductors industry. For instance, TSMC and NVIDIA, the top-two ICs companies at the moment, are situated in Taiwan and US respectively.

In order to give more detailed information about the economic performance of the semiconductors' market, we will analyse the performance of the top 10 firms according to different financial metrics. We will focus on the comparison of the EBITDA margin with both the Revenue (ttm) and the Trailing P/E of the top companies of this sector. Indeed, comparing the EBITDA margin with Revenue (ttm) assesses operational efficiency and cost management, while comparing it with Trailing P/E helps assess investor perceptions of growth potential. This comparison sets good benchmarks for the industry performance. The data are retrieved from Table 3 and possible implications are discussed.

Revenue & EBITDA Margin

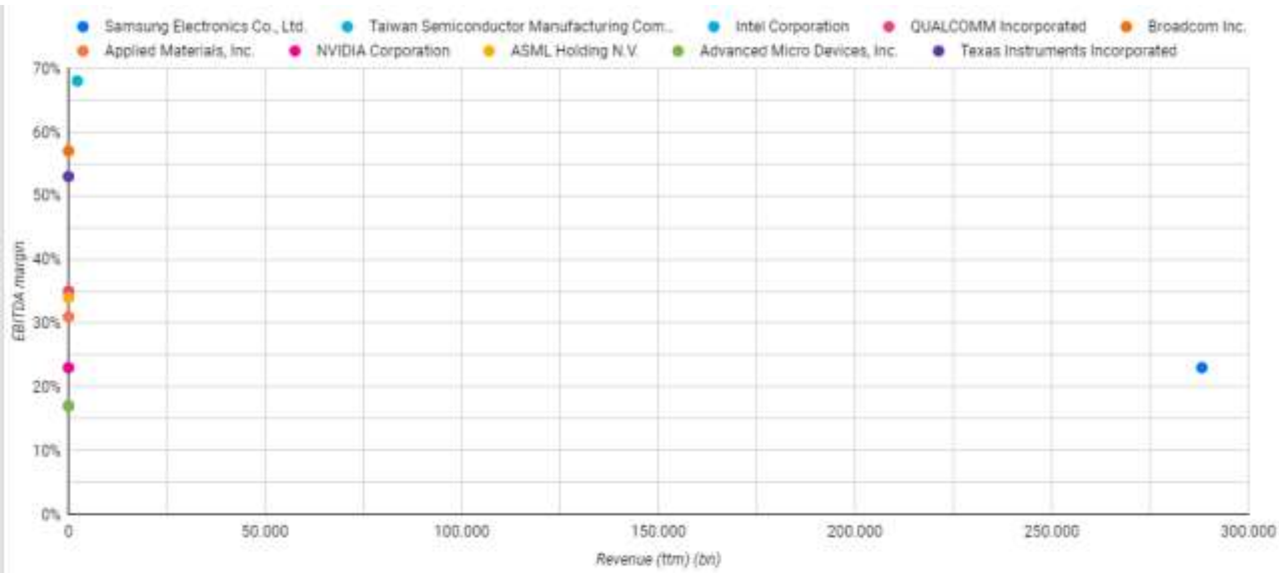


Figure 20. Scatter plot Revenue VS EBITDA margin top semiconductors companies.

- Texas Instruments and TSMC show high revenues and high EBITDA margins of 53% and 68% respectively, suggesting efficient operations and substantial market influence.
- Samsung Electronics, on the other hand, despite its high revenue, reflects a lower EBITDA margin of 23%, indicating potential inefficiencies or high costs that could be impacting their profit margins.
- Advanced Micro Devices (AMD) has comparatively lower revenue and an EBITDA margin of 17%, which may suggest there's room for improvement in both their sales volume and cost management.
- Broadcom Inc. represents a balance of decent revenue and high EBITDA margin (57%), showcasing operational efficiency and substantial sales volume.

Trailing P/E & EBITDA Margin

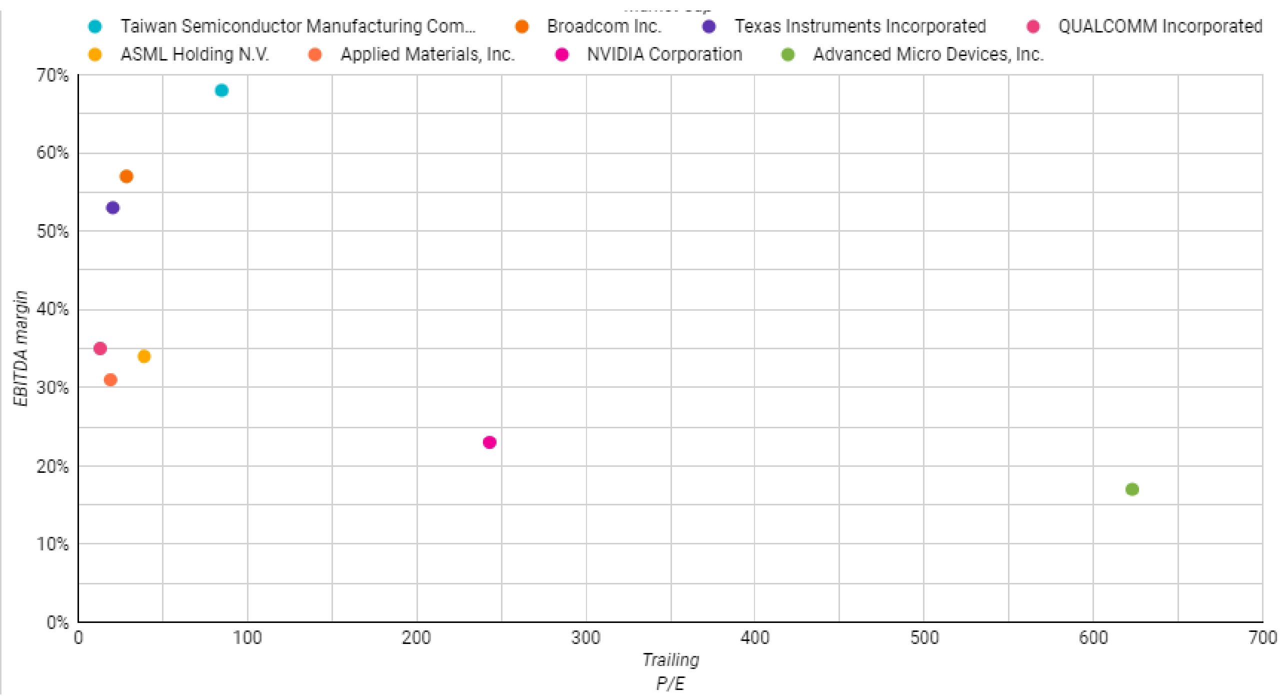


Figure 21. Scatter plot trailing P/E VS EBITDA margin top semiconductors companies

- Qualcomm, with a trailing P/E of 13.16 and a good EBITDA margin of 35%, and Broadcom, with a trailing P/E of 28.54 and a high EBITDA margin of 57%, showcase strong earnings capacities and efficient operations, which might not be fully priced into the market.
- AMD, with its high trailing P/E of 622.74 and a low EBITDA margin of 17%, could be an example of this, indicating potential overvaluation and operational inefficiency.
- NVIDIA also has a notably high P/E ratio (243.25) with a moderate EBITDA margin (23%), suggesting market expectation of significant future growth despite current operational performance.

Based on the gathered data, it is possible to make the following general observations about the semiconductors industry:

1. **Performance Diversity**: The sector demonstrates a wide range of performance metrics among top companies. This highlights that even within the same industry, companies can follow different strategies, target various market segments, and show a diverse set of financial results.
2. **Profitability**: Despite heterogeneity of this metric between the companies, most of these firms maintain a significant EBITDA margin, reflecting a high level of industry profitability. This suggests that these companies are good at managing their operating costs or are operating in high-margin segments.
3. **Growth Expectations**: The high P/E ratios, especially for companies like AMD and NVIDIA, suggest that investors are expecting strong future growth. The semiconductor industry is known for its cyclical nature, but these high ratios could imply a high level of investor confidence in the long-term prospects of the sector, perhaps driven by increasing demand for semiconductor products across a wide array of industries including automotive, consumer electronics, and data centres.

In conclusion, individual company performance varies widely, driven by factors such as management strategy, ability to innovate, supply chain efficiency, and adaptability to market changes. Leading companies often distinguish themselves with high R&D expenditures, swift adaptation to market demands, and a relentless focus on quality and innovation. Indeed, the clearest pattern in the semiconductor industry is the strong correlation between high R&D spending and firm success. These firms have consistently demonstrated strong revenue growth, healthy profit margins, and a commanding presence in their chosen market segments.

CONCLUSIONS AND IMPLICATIONS FOR ICARUS – SEMICONDUCTORS

To figure out what ICARUS might face in the markets it wants to enter, we're going to use a tool called Porter's Five Forces, as mentioned earlier in the report's method section. This tool helps us understand the current market and forecast what might happen in the future of semiconductors. By using it, we can give ICARUS useful advice about how to move forward. This model will help us better understand how the industry works and give the Consortium a clearer picture of what to expect.

1. Threat of New Entrants - Low

Entering the silicon recycling industry of semiconductors requires a substantial amount of investment in research, development, and advanced technology. The sum of these factors creates a significantly high barrier for new entrants. ICARUS, thanks to the collaboration of the 17 firms, which are already developing the operational pilot facilities and investing in R&D initiatives, has a head start in this regard. Indeed, the majority of the companies taking part in this project already have previously established facilities and position in the market, as they have been working in the sector for long time. This allows them to easily access a market that, otherwise, shows some of the highest entry barrier and some of the most profitable companies worldwide. Indeed, due to the latest market trends, which push towards a more sustainable worldwide economy, the nature of ICARUS' product permits the companies part of it, to enter the market already with a competitive advantage. Nonetheless, the potential regulatory barriers and the necessity to form strong relationships with buyers hinder the Consortium easy access to the market, as they still need to purchase the material to be recycled from the companies who are working on the virgin silicon for their products. In any case, ICARUS can leverage the current market conditions, such as the growing demand for semiconductors, the previously mentioned increased focus on sustainability, and the need for supply chain resilience, to further strengthen their market position.

2. Bargaining Power of Suppliers - Low to moderate

The semiconductor industry relies heavily on a select group of suppliers for raw materials, primarily from Asia. This historically gives suppliers significant power. However, ICARUS's technology for silicon recycling can reduce this dependency, turning a potential risk into an opportunity. Indeed, if the new sustainable model, introduced by the Consortium, will start to work effectively, the bargaining power of the suppliers of virgin silicon (mainly mining companies) will be significantly reduced. This because the companies purchasing the virgin silicon to transform it into high-end applications will, with high probability, prefer to acquire their feedstock from sustainable source to meet their ESG annual objectives. Furthermore, the potential geopolitical risks and the ongoing effects of the pandemic further emphasize the importance of ICARUS's initiatives in diversifying the supply chain. Nonetheless, while their unique model decreases the bargaining power of traditional suppliers, it doesn't eliminate it completely, as the amounts of silicon needed by the industry are higher than the quantity produced from recycling activities. This highlights the importance of maintaining a good relationship with equipment manufacturers and other relevant suppliers.

3. Bargaining Power of Buyers - Moderate

In the semiconductor industry, the bargaining power of buyers is often high due to the market's competitive nature and the high volumes purchased by larger tech firms. As ICARUS starts commercializing their products, they need to position their offerings as unique and sustainable, especially considering the current focus on green practices. Indeed, as ICARUS' buyers are composed by the firms' producing semiconductors and not by the general public, they will be strongly interested in purchasing a secondary raw material generated by the recycling of material that would have been wasted, so that they can improve their brand image, announcing their commitment to a more sustainable industry. Moreover, the establishment of such technologies as standard in the industry will reduce the dependence on Asian, in particularly Chinese, supply chains, as their focus is on producing high quantities to dominate the market, but not on producing such amounts with more sustainable processes. This increases the bargaining power of buyers in the semiconductors industry, giving them more options to choose from, but it positions ICARUS in a favourable position when concluding R&D and entering the market.

4. Threat of Substitute Products or Services - Low

Given the wide array of applications that silicon-based ICs have across numerous sectors, there are no effective substitutes in the market. Indeed, the current menace for the industry consists exactly in products like the ICARUS ones which, thanks to their more sustainable production, have a chance to disrupt the market. In fact, if this Consortium will manage to bring their products to the market, the importance of the companies using virgin material will diminish more and more over time. Therefore, the industry itself shows, in this moment of focus on sustainable practices, a high threat of substitutes. Concerning ICARUS, this threat is clearly reduced to low, since they themselves are the players ready to disrupt the industry. Finally, by developing local sources for silicon and setting up processing plants in Europe, ICARUS could contribute to the local economy by creating jobs and fostering growth in the high-tech sector, thus reducing the threat of substitutes once more. The ICARUS model, if successful, could be replicated in other regions, offering a global solution to silicon waste, and contributing to a more sustainable semiconductor industry worldwide.

5. Competitive Rivalry Within the Industry - High

The semiconductor industry is intensely competitive, with major players such as NVIDIA and TSMC already having established supply chains. Despite ICARUS's current R&D phase, once they start the commercial production, they could find themselves in direct competition with the suppliers of these firms. Thanks to their commitment to sustainability and a European-based supply chain they have a unique selling proposition, also taken in consideration the worldwide trend of reducing the dependency from Asia (China in particular). If they effectively leverage these competitive advantages, they will be able to differentiate themselves in a market which is already wide and complex. Finally, while ICARUS is already well-positioned in terms of technology and facilities, the consortium must also ensure the protection of their intellectual property rights, actively working on their strategies for potential competition, and effectively plan for their transition from the R&D phase to commercial production.

In conclusion, ICARUS's unique value proposition places it well within the industry, with the potential to lead a significant transformation in the semiconductor sector and related industries, thanks to its innovative approach to silicon recycling, the growing demand for silicon, and increasing emphasis on sustainable and localized supply chains.

LITHIUM-ION-BATTERIES

MARKET STRUCTURE – LITHIUM-ION-BATTERIES

Lithium-ion batteries (LIBs) have become indispensable in modern technology, from smartphones and laptops to electric vehicles and renewable energy storage systems. Their supremacy in the rechargeable battery market can be attributed to their superior energy density and long cycle life.

The basic structure of a LIB consists of three main components: an anode, a cathode, and an electrolyte. The anode and cathode, often referred to as the battery's electrodes, are typically made of different materials and play a crucial role in the battery's performance. The anode is usually composed of carbon-based materials, such as graphite and it is of particular importance as it determines the battery's capacity and overall performance. For a long while, graphite has been the material of choice for anodes due to its stability and ability to intercalate lithium ions. However, recent technological developments have stimulated a search for alternative materials, capable of enhancing the capacity and longevity of LIBs. Silicon has emerged as a promising candidate for anode material due to its high theoretical capacity, which is ten times that of graphite. (26; 27). This increased focus on silicon-based anodes generated more and more interest in the recycled silicon industry. Indeed, silicon waste has the potential to offer a cost-effective and environmentally friendly source of high-quality silicon for LIBs. Using the recycled silicon not only reduces electronic waste but also presents a good alternative to meet the increasing demand for high-capacity lithium-ion batteries. In the coming paragraphs, we will further examine the structure of the LIBs market, with a specific focus on the future trends involving silicon-based anodes.

The batteries' market is in constant evolution, and this is due to several factors. To begin with, the demand for EVs increased significantly in the last years due to a greater focus on sustainability and what it entails. Furthermore, the last decade saw an increase in the technological advancements made by the field, particularly in terms of energy density, charging speed, and cycle life. Also, the geopolitical landscape favoured developments in this field, thanks to the implementation of numerous policies and incentives aimed at increasing the use of renewable energy and electric vehicles by the public. Finally, batteries are not used just for EVs, they see possible applications throughout almost all the industries, as they are the key technology for energy storage. As a consequence, in the last years, with the increased adoption of renewable energy sources, like solar and wind, batteries have become an indispensable resource across almost all markets.

Table 4 (28) shows the list of the top 10 EV manufacturers worldwide in 2022. The classification is based on the market cap retrieved from yahoo finance for the top 10 firms.

	Country of ori...	Company name	Market cap (bn)	EBITDA (bn)	Revenue (ttm) (bn)	Forward P/E	Trailing P/E	ROA (ttm)	ROE (ttm)	EBITDA margin
1...	South Korea	LG Energy Solution, Ltd.	123.466	3.307	30.000	null	null	2,46%	0,38%	11%
2...	South Korea	SK Innovation Co., Ltd.	14.977	4.488	60.940	null	null	2,61%	4,34%	5%
3...	South Korea	Samsung Securities Co., Ltd.	3.224	null	10.830	null	null	8,3%	6,56%	null
4...	China	Contemporary Amperex Tec...	991,36	51,39	368,95	17,06	24,94	4,64%	27,5%	14%
5...	China	BYD Company Limited	102,6	44,04	477,41	null	35,75	3,31%	18,29%	9%
6...	China	Gotion High-tech Co.,Ltd.	47,85	0,92	26,31	26,37	134,5	-0,2%	1,97%	3%
7...	China	CALB Group Co., Ltd.	34,56	1,5	20,37	null	40,62	0,59%	2,08%	7%
8...	China	Sunwoda Electronic Co.,Ltd.	30,06	1,74	52,02	19,93	33,62	0,46%	1,59%	3%
9...	Japan	Panasonic Holdings Corpor...	27,94	556,86	8.380	8,82	14,52	2,26%	7,86%	6%

TABLE 4 - Top 10 lithium-ion batteries companies by Market CAP with heatmap. Source: Yahoo Finance.

This snapshot of the current competition status in the EVs battery manufacturer industry clearly shows a dominance of the Asian markets and companies. Indeed, South Korea is topping the list with LG Energy Solutions and its impressive market cap of 123.466 USD billions. Interestingly, thanks to data retrieved from the internet (28), we can see how, summing the market shares of these 9 companies, only 9% of the worldwide market shares are left for other companies, giving to this sector an oligopolistic appearance. This oligopoly can be further reduced to the top 4 companies, which have a market cap incomparable to the rest of the list.

The existing Chinese dominance in the EVs battery manufacturer sector (with 6 companies in the list) is expected to increase in the upcoming years, and this can be said on the base of the data reported in Figure 22 (29). Indeed, thanks to its already strong supremacy in the sector, China will see a rise in the revenues from EVs batteries as the market is supposed to grow at a CAGR of 25% between 2022 and 2030, moving from a current market size of $32.50 billion to an impressive $193.8 billion in 2030.

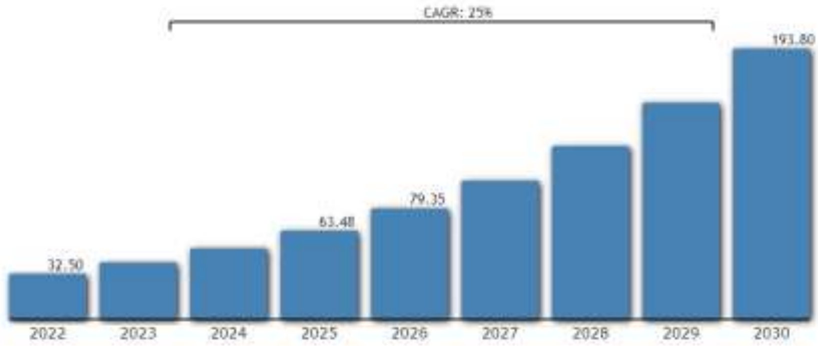


Figure 22. EV Battery Market Size from 2022 to 2030 (USD billion) Source: Vantagemarketresearch.

LIBs with Silicon-based anodes

Silicon-based anodes represent a significant breakthrough in the field of lithium-ion batteries (LIBs). The interest in silicon as an anode material began in the 1970s, even before the graphite (30). As aforementioned, the potential for enhanced energy storage makes silicon an attractive choice for battery applications where high energy density is a priority, such as electric vehicles (EVs) and portable electronics. However, the adoption of silicon in commercial batteries has been hampered by technical challenges. Over the years, various strategies have been developed to address these issues, such as the use of nanostructured silicon, which can better accommodate its volume changes (representing the most dangerous problem), and the development of silicon-carbon composites, which can enhance the stability and conductivity of the anode (26).

In recent years, technological developments and an increased understanding of the underlying mechanisms have started to bring silicon-based anodes closer to a market launch. Important progress has been made in improving the cycle stability, energy capacity, and rate capability of silicon anodes, indicating a promising future for silicon in the lithium-ion battery market. Start-ups occupy a significant position in this process. Indeed, the last decade saw numerous small companies being born, particularly in the US and in Europe, to work on such a silicon-based technology. In order to understand, on a deeper level, the current and future market situation a graph was retrieved (31) from an online source, which shows the trends of this industry up until 2028.

Figure 23. Silicon battery market forecast from 2023 to 2028. Source: MarketsandMarkets

Upon examining Figure 23, it is possible to observe a different regional trend for the battery with a silicon anode. Indeed, the forecast, apart from one single UK firm, showcases how US is supposed to lead the run in this new and disruptive type of technology. Moreover, an impressive data is represented by the CAGR over the next 5 years, which equals 49.5%, making this industry's sector grow at an incredible fast pace. This data is confirmed by the predicted value of this market in 2028 of $414 million, with an eightfold growth when compared to 2023. Finally, a crucial information deducted by this chart is that the level of competition in this specific sector is going to be high as the entry barriers are still not too extreme. This is due to the novelty of the technologies and the fact that the companies are all concentrated in the US and Europe. Concerning batteries with silicon-based anodes, China does not still have a prominent international position, nonetheless, as in a number of other fields, Chinese companies and universities are already patenting different technologies related to this field. Even if it does not appear in the list contained in the graph, we think it is useful to remember the presence of Huawei in China, which, already in 2018, patented a silicon-lithium battery concept, ensuring to maintain the intellectual properties on the product at least for the upcoming years. Indeed, this is one of the possible strategies put in place by China. They aim to patent and reserve for their own companies a series of technologies that they will start mass producing in the next years, invading the market with cutting-edge technologies and products, improving their international market position.

MARKET CONDUCT – LITHIUM-ION BATTERIES

In the course of assessing the competition model of the lithium-ion batteries market, it is possible to say that it is characterized by the presence of several key manufacturers. These are involved in a constant product innovation and development, suggesting an extremely competitive environment. So, even if, when looking at the market shares reported in table 4, it can appear as an oligopolistic structure, it is not. Indeed, the LIBs market is strongly dynamic, thanks to the high R&D intensity throughout all the industry, which continuously brings innovation to the market. Sometimes this makes other technologies quite obsolete, keeping the level of competition high. Nonetheless, the entry barriers for this market are quite high. This is related to the initial costs of development for both the technology itself, and the production line. Additionally, the presence in the market of numerous well-established firms, which constantly monitor the market and the advancements, makes It difficult for a small new company to enter the market unnoticed.

This aforementioned high competition is driving innovation and contributing to rapid capacity expansions in the battery industry. It's expected that the cumulative battery production capacity for EVs will heavily increase to about 800GWh by 2025 (37), when compared to the 550GWh produced in 2022 (38). An increase of 45% which is largely due to the expansion of the top players. Despite this competition, no significant changes are expected in the competitive landscape before 2025, as the EV battery business requires long-term competitiveness and mass production experience, creating yet another high entry barrier.

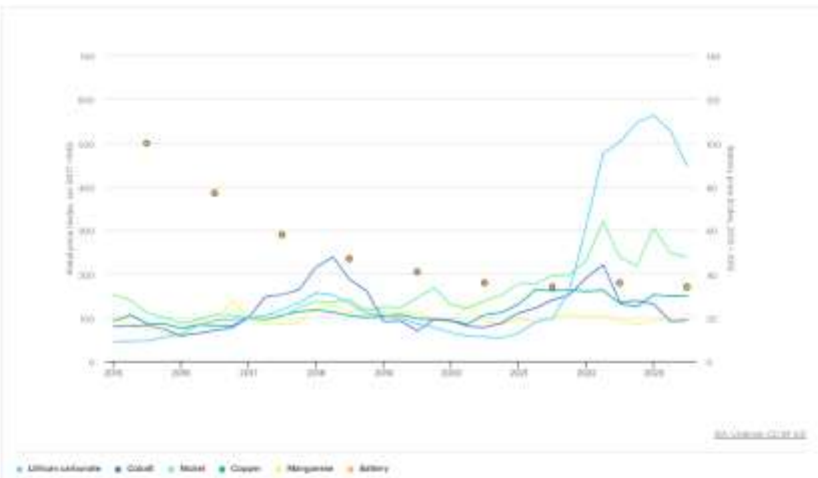


Figure 24. Price of selected battery materials and lithium-ion batteries, 2015-2023 Source: IEA.

Analysing Figure 24, which shows, in orange dots, the price trend of lithium-ion batteries, it is clear how they have been constantly falling during the last 8 years.

Let us consider the reasons behind such a downward tendency. In the graph the price of batteries is put in direct correlation with the prices of the main minerals utilized for the production of such batteries. Indeed, the variability in prices and the readiness of critical raw materials combined with the continuous technological advancements in the field partly explains this downward trend. For years, the prices of the main batteries' components have been pretty stable, with the exception of cobalt, bringing the prices down, thanks also to the pace at which R&D in this industry was and is progressing. In fact, batteries have been looked at, in the past years, as one of the most lucrative markets, because it is set to be one of the energy transition's main drivers. Moreover, the graph confirms the strong relationship between the critical mineral prices and the prices of the final product, as we can see from the data gathered for 2022. As a matter of fact, we see how, with the prices of lithium-carbonate (one of the main precursors for the production of the lithium compounds used in batteries) multiplying of four- to- five-fold during 2021 and the continuation of this trend through 2022, also the price of the final product increased accordingly. Another important factor influencing the prices of the batteries is related to the chemical composition of their anodes and cathodes. Indeed, battery cells manufacturers are investing heavily in R&D to improve the energy density of lithium-ion batteries, while also reducing the ratios of the more expensive and critical raw material utilized. Until 2015, cathode chemistries using equal ratios of nickel, manganese, and cobalt (like NMC 333 or NMC 111) were still very popular. Then the prices of cobalt increased and this, together with the reduced public acceptance of cobalt mining (because of its environmental impact), brought the R&Ds to shift towards cathode chemistries which include lower-cobalt ratios, such as NMC 622 and NMC 811 (for further explanation on batteries' compositions see Appendix 2). Furthermore, these new configurations have also the advantage of improving the energy density of the batteries, making them perfect candidates for substituting the current structures.

Apart from finding ways to improve the main chemistries used in the industry, companies are also working on interesting new technologies. Between these two are the ones worth mentioning: solid-state silicon and sodium-ion batteries (Na-ion). The improvements related to the usage of silicon are explained above (see LIBs with silicon-based anodes). Concerning Na-ion batteries, this new chemistry has a dual advantage when compared to the classic lithium-ion. First of all, they rely on lower cost materials, making the entire manufacturing process cheaper. Secondly, avoiding the use of lithium, it makes it the only type of battery that avoids the usage of critical raw materials. This new trend has been followed, in the past years, by different companies around the world like CATL and BYD in China, NGK Insulators in Japan and FARADION in the UK. To confirm once more the quick evolution pace of this technology we can take a look at the TRL (technology readiness level) change from 3-4 in 2021 to 6 in 2022, with an expected improvement up to TRL 8-9 between 2023 and 2024.

MARKET PERFORMANCE – LITHIUM-ION BATTERIES

Concerning the forecasts for 2024 the industry experts are predicting a positive increase of 11.8% on the global market for these products, bringing slowly the market back to the pre-inflation situation. Once again, because of the high concentration in ICs companies the regions of Asia Pacific and Americas are projected to have the strongest growth worldwide.

When looking at the Lithium-Ion Batteries market's performance, the most useful data is the number of GWh required now and in the future. This will allow to assess a clear forecast for the next steps of this industry. The next ten years are projected to witness a significative surge in the need for Li-ion batteries globally.

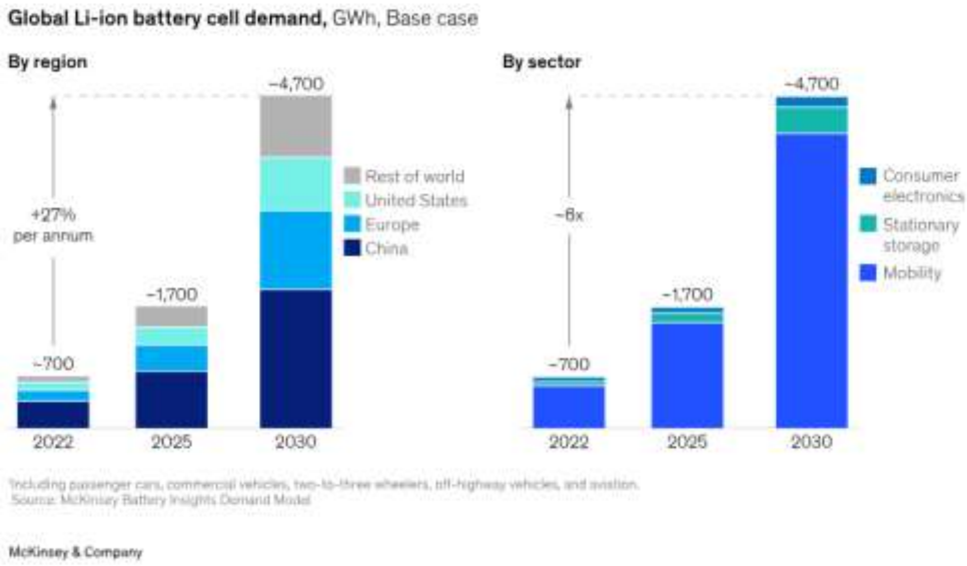


Figure 25. Global lithium-ion battery cell demand. Source: McKinsey.

Upon examining figure 25 (46), we see a predicted surge from about 700 GWh in 2022 to an estimated 4.7 TWh by 2030. A good part of this increasing demand in 2030, roughly 4,300 GWh, is anticipated to be driven by mobility-related uses, particularly electric vehicles (EVs). This growth is primarily due to three key factors:

1. The global shift towards sustainable regulations, incorporating new carbon-neutral targets and guidelines such as Europe's "Fit for 55" program and the US's Inflation Reduction Act.
2. An increase in the rate at which consumers are adopting these technologies, along with an increase in the demand for eco-friendly solutions (nearly 90 percent of all car sales are predicted to be EVs in certain countries by 2030).
3. Declarations by 13 of the leading 15 Original Equipment Manufacturers (OEMs) to phase out Internal Combustion Engines (ICE) vehicles and meet new emission-reduction targets.

The annual growth rate of Li-ion battery demand is projected to be approximately 33 percent, reaching around 4.7 GWh by 2030.

The market of LIBs is composed by different elements, as this technology can have different applications. The sector where the development is expected to go at a faster pace is the Battery energy storage systems (BESS). Indeed, these technologies are projected to experience a compound annual growth rate (CAGR) of 30 percent, with the energy requirements for these applications in 2030 expected to be equivalent to the energy needs for all applications in the present day.

When looking at the distribution of the market share of this specific market, we see how China is predicted to make up about 45 percent of the total Li-ion demand in 2025, and 40 percent in 2030 (46). Despite the maturity of most battery-chain segments in China, the highest growth rates are expected in the EU and the United States. This is driven, as aforementioned, by recent regulatory changes and a trend towards supply chain localization. In response to this, it's estimated that a minimum of 120 to 150 new battery factories will need to be established worldwide between now and 2030.

Coinciding with the growing demand for Li-ion batteries, the revenue along the entire value chain is predicted to rise 5-fold, increasing from around $85 billion in 2022 to over $400 billion in 2030. Active materials and cell manufacturing could be the main contributors to this revenue. Sourcing battery materials does not exclusively involve mining. Indeed, as shown by the ICARUS project, recycling is another viable method, particularly when talking about critical raw materials (CRM). Although the recycling sector may be relatively small in 2030, it is forecasted to triple in size over the next decade as more batteries reach their end-of-life.

Several companies in the EU and the US have announced new initiatives in mining, refining, and cell production to help meet the demand, including the creation or expansion of battery factories, also considering new business models for the recycling segment. Nonetheless, the LIBs market shows still some challenges within the value chain. First, like many other industrial manufacturing sectors, the global battery value chain faces considerable environmental, social, and governance (ESG) challenges. Concerning the environmental part, activities such as raw materials extraction, refining, and cell production can have serious environmental impacts like land degradation, biodiversity loss, hazardous waste production, and contamination of water, soil, and air. Therefore, an improper or illegal battery disposal can lead to severe toxic pollution. On the social side, unless carefully managed, the operations across the battery industry could have unfavourable effects on regional communities through violations of labour laws. Finally, regarding the governance, companies need to avoid corruption, bribery, and tax evasion.

In order to give more detailed information about the economic performance of the lithium-ion batteries market, we will analyse the performance of the top 10 firms according to different financial metrics. We will focus on the comparison of the EBITDA margin with both the Revenue (ttm) and the Trailing P/E of the top companies of this sector. Indeed, comparing the EBITDA margin with Revenue (ttm) assesses operational efficiency and cost management, while comparing it with Trailing P/E helps assess investor perceptions of growth potential. This comparison sets good benchmarks for the industry performance. The data are retrieved from Table 4 and possible implications are discussed.

Revenue and EBITDA Margin:

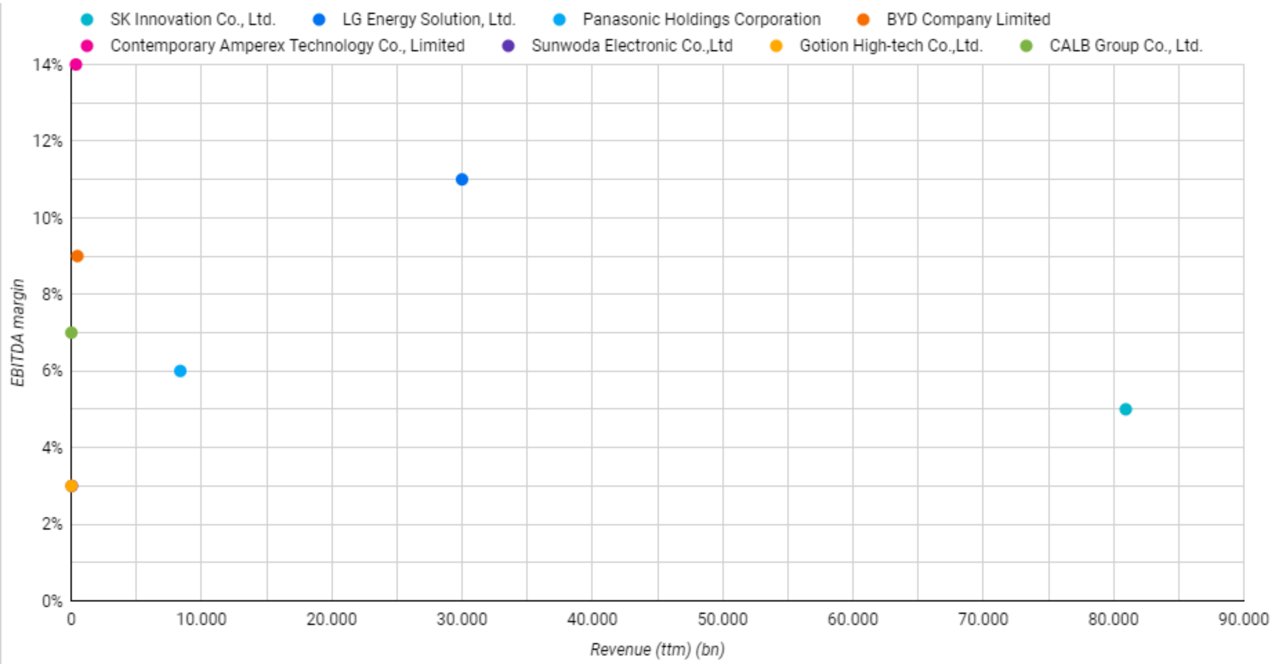


Figure 26. Scatter plot Revenue VS EBITDA margin top lithium-ion batteries companies

- The companies generating the highest revenues are SK Innovation Co., Ltd., LG Energy Solution, Ltd., and Panansonic Holdings Co., indicating a significant market share. Not far behind is BYD Company Limited, demonstrating its prominent presence in the market. However, high revenue doesn't necessarily correlate with high operational profitability. The EBITDA margin is a more accurate measure of a company's operational efficiency and profitability. Despite having less revenue than the companies mentioned above, Contemporary Amperex Technology Co. Limited and BYD Company

Limited have impressive EBITDA margins (14% and 9%, respectively), suggesting a higher efficiency in converting revenue into operating profit.

- Other companies, like Sunwoda Electronic Co., Ltd. and Gotion High-tech Co., Ltd., have lower EBITDA margins, indicating potential areas of improvement in their operations.

Trailing P/E and EBITDA Margin:

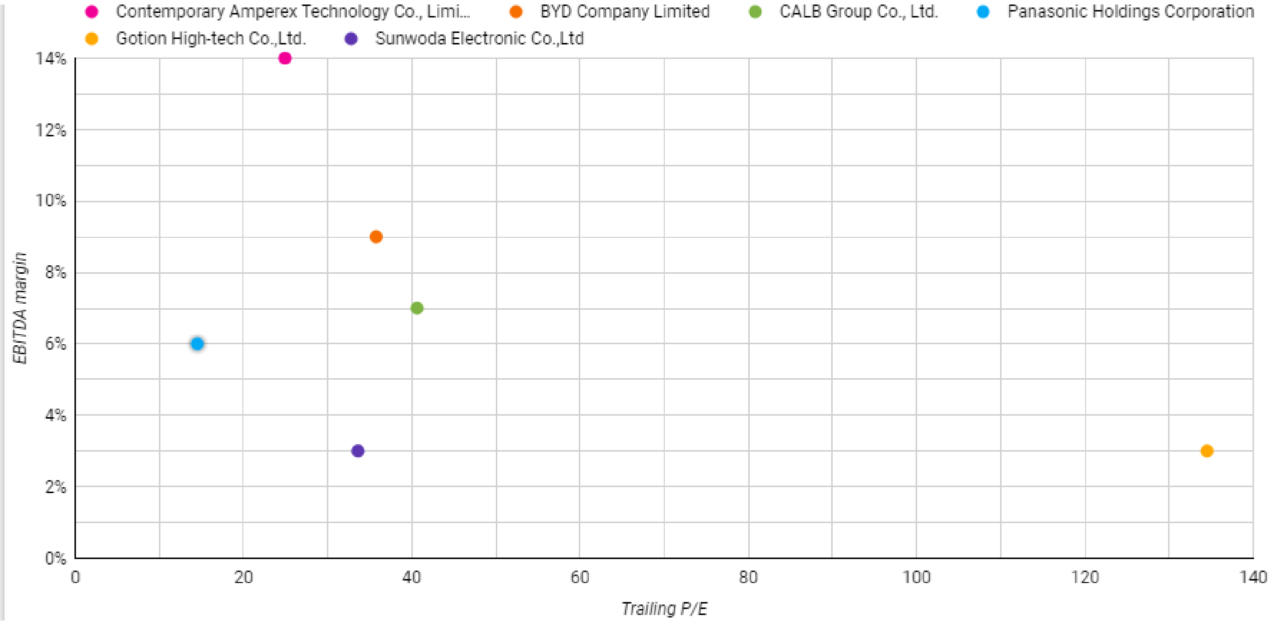


Figure 27. Scatter plot Trailing P/E VS EBITDA margin top lithium-ion batteries companies

- The trailing P/E ratio is an indicator of how much investors are willing to pay per dollar of earnings in the last 12 months. A lower ratio could suggest a company is undervalued or that it is earning efficiently. Panasonic Holdings Corporation and Sunwoda Electronic Co., Ltd. have relatively low trailing P/E ratios (14.52 and 33.62 respectively), suggesting they could be efficient earners or possibly undervalued.

- The EBITDA margin provides insight into a company's operational profitability. A higher margin indicates more efficient profit generation from operations. Consequently, companies such as Contemporary Amperex Technology Co., Limited, BYD Company Limited, and LG Energy Solution, Ltd. show high operational profitability with their EBITDA being 14%, 9% and 11% respectively.

- Thus, companies with low trailing P/E ratios and high EBITDA margins, such as Panasonic Holdings Corporation, Sunwoda Electronic Co., Ltd., and Contemporary Amperex Technology Co., Limited, are potentially more efficient, profitable, and could be safer investments based on these metrics.

- On the other hand, a company like Gotion High-tech Co., Ltd. with a high trailing P/E and a relatively low EBITDA margin may be seen as a riskier investment.

Based on the gathered data, it is possible to make the following general observations about the lithium-ion batteries industry:

1. **High Growth Expectations**: High revenue figures and decreasing forward P/E ratios for many of the companies suggest that the market expects significant growth in the future. This likely reflects the increasing global emphasis on renewable energy and decarbonization, which drives demand for lithium-ion batteries.

2. **Profitability Variances**: The differences in EBITDA margins and ROA among these companies indicate varying degrees of operational efficiency and profitability. These variances could be due to factors like differences in production costs, technological capabilities, or strategic decisions.
3. **Potential Risks**: High P/E ratios and negative ROA for some companies indicate potential risks. These might be related to factors such as overvaluation, economic instability, or industry-specific challenges like raw material availability or technology changes.
4. **Market Consolidation**: Some companies, particularly SK Innovation Co. Ltd. and LG Energy Solution, Ltd. are emerging as significant players based on their revenue, indicating possible market consolidation.

In conclusion, the lithium-ion battery market appears to be a dynamic and high-growth industry with diverse participants, high growth expectations, and varying levels of efficiency and risk.

CONCLUSIONS AND IMPLICATIONS FOR ICARUS – LITHIUM-ION BATTERIES

In order to determine the potential market dynamics and challenges that the ICARUS consortium may encounter in the lithium-ion battery sector, we will use the analytical framework of Porter's Five Forces. As aforementioned in the method section of this report, this model allows us to review the current state of the market and look at possible future trends within the lithium-ion battery industry. Through this analysis, we want to provide strategic guidance to ICARUS as it moves in this market.

1.Threat of New Entrants - Moderate

The LIB industry has shown an incredible growth over the last years and is expected to continue this trend into the near future, attracting potential new entrants. However, to get access to this sector is not easy, as it demands substantial capital investment, intensive research and development, respect of specific safety standards and regulations, and a continuous supply of raw materials. These requirements pose a significant barrier to new entrants, but on the other side, several large corporations, in particular automotive and electronic manufacturers, are showing an increasing interest in this market, with multiple companies worldwide trying to enter the LIBs industry to secure their entire supply chains (e.g., Tesla's Gigafactories). As more companies enter the LIB industry, the demand for raw materials like silicon and graphite will increase year by year, considering an annual growth rate of 33%. Given ICARUS's focus on the recycling and re-purposing of silicon and graphite, there is a clear opportunity to establish partnerships with new entrants, whose desire is to build more sustainable and secure supply chains, and with established companies, who are looking to reach more and more ESG goals. The consortium's commitment to industrial symbiosis and its recycled silicon could prove attractive to these businesses. Moreover, the primary focus of ICARUS should be on companies who work with BESS (Battery Energy Storage Systems), as, according to the forecasts, it is the sector that will record the highest growth within the batteries industry with a CAGR of 30% until 2030. This also in light of the superior energy storage capacity that silicon-based lithium-ion batteries show. In conclusion, we can define the threat of new entrants for this market as moderate, because the entry barrier still results pretty high, but multiple companies who have the capital to invest are turning to it, together with new companies based on more sustainable premisses (ICARUS).

2.Bargaining Power of Suppliers - Moderate

The raw materials for LIBs, such as lithium, cobalt and nickel are vital, as a consequence, securing a steady supply of these materials is essential for all battery manufacturers. In the last years, a growing concern about the sustainability of the practices utilized to retrieve such materials has been triggered. Indeed, this whole set of fundamental materials are recovered through mining, which is renowned to be heavily dangerous for the environment. Considering the consortium's focus on silicon, it is worth examining the rising interest in silicon-based anodes in the lithium-ion battery industry. Silicon's superior energy storage potential makes it an attractive choice for battery applications requiring high energy density, such as electric vehicles (EVs) and portable electronics. Despite early challenges, recent technological advancements and increased understanding of silicon's potential have begun to propel silicon-based anodes towards market readiness. Thus, the recycled material proposed by ICARUS can be disruptive for such an industry, as, once the safety of silicon is ensured, the consortium will be able to propose their greener material as possible substitute for at least a part of the virgin material. Therefore, the presence of ICARUS in the market will reduce the bargaining power of the current suppliers, as the Consortium will enable the possibility of sourcing raw materials from a recycled source instead that from the mining of the virgin material (harmful to the environment). Nonetheless, as the amounts of raw materials needed by the industry are bigger than the ones ICARUS can produce, the mining companies will still be able to partially decide the market, setting the bargaining power of the suppliers for the LIBs industry at a moderate level.

3.Bargaining Power of Buyers - Moderate to High

The rapidly growing electric vehicle (EV) market, together with the increasing application of LIBs in energy storage solutions, means the number of buyers will rise more and more on a yearly basis. The variety of battery technologies and manufacturers available gives the buyers considerable choice and bargaining power. Indeed, with an increasing number of companies, in particular start-ups, working on disruptive technologies that could potentially change the market, the producers of batteries, who did not vertically integrate their supply chain (as Tesla is doing) will have an increasingly high bargaining power. If than you also consider that these buyers are also starting to consider factors such as environmental impact and local sourcing when selecting their suppliers, ICARUS will fit perfectly in the newly shaped LIBs market. Indeed, the consortium's offering aligns with the current market trend towards sustainable, local sourcing. Since they already own working pilot plants which are meant to grow to an industry-scale in the next 5 years they will be in a perfect position to disrupt the market, if they can keep their prices at a competitive level. This price competitiveness needs to be present because, as aforementioned, there is a big number of new players entering the market with interesting technologies, which allows the buyer of the raw material to have a moderate to high bargaining power.

4.Threat of Substitute Products – Moderate to High

At present, LIBs hold a dominant position in the EV and renewable energy storage market due to their high energy density, decreasing costs, and improving performance. However, research continues into potential substitute technologies, including solid-state batteries, sodium-ion batteries, and hydrogen fuel cells, which could eventually pose a threat to LIBs. This is where ICARUS can find its competitive advantage, producing raw materials for both silicon-based anodes (pilots A,B and C) and hydrogen fuel cells (green hydrogen of Pilot D). Indeed, over the last few years, important progress has been made in improving the cycle stability, energy capacity, and rate capability of silicon anodes and in the safety of hydrogen transportation, indicating a promising future for both materials in the battery market, with start-ups occupying a significant position in this process. Considering that the majority of start-ups are being developed in Western countries (Europe and USA) the future market will probably have a different geographic distribution. In fact, China, which has a dominant position in the current LIBs market seems to lack a significant international presence in the silicon-based anode sector. However, it's worth noting that Chinese companies and universities have started filing patents related to silicon-anode technologies, suggesting they may catch up soon. This whole set of considerations makes the threat of substitute products in this industry moderate to high. Therefore, as ICARUS works on these possible future substitutes, one of their competitive advantages could stem exactly from this present situation.

5.Competitive Rivalry within the Industry - High

The LIBs market is characterized by intense competition with numerous established players, including LG Chem, Panasonic, Samsung SDI, BYD, and CATL, among others. The rivalry is further amplified by new entrants, technological advancements, and the immense growth prospects of the industry, setting this parameter of the model as high. The ICARUS consortium should consider this fierce competition, developing because of the lowering barriers to entry linked to the novelty of the technology. However, this rapid growth and the focus on local sourcing also present an opportunity for ICARUS to establish themselves as trendsetters of this market, thanks to their sustainable products and supply chains. The consortium's focus on recycling silicon could, therefore, provide a crucial advantage, in light of both the new silicon-based battery technologies and the environmental-friendliness of their processes.

In summary, the future growth and direction of the LIB industry present numerous opportunities for the ICARUS consortium. The increasing focus on sustainability and supply chain resilience perfectly combines with the consortium's vision of turning silicon waste into a valuable commodity. By strategically positioning itself within this industry, the consortium could ensure a constant demand for its recycled materials, drive growth, and make a significant contribution to a greener and more sustainable future.

SILICON-ALLUMINIUM ALLOYS (Si/Al)

MARKET STRUCTURE – Si/Al ALLOYS

Silicon-Aluminium (Si-Al) alloys are metallic materials, notable for their versatility, durability, and applications across a multitude of industries. These alloys are typically derived from a blend of silicon, known for its hardness and resistance to heat, and aluminium, interesting for its light weight, malleability, and resistance to corrosion. When combined, these two elements, embody the advantages of both, offering a multitude of benefits. The purity grade and particle size required for making Si-Al alloys varies a lot according to the final application the alloy will have. For example, certain applications, like the production of high-strength and heat-resistant alloys requires a higher purity of silicon due to its greater heat resistance and strength. Meanwhile, the particle size of the silicon plays a crucial role in determining the microstructure and hence, the mechanical properties of the final alloy.

Silicon-Aluminium alloys find extensive use across different industries including the automotive, aerospace, electronics, and construction industries, amongst others. In the automotive and aerospace industries, Si-Al alloys are favoured for components like engine blocks and parts, cylinder liners, and pistons. In the electronics industry, these alloys are often used in electronic packaging.

The market for Si-Al alloys is driven by a few key factors. The continual growth and advancement in the aforementioned industries, particularly automotive and aerospace, together with an increasing demand for lightweight and heat-resistant materials are two of the main industry drivers. However, there are certain market restraints as well. The high cost of high purity silicon and the technical challenges associated with controlling particle size during the alloy production process can inhibit market growth. Additionally, fluctuating raw material prices and potential environmental regulations can further impact the market.

In the following paragraphs, we will discuss the structure of this specific market, with a focus on the top 10 aluminium companies worldwide, making some consideration on the trends, the regional distribution, and the future direction.

Table 5 shows the list of the top 10 aluminium producers. A specification is needed, the companies listed are not specialized on the production of Si-Al alloys, as aluminium has a number of different uses. As a consequence, in this list the majority of the companies are producing Si-Al alloys together with other products or they are aluminium mining companies, as they still count as players in the aluminium industry.

	Company Name	Country of origin	Market Cap (bn)	EBITDA (bn)	Revenue (ttm) (bn)	Forward P/E	Trailing P/E	ROA (ttm)	ROE (ttm)	EBITDA margin
1.	Vedanta Limited	India	1.053	331,56	1.460	7,71	4,84	7,8%	21,95%	24%
2.	Hindalco Industries Limited	India	981,84	238,74	2.230	null	9,68	4,41%	11,67%	10%
3.	United Company RUSAL, Int...	Russia	129,25	2,02	13,97	2,01	3,49	4,39%	15,71%	14%
4.	Norsk Hydro ASA	Norway	128,69	58,99	209,85	9,08	6,63	15,57%	17,87%	28%
5.	Rio Tinto Group	UK/Australia	108,95	22,35	55,55	15,95	8,79	11,24%	24,02%	40%
6.	Shandong Nanshan Alumini...	China	36,3	6,27	32,93	8,86	11,48	3,64%	7,48%	19%
7.	South32 Limited	Australia	12,14	3,25	9,16	null	5,38	10,98%	23,02%	38%
8.	Alcoa Corporation	USA	6,25	1,13	11,83	12,04	null	2,14%	-11,9%	9%
9.	Saudi Arabian Mining Comp...	Saudi Arabia	null	15,9	39,41	22,35	21,38	6,45%	18,83%	40%
10.	Aluminum Corp of China Ltd	China	null	null	null	null	null	null	null	null

TABLE 5 - Top 10 lithium-ion batteries companies by Market CAP with heatmap. Source: Yahoo Finance

The companies listed in table 5 are at the top of the aluminium industry when analysing their market capitalization. According to this classification, the aluminium industry appears truly global, with big players spread all over the five continents. What determines the regional distribution of these companies is, mainly, the availability of bauxite (primary ore of aluminium metal), energy resources and demand for aluminium products. Therefore, if we take the European continent as an example, we see that Russia and Norway are the only countries in the list, and this is obviously due to the availability of bauxite in these two territories. One more reason for which they find themselves in such a high position, even if other regions show similar availability, is linked to one of the aforementioned determinants of this industry: the demand for it. Indeed, Europe is home to a lot of large automotive producers, such as BMW and VOLVO, which require big amount of aluminium alloys as car parts. Another example of how the regional distribution is mainly dictated by these three factors is the United States. Indeed, they do not have big reserves of bauxite, but they are still a prominent market thanks to its vast consumption market, which allow them to capitalize big amounts of money.

Interestingly, the perception of this specific market changes completely when the analysing metric changes. In fact, if we move from Market CAP to production output, the regional distribution gets completely twisted, showing how, once again, China and the Asian pacific market are actually the strongest, as reported in Figure 28.

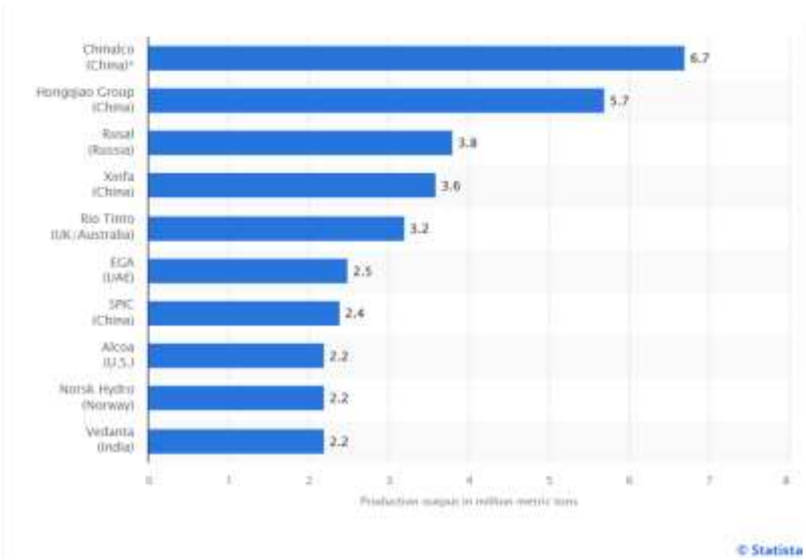


Figure 28. Top 10 aluminium producers by output in million metric tons

This dominant position of China is related to a series of factors influencing their economic and political situation. To begin with, as for the two European aluminium producers, China has substantial reserves of bauxite, providing a ready source for the production of this metal. Secondly, the country's growth in the construction, automotive and packaging sectors boosted the aluminium consumption. This ensures a high domestic demand which allows the Chinese companies to do most of their business inside their borders. Furthermore, the government provided numerous subsidies and favourable policies which helped their own companies to grow bigger more easily. This help received by the state also influenced the infrastructures which have been improved, making the industry more efficient. Finally, China is advantaged by having available an immense workforce and, this, together with low labour costs, often close or equal to exploitation, contribute to its competitive advantage in the global aluminium industry.

MARKET CONDUCT – Si/Al ALLOYS

In the Silicon-Aluminium (Si-Al) alloys market, competition is intense due to the substantial demand for lightweight materials in various industries such as automotive, aviation, and construction. Companies try to outperform their competitors by investing in R&D to improve the efficiency of their products and their cost-effectiveness. These strategies might involve creating unique alloys with superior qualities, expanding global reach through partnerships or acquisitions, or diversifying their product lines to serve multiple industries. Moreover, as the Si-Al alloys market is already an established one, its entry barriers are relatively high, particularly considering the cost of extracting the material and build up the production line with the correct machinery. The aforementioned increase in need for lightweight materials will likely work as an expansion driver for this market. Indeed, the rising adoption of electric vehicle is forecasted to boost the aluminium alloys demand as these light compounds are used to counterbalance the heavy weight of the batteries (39). Other qualities of these alloys, that will boost their production and revenues are its high strength to weight ratio, making it a safe component for means of transport, it ductility at low temperature, which makes it easier to model it in the desired shape, and the absence of toxic byproducts.

An important metric to analyse the trends in a market, previously used in this report, is the CAGR (Compound Annual Growth Rate), from past and future years. It shows how much the industry is expected to grow in the years based on a forecast of its future market value. For the reason that were explained in the previous paragraph, this market is expected to sustain its current growth. Indeed, upon examining data retrieved from the internet (39), we see how its CAGR is expected to be of 8.1% in the years between 2022 and 2032, based on US$ 131 bn of value in 2022 and a forecasted value of US$ 287 at the end of 2032. This shows how this market can be an interesting direction for companies involved in the production of metals usable in aluminium alloys, but also that, when compared to the expected CAGR of other industries such as Semiconductors (8.1%) and Photovoltaic industry (10.6%) it is one of the markets that is forecasted to increase the most.

When talking about growth of a market, it is also useful to discuss its pricing policies and trends. These are, in the Si-Al alloys market, largely influenced by factors such as production costs, supply-demand dynamics, and global economic conditions. Recent data (Figure 29) show an increase in silicon-metal prices due to increased demand and difficulties in maintaining supply. The production costs, in turn, have also risen due to factors like increasing power rates, raw material and electrode costs.

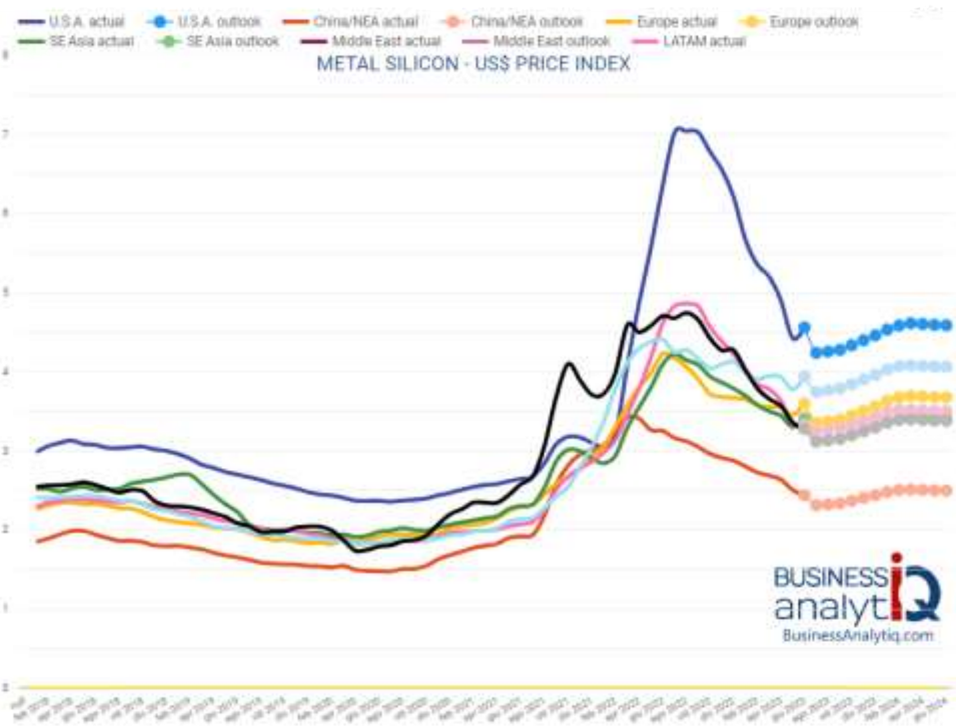


Figure 29. Metal silicon - US$ price index by region. Source: BusinessAnalystiq

Concerning the pricing strategy, in the SI-AL alloys industry, companies normally follow a cost-plus pricing strategy where the prices are determined by adding a certain profit margin to the total production cost. However, in a highly competitive environment, some companies might adopt competitive pricing strategies to capture a larger market share. Price discrimination is also probably being used, dividing the customers in groups and segments depending, for example, on the industry for which the alloy is intended and the volume of purchase each of these needs.

Alloy companies adopt a customized approach when working with customers. They engage in close collaboration with clients to ensure that the product aligns with their specific application requirements. Therefore, firms invest in R&D to design alloys with particular property, such as alloys designed for high temperature, or optimized for strength and corrosion resistance. Expanding upon customer relations, it is worth noting that the alloys industry primarily operates within a business-to-business (B2B) framework, so companies tend to create long-term relationships with their clients, emphasizing the technical expertise, quality assurance and after-sales services. Furthermore, this kind of industry works also through networking during global conferences on the specific topic, where firms find new clients or partner with other companies working in the same sector.

In conclusion, the Silicon-aluminium alloys market is in constant development, as its product are becoming more and more essential throughout different types of industries, assuring constant growth and technological advancement.

MARKET PERFOMANCE – Si/Al ALLOYS

When evaluating the performance of the Silicon-Aluminium (Si-Al) alloys market, it's crucial to consider the measurable outcomes that reflect the impact of both market structure and conduct. When analysing such a complex market, shaped by years of R&D and investments, it is useful to take a quick look at various key performance indicators (KPIs), including financial metrics, market share, production volume, sales volume, operational efficiency, environmental impact, among others.

Financially, the market's performance is generally assessed in terms of revenue, profitability, and return on investment. Given the significant demand for Si-Al alloys in various industries, the revenue generated by companies in this market is substantial. The profitability, on the other hand, is influenced by factors such as production costs, pricing strategies, market dynamics, and operational efficiency. Despite the relatively high cost of high purity silicon and the challenge of controlling particle size during alloy production, companies have been able to maintain decent profit margins by leveraging technological advancements and operational efficiency (50). Return on investment, although varied across different companies, has been positive overall, reflecting the profitability of this industry. In light of this positive returns, the companies listed in Table 5 have demonstrated a commanding presence in the global Si-Al alloys market. Indeed, their market share is a result of several factors including the quality and diversity of their product lines, brand recognition, pricing strategies, and global distribution networks. Furthermore, as aforementioned, their investments in R&D have led to the creation of innovative and superior alloys, helping them maintain and expand their market share.

From a production volume point of view, Si-Al alloys have seen a significant increase over the years, driven primarily by the growing demand in the automotive, aerospace, electronics, and construction industries (48).

Companies have scaled up their production capacities to meet this demand, resulting in a steady rise in the production volume of these alloys. Together with the increase in production, there was a surge also in the sales volumes. The augmented demand for Si-Al alloys, coupled with the successful marketing and sales strategies employed by companies, has led to higher sales volume. This has, in turn, contributed to the revenue and profitability of these companies, enhancing the overall market performance.

Operational efficiency, measured by the ratio of output to input, is another crucial performance metric. Despite the technical challenges in the production process of Si-Al alloys, companies have managed to improve their operational efficiency by adopting advanced technologies and optimizing their production processes. This has not only increased their production volume but also reduced their production costs, contributing to their profitability. Lastly, in terms of environmental impact, the Si-Al alloys market has had its share of challenges. The extraction and processing of silicon and aluminium, which are the primary raw materials for Si-Al alloys, have potential environmental implications (Error! Reference source not found.). However, companies have made steps in mitigating these impacts by adopting more environmentally friendly practices, including the recycling of aluminium and silicon, the use of renewable energy in production processes, and the reduction of waste and emissions. This has improved their sustainability profile, an increasingly important performance metric in today's business environment.

In order to give more detailed information about the economic performance of the silicon-aluminium alloys market, we will analyse the performance of the top 10 firms according to different financial metrics. We will focus on the comparison of the EBITDA margin with both the Revenue (ttm) and the Trailing P/E of the top companies of this sector. Indeed, comparing the EBITDA margin with Revenue (ttm) assesses operational efficiency and cost management, while comparing it with Trailing P/E helps assess investor perceptions of growth potential. This comparison sets good benchmarks for the industry performance. The data are retrieved from Table 5 and possible implications are discussed.

Revenue and EBITDA margin

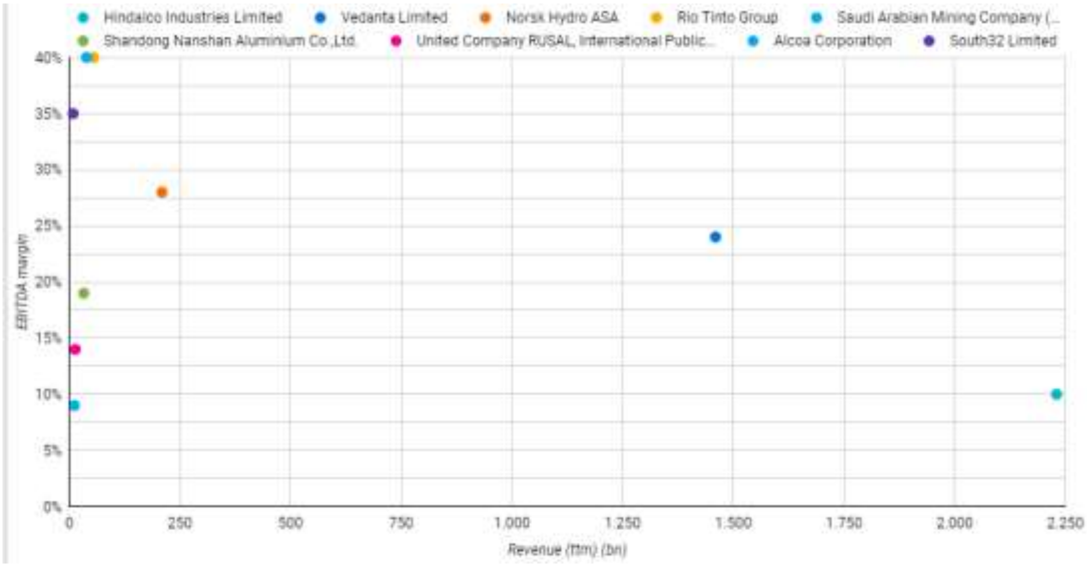


Figure 30. Scatter plot Revenue VS EBITDA margin top Si/Al alloys companies

- The analysis clearly shows that a high revenue doesn't always imply superior operational efficiency. Indeed, for example, the company Hindalco Industries Limited exhibits significant revenues, but its EBITDA margins suggest it could potentially optimize its operational efficiency further.
- Companies with smaller revenue, such as South32 Limited, have demonstrated an ability to maintain high EBITDA margins, indicating excellent operational efficiency irrespective of their revenue size.
- Companies like Rio Tinto Group and Norsk Hydro ASA have shown strong capabilities in both generating considerable revenue and maintaining high EBITDA margins, indicating they're leaders in operational efficiency in this industry.

Trailing P/E and EBITDA margin

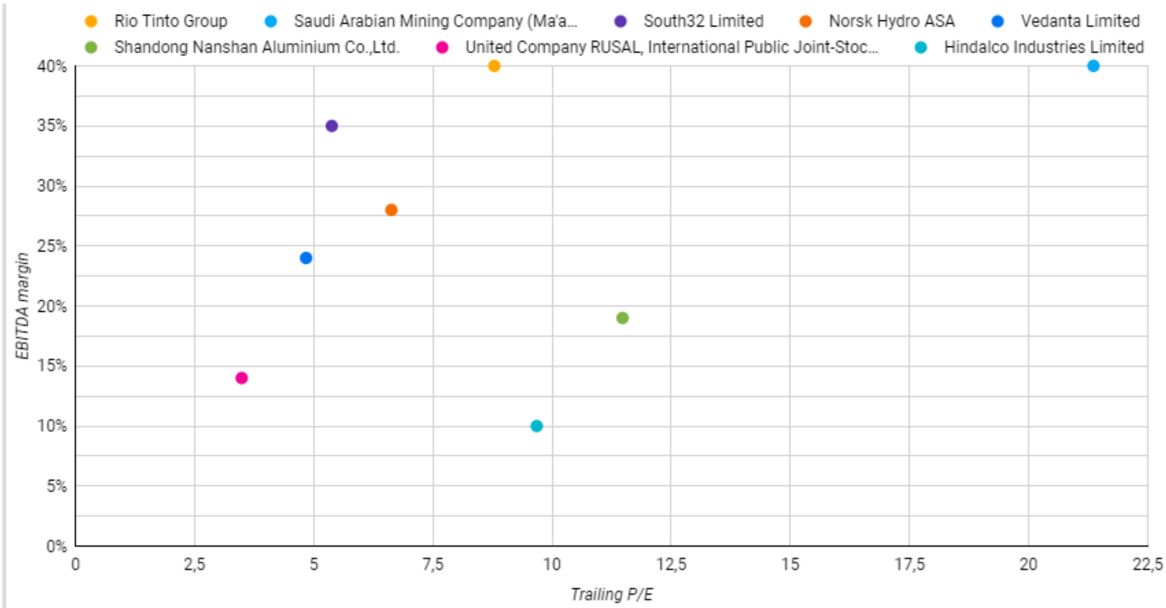


Figure 31. Scatter plot Trailing P/E VS EBITDA margin top Si/Al alloys companies

- Companies like South32 Limited, despite their high EBITDA margins, have lower trailing P/E ratios, suggesting potential undervaluation by the market.

- High EBITDA margin and high trailing P/E in companies like Saudi Arabian Mining Company (Ma'aden) indicate that the market highly values their operational efficiency and profitability.
- The market valuations of these companies, reflected in the trailing P/E ratios, do not always match their operational efficiencies, identifying different market inconsistencies or constantly changing investor expectations.

Based on the gathered data, it is possible to make the following general observations about the silicon/aluminium alloys:

1. **Variation in Efficiency and Profitability:** There's a broad variation in operational efficiency and profitability among the companies, as indicated by metrics such as ROA, ROE, and EBITDA margins. This could be due to differences in management practices, production capabilities, market positioning, and regulatory environment in the respective countries of operation.
2. **Diverse Market Valuations**: There's a significant diversity in market valuations as indicated by the Trailing and Forward P/E ratios. Some companies seem undervalued relative to their earnings (e.g., South32 Limited and United Company RUSAL), while others appear highly valued (e.g., Saudi Arabian Mining Company (Ma'aden)). This suggests that investor sentiment and expectations are varied across these companies.
3. **Industry Resilience**: Despite the diverse operational efficiency and market valuations, the industry as a whole appears to be resilient. Many of the top companies are maintaining substantial revenues and decent profitability margins, signalling a generally healthy state of the market.

Overall, the Si-Al alloys market has exhibited strong performance across multiple indicators, demonstrating its robustness and potential for continued growth. Despite some challenges, the future prospects for this market remain bright, driven by ongoing technological advancements, increasing demand in various industries, and the commitment of companies to improve their operational efficiency and sustainability.

CONCLUSIONS AND IMPLICATIONS FOR ICARUS – SI/AL ALLOYS

To verify the dynamics that the ICARUS consortium could encounter in the silicon-aluminium alloys industry, we will utilize a strategic analysis tool known as Porter's Five Forces. This was referenced in the methodology section of the report and through this framework we will probe the current market conditions and anticipate potential shifts within the silicon-aluminium alloys industry.

1. Threat of New Entrants - Low

The Silicon-Aluminium alloy industry presents high entry barriers primarily because of the requirements of advanced technologies and machineries able to work on metal alloys, which entail a considerable initial capital investment. The research for better product is a constant in this field. Indeed, they aim to create alloys with better physical properties that can withstand more stress and be used for more and more diverse purposes. Taking in consideration that this industry has been evolving over the decades, we find numerous established firms worldwide which already possess the know-how and the right machineries, making it difficult for new companies to find a competitive advantage, resulting in a really low threat of new entrants. For these reasons, this industry could present a significant opportunity for the ICARUS consortium. Through the recycling and transformation of silicon waste, the consortium's member companies could create a niche within this industry. Producing low-purity silicon adapted for Silicon-Aluminium alloys production, increasing the possibility of establishing a fresh market segment within the industry for the consortium, whose products come from a more circular model, which follows the current market trend.

2. Bargaining Power of Suppliers - Moderate

At present, the suppliers wield considerable bargaining power as a result of the industry's heavy reliance on predominantly Asian sources for silicon and other mined minerals. This dependency was brought to light by the supply chain disruptions caused by the COVID-19 pandemic, when all these countries, and in particular China, stopped their exportations initiating major issues worldwide. Nevertheless, the ICARUS consortium's disruptive approach of creating a good alternative to the virgin material could result a game changer for the industry. Indeed, using a secondary raw material source could significantly reduce this dependence. In light of this, Europe, thanks to the efforts of the ICARUS' companies, could recreate itself as a new born central hub for the sourcing of such materials, putting the EU back on the podium of major silicon suppliers. Certainly, by efficaciously recycling silicon, they can limit the control of suppliers and render the industry less susceptible to potential supply chain disruptions, thus fostering greater resilience. Nonetheless, the bargaining power of the current suppliers will not abruptly diminish, as the amounts required by this industry cannot still be met by the Consortium's production capacities.

3. Bargaining Power of Buyers - Low

Buyers in this industry typically possess low bargaining power, given that the virgin silicon used to produce the alloys is sourced by the same mining companies who serve a large number of other industries. Indeed, if one of the buyers stop sourcing form a certain company, this same company has the possibility to further differentiate its buyers base expanding in similar markets that require the same material. Indeed, the buyer base is so diverse, that reduces their power to negotiate prices or switch suppliers. However, the ICARUS consortium's initiative, with its disruptive products, originated from a more sustainable and controlled supply chain, could potentially innovate the sector, offering another, greener, possibility to the buyers, who will see their bargaining power increase as a consequence.

4. Threat of Substitutes - Low

The threat from substitute materials in this industry is generally regarded as moderate to low. Although other materials might be used in analogous applications, the specific characteristics of Silicon-Aluminium alloys are challenging to duplicate. However, the continual progression of material science and technology could prepare the way for new substitute materials, with similar capacities. Using this situation to its advantage, the Consortium could enter this market proposing their recycled product as the latest substitute to the virgin material utilized nowadays, potentially creating a disruptive trend in this industry.

5. Competitive Rivalry – moderate

The Silicon-Aluminium alloys industry is a well-established one and is marked by intense competitive rivalry with several known global players. This competition is stimulated by factors such as price, quality, and technological innovation. By generating a sustainable silicon source and fostering the development of new, high-end applications, the ICARUS consortium can offer a unique selling proposition within the industry, thereby setting their product apart and introducing a new dimension to the competitive landscape.

In sum, the ICARUS consortium's innovative approach to silicon recycling could prompt a significant transformation in the competitive environment within the Silicon-Aluminium alloys industry. This innovative process presents opportunities for increased resilience, market diversification, and potential entry into previously unexplored market segments.

GO-TO-MARKET STRATEGY – INCLUDING ALL CONSORTIUM SECTORS

1. **Target Market Segments**: ICARUS operates across a spectrum of industries and offers several different products and services. The key markets, as per this analysis, include the lithium-ion battery sector, silicon-aluminium alloy industry, and PV solar industry. To go more specific in the different industries ICARUS should focus on certain specific market segments (specific products or specific locations). Concerning polysilicon and the PV industry, the target should be represented by the

Chinese producers of both products as they dominate the landscape throughout all the supply chain. Within the lithium-ion battery sector, instead, ICARUS should specifically target Battery Energy Storage Systems (BESS) due to its expected high growth rate. In semiconductors, the segment that is expected to grow more in the following years is the AI-driven one, with NVDIA being the major player, therefore the consortium should focus in creating relationship with it and the others in this niche, to ensure a prolific future. Finally, the silicon-aluminium alloy is an already mature market where players have strong positions, nonetheless, as previously cited in the conclusions, ICARUS should aim at becoming the substitute of a part of the raw material suppliers to the industry, thank to their greener and more circular products.

2. **Value Propositions**: Across these sectors, ICARUS' unique value proposition is the innovative, sustainable, and more circular approach to recycling silicon, as they offer greener and locally sourced raw materials. Additionally, ICARUS' expertise in processing silicon and graphite waste can add value in multiple markets. For PV solar, ICARUS offers a solution to the critical issue of PV waste (with 45% of the silicon currently land-filled). For the lithium-ion battery industry, like for the semiconductors, ICARUS provides a potentially more sustainable and efficient source of raw materials. And in the silicon-aluminium alloys industry, ICARUS can offer a more sustainable and resilient supply chain, when compared to the existing players who mainly source their product from quartz mining operations.

3. **Product Positioning**: ICARUS should position itself as a leader in sustainability, innovating in areas of silicon and graphite waste recycling, repurification, and re-purposing. Indeed, thanks to the 4 pilots, working on repurposing the waste silicon for different uses, while generating useful by products that can be applied in multiple industries (green hydrogen from pilot D), the Consortium can target a series of diverse fields. The products of ICARUS will be positioned differently according to the industry that we take in consideration.

   Regarding polysilicon and PV, these industries are mostly dominated by Chinese companies and the Consortium could position itself both as a buyer and as a supplier to these businesses. Indeed, they could buy the silicon waste produced by this firms, repurify it and then sell it back as secondary raw material, generating, this way, more circular final products. Nonetheless, as one of the main objective of ICARUS is to reduce the dependency on Chinese firms, to safeguard against geopolitical unrest, ICARUS could try to position its product as a substitute in the industry, buying waste product from Western companies (European and American) to then resell the improved product only in the Western markets, helping to create a self-sufficient and circular silicon-economy reducing the reliance on China.

   Concerning the semiconductors and the SI/Al alloys, the Chinese presence is significant, but it still does not dominate these markets. Therefore, the probability of ICARUS' companies being able to position themselves as substitutes is higher. Nonetheless, both industries rely on China for most of the raw material used to produce their final products. Indeed, most of the raw silicon and aluminium comes from mines, most of which are located in China, making these markets susceptible to geopolitical destabilisation. More specifically, the semiconductor market is mostly in the hands of the Taiwanese TSMC, adding a further degree of danger to the market. China has been trying to occupy the island for years, claiming it as its own and opposing their government, which is considered illegal by them and is, in turn, supported by the US. If something was to happen to Taiwan in this regard, the industry would face a strong disruption, which could bring to prices heavily falling or skyrocketing. This whole particular situation could, on the other hand, help the Consortium, who could start positioning itself as a substitute of the primary raw materials sourced from mining, proposing its sustainable and circular secondary raw material as the perfect surrogate. At the moment, the price of this repurified material would still be higher than its virgin counterpart, but as the production of silicon-based products is forecasted to increase in the next decades, the waste produced will grow accordingly, reducing its price and increasing the possibility of ICARUS to present themselves as an alternative with competitive prices and a greener supply chain.

Finally, the Lithium-Ion Batteries market is in a particular situation. Indeed, it is currently dominated by Chinese companies (like CATL and BYD), who at the moment are able to support big parts of it thanks to their immense resources. Nonetheless, it also faces a continuous innovation which, in the last years, is taking place mainly in the Western countries, with new products on the horizon. One example are the silicon-based anodes, which, as previously stated, have the possibility of disrupting the market. If this were to happen, ICARUS would find itself producing a circular product that will become more and more indispensable to this market, creating a complete new segment in this industry and reducing the dependency on China.

4. **Strategic Partnerships**: ICARUS should establish partnerships with stakeholders in each market segment. Their prime focus should be on European and Western companies, in order to reduce the reliance on the Chinese markets. For example, they could buy the waste produced by the numerous German and Norwegian companies, repurify it and then put it back in the European market as secondary raw material. This will be possible in the future, when the amounts of waste produced will be higher and the necessity of virgin material will further decrease, however, with the current market situation, the Consortium, will be forced to establish some relations also with the Chinese companies. Indeed, they own more than 95% of the production stages of silicon ingots and wafer, where most of the waste repurposed by ICARUS is generated, reducing the possibility of complete independence from the Chinese markets. Therefore, the companies have to evaluate different possibilities for market entry with the current situation. For example, they should consider the creation of strategic partnerships with the Chinese counterparts, where they share the technologies to recover the waste, without sharing the know-how behind it. Indeed, they should develop a clear IPR strategy, evaluating which parts of the technology can be disclosed and which parts need to be treated as a secret. In doing so, they will be able to exercise the right amount of control on these partnerships.

   Another option is represented by keeping the technologies inside the European borders, always using a similar disclosure strategy. The aim of this would be to slowly recreate a strong silicon market in Europe, allowing the EU-based firms to greatly reduce the dependence on China, as they would be able to reuse their own waste, while creating a circular economy and boosting the markets inside the continental borders. This can be done for the PV, Lithium-Ion Batteries and Si/Al alloys markets thanks to the presence of different companies working in these sectors inside the union borders. Indeed, the EU hosts some of the top companies working in these fields and also numerous start-ups currently developing potential disruptive technologies, particularly in the Netherlands, which could act as game changers. The same cannot be said for the polysilicon and semiconductors industries where the role of Asia and US based companies is still prominent and, therefore, the creation of strategic partnerships with them will be inevitable.

   Finally, ICARUS' companies should consider the possibility represented by the emerging economies of Africa and South America. Indeed, these countries started investing on greener technologies, especially related to the PV market. Therefore, the Consortium should consider establishing relationships with companies operating in these geographic areas as, due in part to their location's high exposure to the sun, their importance in the international silicon markets will increase significantly in the coming years. To enter these markets, which have been already partly accessed by Chinese companies, ICARUS could offer more sustainable and circular alternatives to the virgin silicon used by China.

5. **Price Strategy**: Pricing should be competitive, considering both the cost of virgin materials and the added value of sustainability and local sourcing. This could be a problem in the early days of ICARUS, as the prices of virgin silicon are still much lower than its recycled counterpart. The belief is that thanks to the increase in production of silicon-related products, the waste will increase accordingly, consequently lowering the prices at which the Consortium will be able to purchase the Si-Kerf. This will have a direct effect on the prices of the final product offered by ICARUS, ensuring a price competitiveness in the long run.

6. **Stay Ahead of Innovation**: To conclude, ICARUS should maintain its edge in innovation, continually improving its recycling processes, and exploring new applications for its recycled silicon. This could involve investing in R&D or partnering with academic institutions or innovative startups inside the European borders. The focus should be on the Lithium-Ion Batteries market, where Europe can, supposedly, be able to develop more disruptive technologies.

This comprehensive Go- To- Market Strategy aims to help ICARUS successfully market its innovative and sustainable solutions, create valuable partnerships, and secure its position in the semiconductors, lithium-ion battery, PV, and silicon-aluminium alloy markets.

APPENDIX

Appendix 1 – processes for Polysilicon, monocrystalline and conclusion of the process of solar cell formation

- **Siemens process.** Despite different attempts to develop a less expensive alternative to the Siemens process, it remained the predominant technology to create high-purity silicon. This was in part helped by the development of super low-cost plants in China, thanks to the subsidized capital expenditures they benefit from. It was first developed in 1950s by the German companies Siemens and Wacker to materials for the semiconductor industry. The Siemens process was created to remove the impurities contained in MG-Si. It starts by creating trichlorosilane (TCS) as intermediate product with a low boiling point (31.8°C), which can be distilled in tall columns relatively easily. Silicon is then deposited on slim silicon filaments with a high-purity that are electrically heated to 1150°C in a steel bell-jar until they grow polysilicon rods of 15-20 cm in diameter (chemical vapor deposition). The rods are broken into small chunks that can possess different purity grades.

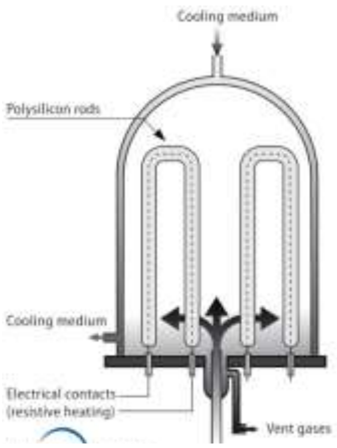


Figure A1. The siemens process. Source: Bernreuter research

- **Fluidized Bed Reactor technology (FBR technology).** It starts with the injection of a silicon containing gas together with oxygen through nozzles, creating fluidized bed capable of carrying tiny silicon particles fed from the top. The temperature is then increased until the reaction zone (it can be 700°C or 1000°C, depending on the feed gas used), so that the silicon deposits on the seed particles, until larger granules are formed and be withdrawn continuously, with no need to stop the reaction. The FBR technology consumes one tenth of the electricity used by the Siemens process and therefore is more convenient, nonetheless there are still different obstacles stopping its worldwide adaptation. This happens for a number of reasons: the high number of patents related to FBR technology, the complex fluid dynamics for which a lot of time and capital are required, the high costs related to multiple parts and, finally, a big amount of silicon dust as output. Therefore, currently, this process is used in large FBR plants only by the Norwegian company REC Silicon, but the technology is promising, entailing possible future developments.

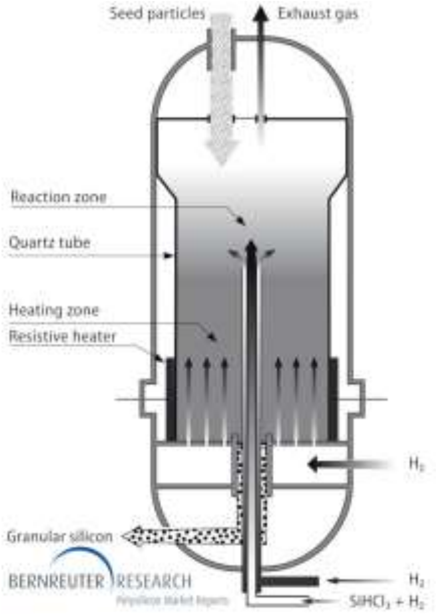


Figure A2. The FBR process.
Source: Bernreuter research

- **Upgraded metallurgical-grade (UMG) silicon.** The UMG technique does not purify the raw material of MG-Si. Instead, it uses an array of physical methods (e.g., vacuum melting, directional solidification). All these methods have the aim of extracting impurities directly form the silicon metal, consuming less energy than the dominating Siemens process. Nonetheless, the purities reached through this process are much lower when compared to the other two and, thanks to different improvements to the Siemens process, the cost advantages of the UMG became negligible in recent years. For these reasons, the last commercial manufacturer of UMG (REC SILICON) stopped the production in 2020.

As previously noted, these processes are used to create polysilicon chunks or rods. These pieces are then melted in a crucible. This container is heated and the polysilicon melts. The silicon ingots needed for the production of wafers are then obtained through a dedicated crystallization process.

It is important to note that the process to produce monocrystalline silicon is more complex and energy-consuming when compared to the one used for polycrystalline silicon (25kWh/kg compared to only 8kWh/kg). Two procedures can be used to this end:

- **The Czochralski (CZ) method**. The majority of the commercially used ingots of mono-Si are done using this method due to its better resistance to thermal stress, the speed of production and the low-cost. It starts with melting high purity polysilicon with specific dopants, accordingly to the type of solar cell needed. The process involves the insertion of a small seed crystal on the surface of the molten silicon and slowly brings it upwards, while simultaneously rotating counterclockwise. This draws the silicon and allows it to solidify into a continuous crystal extending from the seed, creating single crystal ingot.

- **The floating zone (FZ) method.** It is a crystal growth technique that doesn't require a container. During FZ growth, the molten zone is held between two vertical solid rods by its own surface tension (as shown in Figure 4). A single crystal is created by immersing a seed crystal into one end of the zone and slowly moving the molten zone towards the feed stock. The primary benefit of using the FZ technique is that the absence of a container eliminates the possibility of contamination by the crucible material and prevents the formation of crystal defects caused by the interaction between the growing crystal and the container.

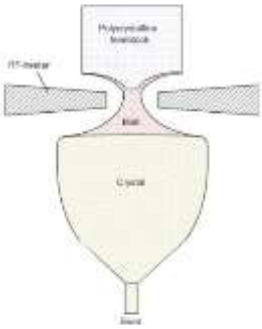


Figure A3. The Float Zone (FZ) method

(Error! Reference source not found.) After the silicon ingots are completed, the next step in the process involves cutting the silicon into wafers for use in solar cell production. This is accomplished through two main steps. First, the ingots are transformed into blocks using various methods such as heat exchange, electro-magneto casting, and directional solidification. The blocks are then cut into wafers, with the most common method worldwide being wire saw cutting.

(9) Wire saw cutting involves a series of wires that are spaced at a specific distance from one another, determining the width of the wafer. There are two main types of wire saw cutting: slurry cutting and diamond wire cutting. Slurry cutting is an older method that is used by few companies due to being slower, producing more waste, and requiring expensive equipment. The wire used in slurry cutting is made of steel and has a smooth surface.

On the other hand, diamond wire cutting is the most commonly used method nowadays due to being more environmentally friendly, easier to clean, faster, and using an aqueous coolant. The main difference is in the wire, which is made of steel coated with diamond.

To conclude the description related to the production of solar cell starting from the high purity quartz rock, the only steps left are the ones needed to go from silicon wafers to solar cells. This process, that will not be investigated in detail as it is not part of the objectives of this report, is divided as follows:

1) Pre-check and pre-treatment
2) Texturing
3) Acid cleaning
4) Diffusion
5) Etching & edge isolation
6) Post-etching washing
7) Anti-reflective coating deposition
8) Contact printing and drying
9) Testing and cell sorting

The solar cells ready are then used in the assembly of solar PV modules, The quality of the solar cell is classified into various grades based on the smoothness of the production process and the quality of the basic silicon wafer material.

Appendix 2 – Lithium-Ion batteries anodes and cathodes compositions

Anode Materials

Traditionally, graphite is the most commonly used anode material in lithium-ion batteries. This is due to its stability and ability to intercalate lithium ions between its layered structure.

However, recent advancements have led to the development of other anode materials, such as:

1. Lithium Titanate (LTO): This anode material has a higher rate capability and longer cycle life compared to graphite. It is safer, but has a lower energy density.

2. Silicon-based anodes: Silicon anodes have a significantly higher capacity than graphite anodes, as a single silicon atom can bond with up to 4.4 lithium ions. However, this can cause the silicon to expand and contract dramatically during charging and discharging, which can lead to degradation.

Cathode Materials

The cathode is more varied in terms of material composition. The choice of cathode material has a significant impact on the battery's overall performance characteristics. Here are a few common types:

1. Lithium Cobalt Oxide (LCO): LCO has a high energy density and is commonly used in portable electronic devices such as mobile phones and laptops. However, it has a relatively short lifespan and poses safety risks.

2. Lithium Manganese Oxide (LMO): LMO is generally safer and has a longer lifespan than LCO. It is often used in power tools and electric vehicles.

3. Lithium Iron Phosphate (LFP): LFP is very stable and safe, but it has a lower energy density. This makes it ideal for use in electric vehicles and large-scale energy storage systems.

4. Lithium Nickel Manganese Cobalt Oxide (NMC): NMC is a combination of nickel, manganese, and cobalt, and is typically represented as $LiNiMnCoO_2$. It offers a good balance of power capacity, lifespan, and safety. NMC batteries are commonly found in electric vehicles.

5. Lithium Nickel Cobalt Aluminium Oxide (NCA): NCA has a very high energy density and is used in electric vehicles and grid storage. Tesla, for example, uses NCA batteries in many of its vehicles.

6. Lithium Nickel Cobalt Manganese Oxide (NCM): Similar to NMC, NCM is another mixed metal oxide, but the composition ratio of nickel, cobalt, and manganese is different. It offers similar performance characteristics to NMC.

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