Horizon 2020 Programme

SCRREEN2

This project has received funding from the European

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Start date: 2020-11-01 Duration: 36 Months

SCRREEN

Solutions for CRitical Raw materials - a European Expert Network

FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

SILICON METAL

AUTHOR(S):

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MATERIAL

OVERVIEW

Silicon metal (chemical symbol Si) is the second most abundant element in the Earth's crust in the form of silicate minerals. It is an inert element extracted from vein quartz and quartz pebbles due to their high silica content. Silicon has no metallic properties but is known as silicon metal in the industry because of its lustrous appearance. There are two grades of silicon metal: metallurgical grade silicon (typically around 99% of Silicon, trade code CN 28046900), representing the majority of the volumes produced, and polysilicon (with a 6N to 11N purity, trade code CN 28046100).

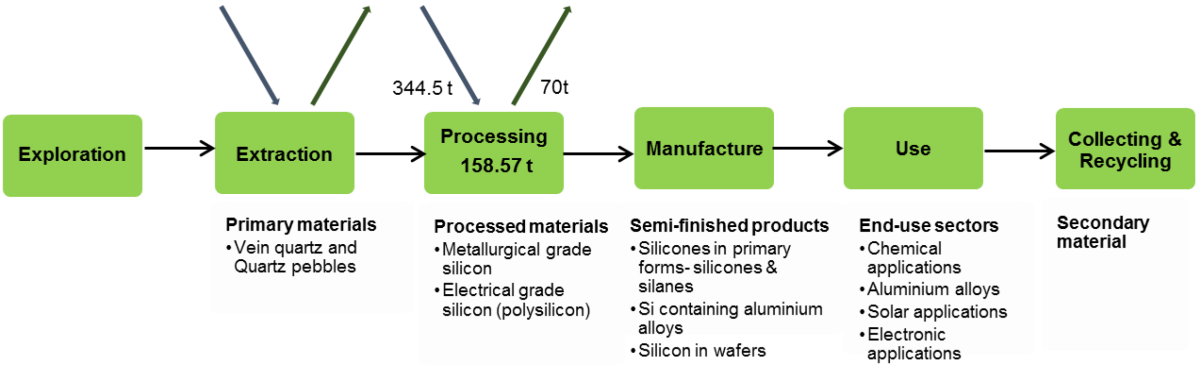

Figure 1. Simplified value chain for silicon metal in the EU[1]

Table 1. Silicon metal supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
3,011,920	China 77% Brazil 7% Norway 6% France 4%	421,141	14%	Norway 35% France 29% Brazil 10% Spain 5%	64%

Prices: Silicon metal prices increased slowly between 2002 and late 2007 and reached the peak in 2008. The economic recession in 2008 and 2009 resulted in prices decreasing sharply back to 2007 levels. Another pike in silicon prices was experienced in 2011. In 2016, the price of silicon metal dropped again. The oversupply in the market combined with decreased steel production and weak aluminium alloy demand contributed to decreased silicon prices in 2015-2016 (USGS, 2022). At the end of 2021, silicon price increased drastically (up to 300%) due to a shortage of silicon metal generated production cuts in China (*Chia, Murtaught and Burton, 2021*).

[1] JRC elaboration on multiple sources (see next sections)

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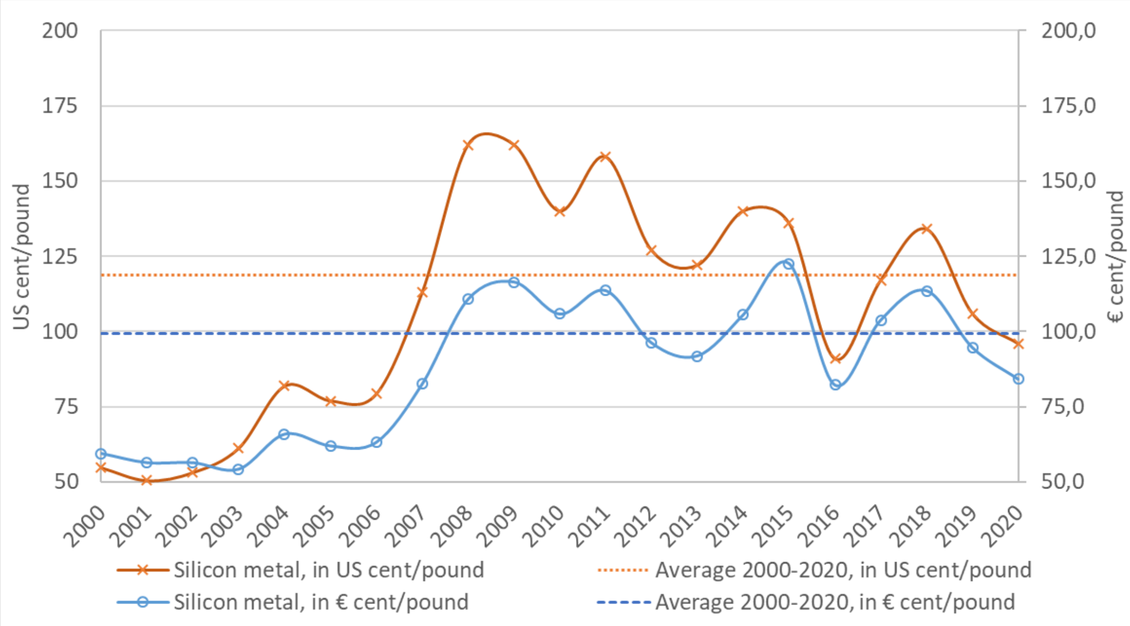

Figure 2. Annual average price of silicon metal between 2000 and 2020 (USGS, 2021)[2].

Primary supply: Once mined, quartz is reduced to silicon metal by carbothermic reduction. This takes place in a submerged electric arc furnace containing quartz and carbon materials, such as coke and charcoal. Electric energy is supplied by electrodes submerged in the charge – with temperatures from 800 to 1,300°C at the top of the furnace, and exceeding 2,000°C at the bottom, near the electrodes (Aasly, 2008). Molten silicon metal is produced at the bottom of the furnace. The production over 2016-2020 reached an average of 3,215 kt per year. Global supply of silicon metal is dominated by China with about 2,224 kt per year equivalent to 77% of the global annual production over the years 2016-2020. Brazil, accounting for 190 kt (7% of global supply), was the second largest producing country, followed by Norway, accounting for 148 kt (6% of global supply). The EU production was limited to 167 ktonnes, in France (75%), Germany (18%) and Spain (7%).

Secondary supply: Most chemical applications of silicon metal are dispersive, thus not allowing for any recovery. In recent years there have been functional recycling plants of Si scrap from wafers and from photovoltaic panels. European companies are trying to improve the recycling of these materials, with examples such as the ICARUS or Reprosolar projects. There is no functional recycling of silicon metal in aluminium alloys. Although there were new functional recycling plants for silicon metal, it has not been possible to quantify the precise updated end of life recycling input rate for silicon metal.

[2] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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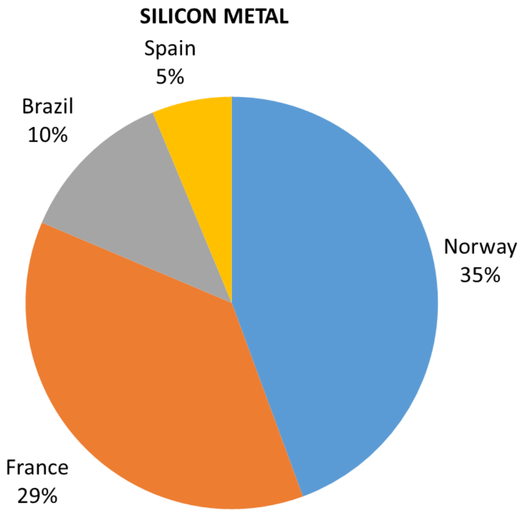

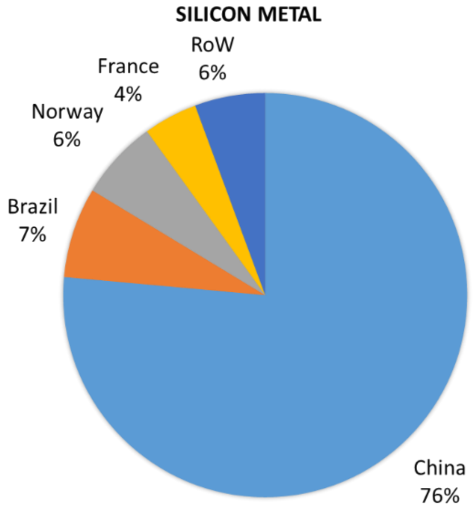

Figure 3. EU sourcing of silicon metal and global mine production (update)

Uses: The main uses of silicon metal are in the aluminium and chemical industries (BRGM, 2021). In addition, silicon metal is a strategic raw material used in the renewable energy (photovoltaic industry), in electronic devices, and to a smaller extend in batteries.

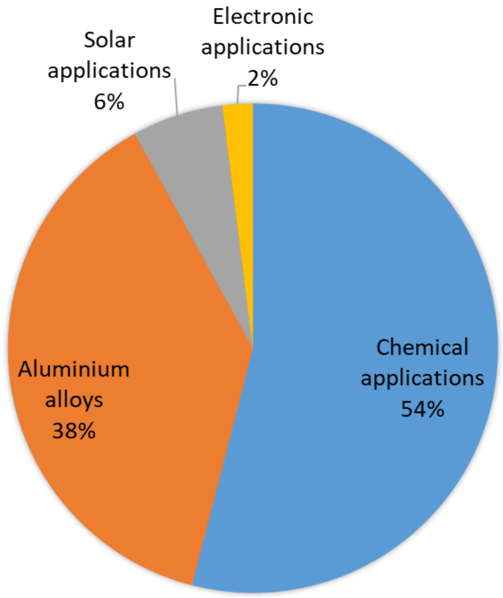

Figure 4: EU uses of silicon metal

Substitution: There are no materials that can replace any of the main uses of metallurgical silicon without serious loss of end performance or increase of cost.

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Table 2. Uses and possible substitutes

Application	%*	Substitute(s)	SubShare	Cost	Performance
Chemical applications	54%	Thermoplastic (PVC, TPE)	5%	Similar or lower costs	Reduced
		Rubber	5%	Similar or lower costs	Reduced
Aluminium alloys	38%	Silver	0%	Very high costs (more than 2 times)	Reduced
Solar applications	6%	Germanium	1%	Slightly higher costs (up to 2 times)	Reduced
		Gallium phosphide (GaP)	1%	Similar or lower costs	Reduced
		Gallium arsenide (GaAs)	1%	Similar or lower costs	Reduced
		Gallium antimonide (GaSb)	1%	Similar or lower costs	Reduced
		Indium phosphide (InP)	1%	Similar or lower costs	Reduced
		Indium arsenide (InAs)	1%	Similar or lower costs	Reduced
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		Indium arsenide (InAs)	1%	Similar or lower costs	Reduced
		Indium antimonide (InSb)	1%	Similar or lower costs	Reduced

Other issues: In their LCA study, Heidari and Anctil (2022) calculate that the cradle-to-gate production of metallurgical grade silicon potentially generates from 12 to 16.5 kg CO_2-eq/kg silicon metal, while its Cumulative Energy Demand (CED) ranges from 186 to 286 MJ/kg silicon metal, depending on the producing country/mine and the level of purity of the silica sand used as input to the process. Through a hotspot assessment considering 18 impacts categories, Zhang et al. (2023) identify that, overall, the environmental impacts of silicon metal are essentially driven by: i) the important energy consumption from the production process; ii) the use of graphite anodes in the process; and iii) the use of coal. The EU and the USA restrict the international trade of silicon metal. Europe sets an antidumping import tax on silicon metal coming from China; the USA as well, but their rules are very dynamic and may change from one administration to another. Some taxes are also set in the EU and in the US on photovoltaics components containing crystalline silicon coming from Asian countries (BRGM 2019).

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3. Silicon metal supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
3,011,920	China 77% Brazil 7% Norway 6% France 4%	421,141	14%	Norway 35% Brazil 29%	64%

According to the USGS Mineral Commodity Summaries (U.S. Geological Survey, 2022), the five biggest producers of silicon metal in terms of estimated quantity (including ferrosilicon) in 2021 are China (5,600 tonnes), Russia (580 tonnes), Brazil (390 tonnes), Norway (350 tonnes), and the United States (310 tonnes). Ferrosilicon accounted for almost 70% of world silicon production[3] on a silicon-content basis in 2021 (U.S. Geological Survey, 2022), with market size value reaching approximately US$ 10 Billion according to several market research estimations[4]. Ferrosilicon is not covered in this assessment.

Silicon metal is produced from the reduction of quartz is reduced to silicon metal by carbothermic reduction in a submerged electric arc furnace containing quartz and carbon materials, such as coke and charcoal (European Commission, 2020). The quality of raw materials used in the production of silicon metal determines the quality of silicon metal, and thus whether silicon metal can satisfy specific requirements of various end users (United States International Trade Commission, 2017). Despite being an abundant material on earth, quartz with commercial production value is mainly found in China, Brazil, Europe and the United States (First Continental International, 2019). In these locations the content of silicon metal is comparatively high, making quartz in these areas more cost efficient (First Continental International, 2019). Further purification is required to process the output into high-purity silicon metal used in solar cells and electronics. The processing of silicon metal is energy-intensive, requiring about 13,000 Kwh/t of silicon (CRM Alliance, 2022). The cost of energy was considered as a factor that could limit the market growth of silicon metal in 2021 (Research and Market, 2021).

In trade statistics, there are two codes that refer to silicon metal; 28046900 Silicon containing < 99,99% (4N) by weight of silicon; also known as metallurgical grade silicon (MG Si) and 28046100 - Silicon containing >= 99,99% (more than 4N) by weight of silicon. Excluding silicon metal accounted in ferrosilicon, the leading producers of silicon metal in 2021 were China, Brazil, and Norway. China accounted for approximately 70% of total global estimated production of silicon materials in 2021 (U.S. Geological Survey, 2022).

[3] The leading countries for ferrosilicon production were, in descending order and on a silicon-content basis, China, Russia, and Norway. (U.S. Geological Survey, 2022)

[4] Imarc Group estimation at US$ 11.60 Billion, Source: https://www.imarcgroup.com/ferrosilicon-market, Grandview Research estimation was US$ 11 Billion, Source: https://www.grandviewresearch.com/industry-analysis/ferrosilicon-market

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The global metallurgical grade silicon market was valued at US$ 6.7 billion in 2021 according to a market research estimation (FactMR, 2023). The production of MG Si is commercially practical in countries with pure quartz deposits, > 97% SiO_2, and inexpensive, abundant electrical power (Source: J.E.A. Maurits, in Treatise on Process Metallurgy: Industrial Processes, 2014). The main obstacles to an increase in Si metal production are a high dependency of intense and continuous power supply (11-14 kWh/kg Si), increasing raw materials' cost, and significant environmental impacts of fossil fuel use (coal, lignite, coke) (BRGM, 2019).

Chemical grade (4N) silicon metal is used in silicones, sealants and lubricants, silanes, desiccant, thickening agent (HPG Silicon, 2022). Solar grade polysilicon (6N-9N) is used for making solar cells. Over 90% of polysilicon is consumed by the PV Industry in 2017 (Chalamala, B., 2018). Electronic grade polysilicon (9N-11N) is used for producing silicon chips/wafer (ICIS, 2013). Almost 80% of electronic grade silicon is utilized in integrated circuits and microelectronics (FactMR, 2022).

Global polysilicon manufacturing capacity sat at 621,000 tons in 2021 – with real supply under 579,000, tons (Whitlock, R., 2022). China accounted for 77% of global polysilicon production in 2020. (Fugmann, U., 2021). China's introduction of duties on polysilicon imports in 2013 was the start signal for its domestic polysilicon industry to expand (Bernreuter, 2022). The 'modified Siemens process' is currently the dominant technology in China. The other two technologies are upgraded metallurgical-grade silicon process (UMG) and Fluidised bed reactor process (FBR) (Fugmann, U., 2021).

EU TRADE

For this assessment, silicon metal is evaluated at the processing stage.

Table 4. Relevant Eurostat CN trade codes for silicon metal

Processing/refining	
CN trade code	**title**
28046900	Silicon containing < 99,99% by weight of silicon
28046100	Silicon containing >= 99,99% by weight of silicon

The listed CN codes that referring to silicon metal are: 28046900 Silicon containing < 99,99% (4N) by weight of silicon; also known as metallurgical grade silicon (MG Si) and 28046100 - Silicon containing >= 99,99% (more than 4N) by weight of silicon.

Figure 5 shows the import and export trend of silicon <99,99% weight of silicon metal. The EU exports is much lower than the EU import of silicon metal. In 2021, the EU export sat at 31,419 tonnes while the import was 365,228 tonnes. The import of silicon metal fell 368,657 tonnes in 2018 to 326,316 tonnes in 2020 as COVID-19 pandemic happened. Instead, the EU export seemed to maintain the same level during this period.

Figure 6 illustrates the share of import in EU for silicon metal with <99.99% of silicon metal content from various countries. The main supplier to EU in the past two decades (2000-2021) was Norway (40% of share), followed by Brazil, China, and Russia (19%, 13%, and 6%, respectively).

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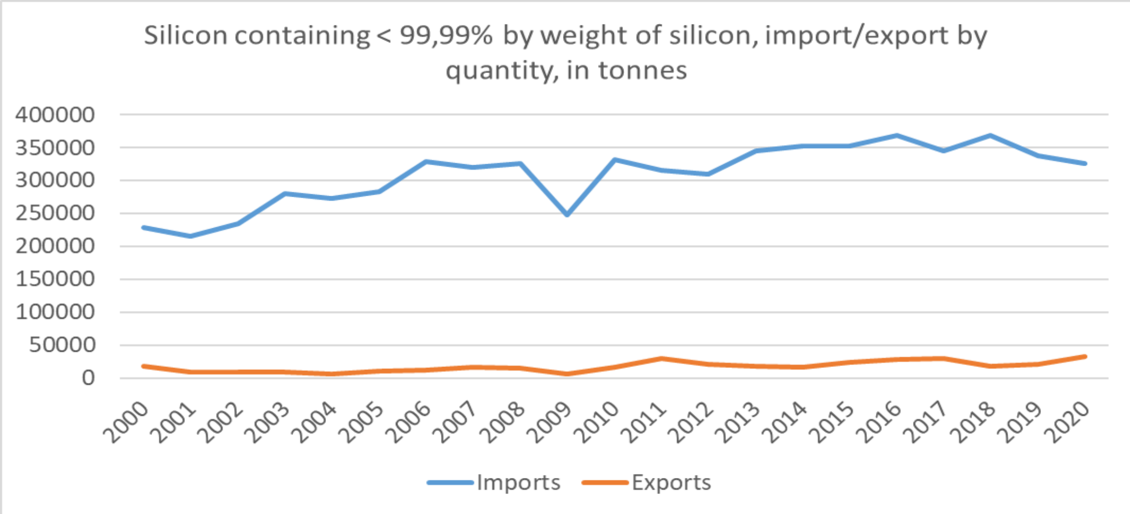

Figure 5. EU trade flows of Silicon containing < 99,99% by weight of silicon (CN 28046900) from 2000 to 2021 (Eurostat, 2022)

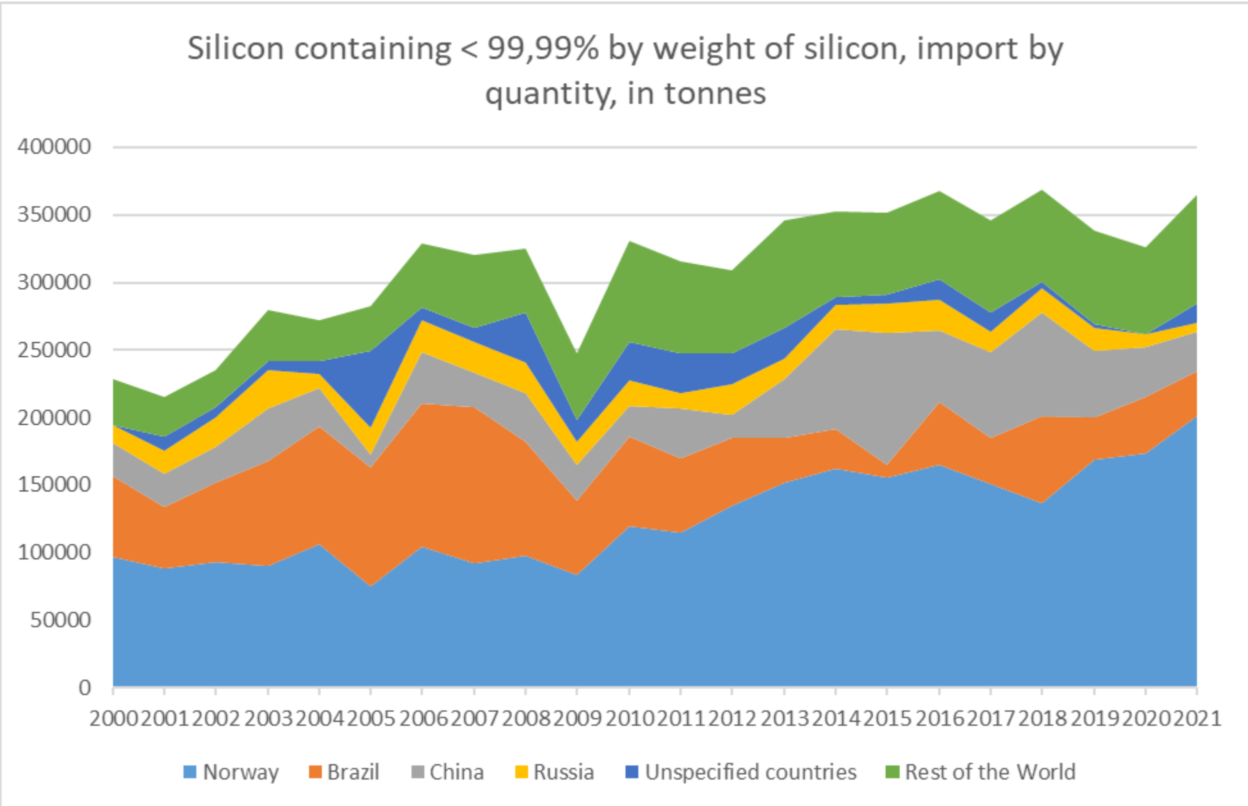

Figure 6. EU imports of Silicon containing < 99,99% by weight of silicon (CN 28046900) by country from 2000 to 2021 (Eurostat, 2022)

Figure 7 shows the import and export trend of silicon containing =>99,99% weight of silicon metal. During the year 2000-2007, the EU import and export showed to be relatively stable, with export showing a lower quantity than the EU import. However, EU export started to experience a high jump from 2,464 tonnes in 2008 to 65,642 tonnes in 2021. The EU exports also increased from 3008 tonnes in 2007 to all time-high (2000-

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2021 period) in 2011, at 11,107 tonnes. In 2021, the EU import reached 8,118 tonnes. COVID-19 pandemic seemed to have impacted the import and export in the same manner, shown by lower quantity of silicon metal traded in 2020.

Figure 8 illustrates the share of import in EU for silicon metal containing >=99.99% of silicon metal content from various countries. The import of high purity silicon metal to EU in the past two decades (2000-2021) fluctuated rather greatly. The United States, South Korea, Japan, the UK, and China were the competing major suppliers to the EU. The most notable trend is the increasing imports from the United States and the decreasing imports from other nations, especially from 2018 to 2021. Nevertheless, these figures may not completely picture the EU demand for high purity silicon metal. Polysilicon is embedded in photovoltaic (PV) cells and electronic products imported to the EU.

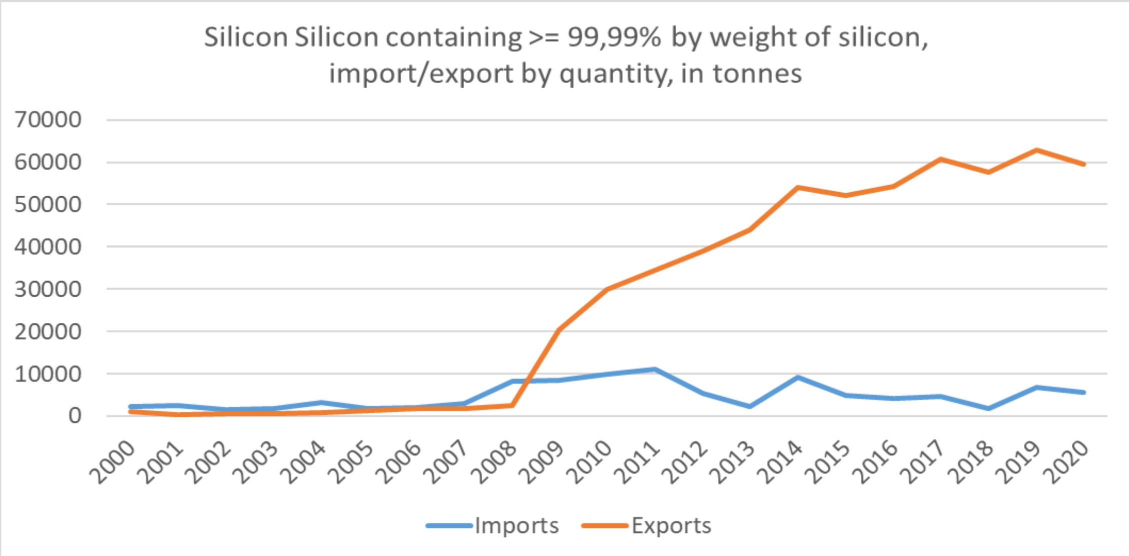

Figure 7. EU Trade flows of Silicon containing >= 99,99% by weight (CN 28046100) from 2000 to 2021 (Eurostat, 2022)

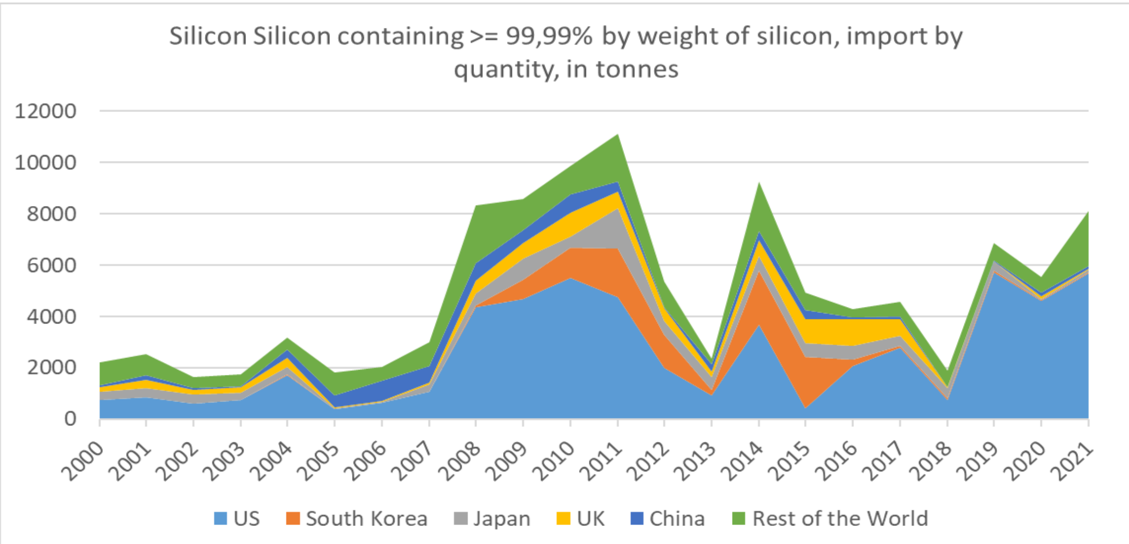

Figure 8. EU imports of Silicon containing >= 99,99% by weight (CN 28046100) by country from 2000 to 2021 (Eurostat, 2022)

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PRICE AND PRICE VOLATILITY

Silicon metal prices increased slowly between 2002 and late 2007 and reached the peak in 2008. The economic recession in 2008 and 2009 resulted in prices decreasing sharply back to 2007 levels. Another pike in silicon prices was experienced in 2011. In 2016, the price of silicon metal dropped again. The oversupply in the market combined with decreased steel production and weak aluminium alloy demand contributed to decreased silicon prices in 2015-2016 (USGS, 2022). At the end of 2021, silicon price increased drastically (up to 300%) due to a shortage of silicon metal generated production cuts in China (*Chia, Murtaught and Burton, 2021*).

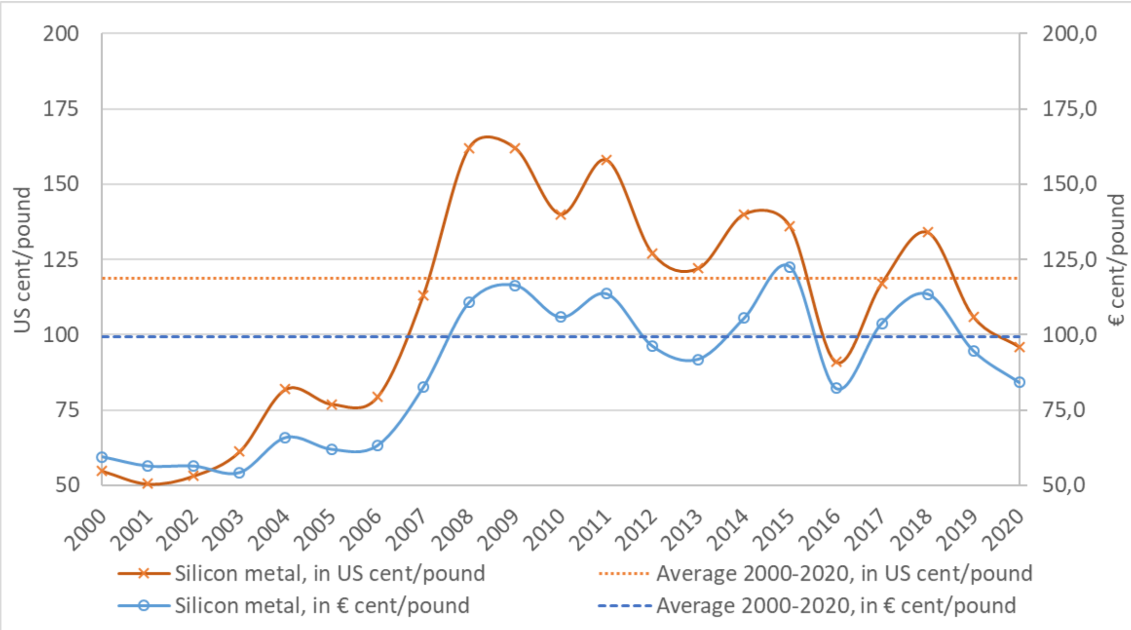

Figure 9. Annual average price of silicon metal between 2000 and 2020, in US cent/pound and € cent/pound[5]. Dash lines indicate average price for 2000-2020 (USGS, 2022)

OUTLOOK FOR SUPPLY AND DEMAND

Solar PV cells are predicted to become a crucial part of the overall energy mix between 2013 and 2050 to meet low carbon future (World Bank, 2017). Strong policy support for solar PV in China, United States, European Union, and India will drive the acceleration in capacity growth (IEA, 2022).

Currently valued at US$ 3.8 billion, the global electronic grade silicon market is also predicted to expand, driven by high demand from the semiconductor industry (FactMR, 2022). Despite representing a smaller share of application of electronic grade silicon, the downstream semiconductor market sales reached a value of $600 billion in 2021 (Burkacky, O., Dragon, J., Lehmann, N., 2022). About 70 percent of growth of this sector is predicted to be driven by the automotive (particularly electric vehicles), data storage, and wireless industries (Burkacky, O., Dragon, J., Lehmann, N., 2022).

[5] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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The supply of polysilicon has experienced both surplus and shortages of supply in the past since 1981 according to the analysis by Bernreuter, 2022b. Regarding supply, several polysilicon major companies in China are in expansion. China's Polysilicon and solar cell manufacturer Tongwei expects to increase its polysilicon capacity from 180,000 tonnes in 2022 to reach 230,000 tonnes by the end of 2022 and 350,000 tonnes at the end of 2023 (PV Magazine, 2022). In 2021, the polysilicon output of Tongwei was estimated between 80,000[4]-109,000 metric tonnes (Taiyangnews 2022a and Marketscreener 2022), accounting for roughly 22% of China's yearly output and about 18% of the world's annual output. GCL, another Chinese player, is expected to reach a production capacity of 370,000 MT by 2023. The annual output of GCL was 100,000 tonnes in 2021 (TaiyangNews, 2022b). A Munich-based chemical company, Wacker Chemie AG is preparing to expand its production capacity for silicon metal at Holla, Norway. The future furnace is expected to increase capacity in Holla by around 50 percent of its current level (Christof, B., 2022). This project is scheduled for completion in 2025. The annual production of hyper pure polysilicon totals 80,000 metric tons in 2022 (Wacker Chemie AG, 2022). In June 2022, Emirates Global Aluminium, announced that the company is to develop a project to manufacture silicon metal in the United Arab Emirates (UAE), securing supplies of a key raw material for 'premium aluminium' and unlocking potential new industries in the UAE (Emirates Global Aluminium (EGA), 2022).

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

Silicon metal processing stage EU consumption is presented by HS codes CN 280469 Silicon containing < 99,99% by weight of silicon and CN 280461 Silicon containing >= 99,99% by weight of silicon. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from BGS (2021).

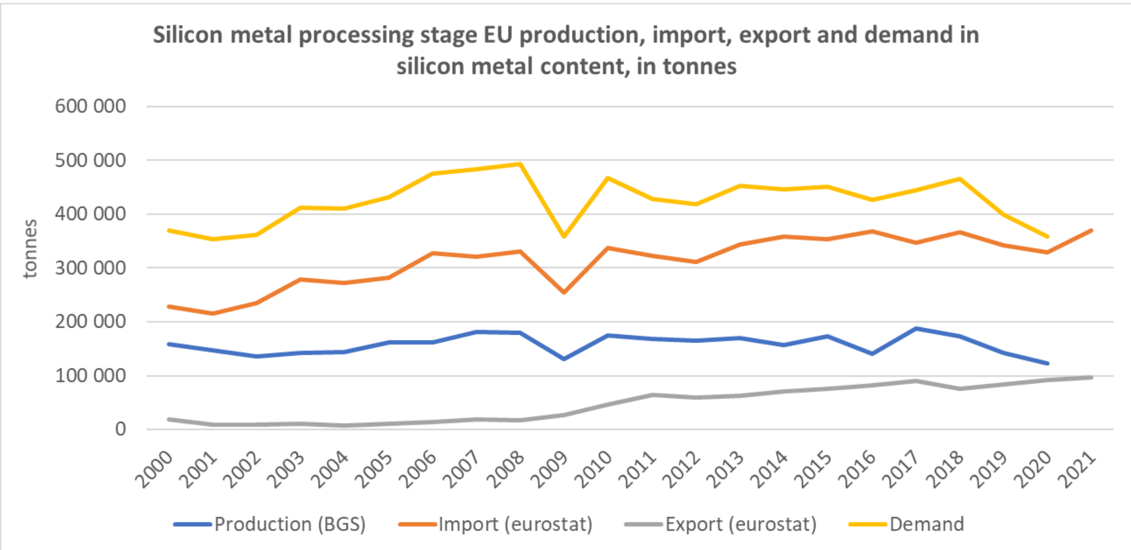

Figure 10. Silicon metal (CN 280469 and CN 280461) processing stage apparent EU consumption. Production data is available from BGS (2021). Consumption is calculated in silicon metal content (EU production+import-export).

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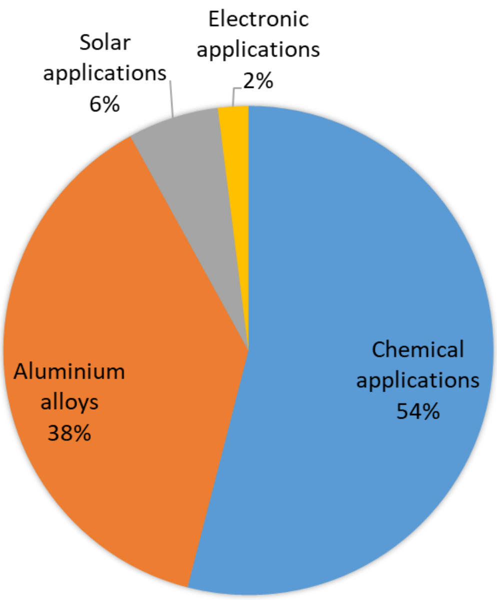

Figure 11: Global end uses of silicon metal according to BRGM (2021) based on data by Roskill, RoSi, Bernreuter, CRU, Fraunhofer ISE, and Elémentarium. Material losses within the production and manufacturing processes are included in the other uses.

Table 5: Silicon metal applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector for 2018 (*for 2014) (Eurostat, 2021).

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Chemical applications	C20 - Manufacture of chemicals and chemical products	117,093*	C2016 - Manufacture of plastics in primary forms; C2017 - Manufacture of synthetic rubber in primary forms; C2030 - Manufacture of paints, varnishes and similar coatings, printing ink and mastics; C2041 - Manufacture of soap and detergents, cleaning and polishing preparations
Aluminium alloys	C24 - Manufacture of basic metals	71,391	C2442 - Aluminium production
Solar applications	C26 - Manufacture of computer, electronic and optical products	84,021*	C2611 - Manufacture of electronic components
Electronic applications	C26 - Manufacture of computer, electronic and optical products	84,021*	C2611 - Manufacture of electronic components

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The main uses of silicon metal are in the aluminium and chemical industries (BRGM, 2021), as shown in Figure 11. In addition, silicon metal is a strategic raw material used in the renewable energy (photovoltaic industry), in electronic devices, and to a smaller extend in batteries.

The required purity of silicon differs significantly for these uses. While a low purity of close to 99 % is sufficient for the aluminium industry, the silicon semiconductor production for photovoltaics and electronics requires an enormous purity of at least 99.9999999 % (BRGM, 2020).

This chapter includes only the silicon metal applications, with (for example) ferrosilicon or silicomanganese excluded. To the best of our knowledge, there is no data on the European end use distribution of silicon.

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 5 and visualised in Figure 12.

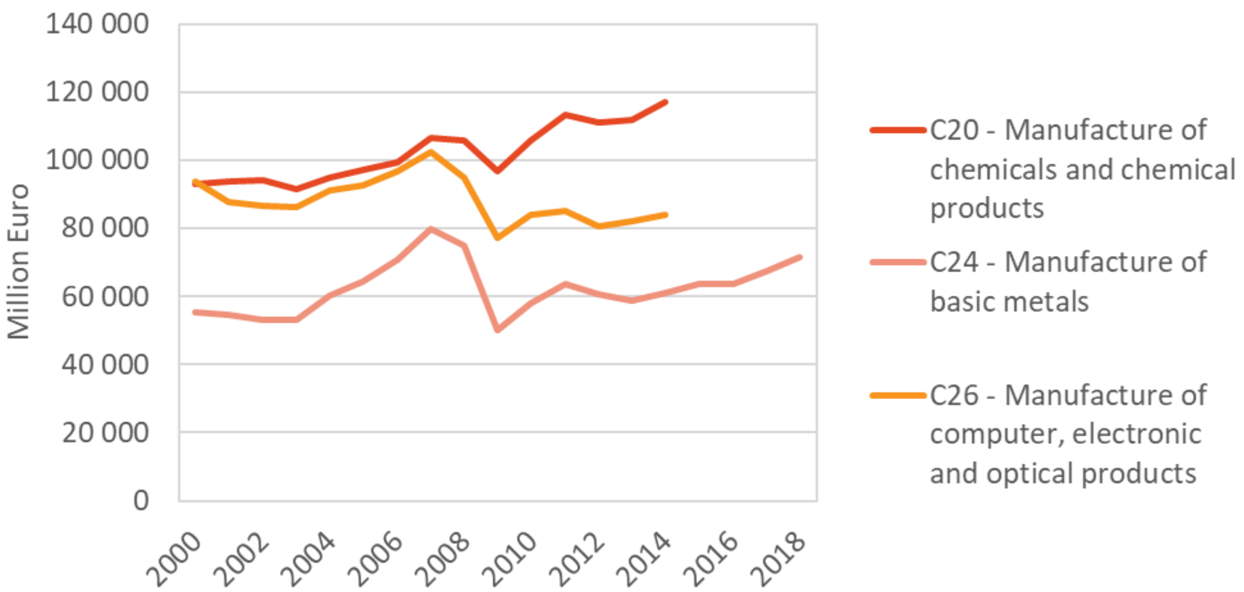

Figure 12. Value added per 2-digit NACE sector over time (Eurostat, 2021).

APPLICATIONS OF SILICON METAL

CHEMICAL INDUSTRY

Silicon metal is used to produce silicones, synthetic silica and silanes.

Silicone products such as surfactants, lubricant, sealants and adhesives are used in various sectors including construction (e.g., in insulating rubbers), industrial processes (e.g. as an antifoam agent in the oil and gas industry), and in personal care (e.g. cosmetics) and transport (CES, 2016).

Silanes are used in the glass, ceramic, foundry and painting industries (European Commission, 2014; Euroalliages, 2016).

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ALUMINIUM ALLOYS

Silicon is dissolved in molten aluminium to improve the viscosity of the liquid aluminium and to improve the mechanical properties of aluminium alloys.

There are two important groups of aluminium alloys which contain silicon as a main element: casting alloys and wrought alloys. In the former the silicon content is 7% to 12%. Wrought alloys contain magnesium and silicon, where the silicon content is between 0.5% and 1%. The primary use is in castings in the automotive industry due to improved casting characteristics described above and the reduced weight of the components (European Commission, 2014; Euroalliages, 2016).

SOLAR CELLS

Ultrahigh-purity grade silicon is used for the production of solar panels. Silicon solar cells are the most common cells used in commercially available solar panels. Crystalline silicon PV cells have laboratory energy conversion efficiencies as high as 25% for single-crystal cells and 20.4% for multicrystalline cells. However, industrially produced solar modules currently achieve efficiencies ranging from 18%–24%.

Solar cell prices dropped significantly in 2011, partly due to polysilicon selling price decrease resulting from over production (European Commission, 2014; Euroalliages, 2016).

ELECTRONICS

Ultra-high purity grade silicon is used extensively in electronic devices such as silicon semiconductors, transistors, printed circuit boards and integrated circuits. Semiconductor-grade silicon metal used in making computer chips is crucial to modern technology (European Commission, 2014; Euroalliages, 2016).

BATTERIES

Currently, only less than 1 kt of silicon metal is used for the graphite anodes of lithium-ion-batteries. This amount and its share on the overall silicon metal demand is expected to increase significantly within the next decade (BRGM, 2021).

OTHER APPLICATIONS

Other applications of silicon metal include explosives, refractories and ceramics.

SUBSTITUTION

Substitutes have been identified for the applications of silicon metal.

There are no materials that can replace any of the main uses of metallurgical silicon without serious loss of end performance or increase of cost.

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Table 6: Substitution options for silicon metal by application (SCRREEN Validation Workshop, 2022; EC Data 2023 files). USGS 2022.

Application	%*	Substitute(s)	SubShare	Cost	Performance
Chemical applications	54%	Thermoplastic (PVC, TPE)	5%	Similar or lower costs	Reduced
		Rubber	5%	Similar or lower costs	Reduced
Aluminium alloys	38%	Silver	0%	Very high costs (more than 2 times)	Reduced
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		Indium arsenide (InAs)	1%	Similar or lower costs	Reduced
		Indium antimonide (InSb)	1%	Similar or lower costs	Reduced

CHEMICAL APPLICATIONS

- In chemical applications, there are no materials for replacement of silicon in silicones and silanes, or in end-use products based on these chemicals. In comparison, materials such as thermoplastics or rubber are not as durable and heat resistant as silicones. Therefore, the use of silicones vs. substitutes depends on the expected properties of the final product; this characteristic is already accounted for when selecting the most appropriate material. No viable substitute is currently considered (CES, 2016).

ALUMINIUM ALLOYS

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- In manufacturing of aluminium, silicon is used to lower the melting point in aluminium manufacturing and to increase strength, machineability and corrosion resistance in aluminium products. There is no substitute to silicon metal for this application (Tercero, 2018).
- Aluminum, silicon carbide, and silicomanganese can be substituted for ferrosilicon in some applications (USGS 2022).

SOLAR APPLICATIONS

- In solar applications, replacement technologies to silicon-based technology for solar applications exist, albeit with reduced performance.
- An example is CIGS (copper indium gallium selenide**)** technology, which is up to twice more expensive than silicon-based technology. It is estimated that Si technology represent 92% of the EU market; the rest is shared between CdTe (cadmium telluride) and CIGS technologies.

ELECTRONIC APPLICATIONS

- In the micro-electronics industry, gallium arsenide (GaAs) is a possible substitute for silicon, but with lower performance and is not used for mainstream applications.
- Germanium may be used as well in combination to silicon (i.e. silicon remains as physical support/monocrystalline, Ge on the top of layer).

SUPPLY

EU SUPPLY CHAIN

The EU supply chain of silicon metal can be described by the following key points:

Quartz mines and resources in the EU were reported by Lauri, L. et. al, (2018). However, it is not clear if any of these has high-purity quartz necessary for silicon metal production. High purity quartz is extracted in three EU Member States and processed into silicon metal – namely France, Spain and Germany. There is no precise data on high purity quartz extraction, at EU level or at global level. The majority of high purity quartz is directly turned into silicon metal onsite (Bio Intelligence Service, 2015).

The 5-year average EU production of silicon metal between 2016 and 2020 was 167 kt per year, which accounts for about 5% of the global production. Producing EU countries are France, Spain and Germany (USGS, 2022).

The traded quantities of silicon metal show that the EU is a net importer of silicon metal. Domestic production of silicon cannot satisfy the EU demand. Norway is the main country supplying silicon metal to the EU due to its geographical proximity, and accounts for about 45% of total imports over the year 2026-2020 (Eurostat, 2022).

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Europe imports silicon in the forms of silicon metal as well as intermediate products such as silicon-based chemicals and silicon wafers.

The import reliance for silicon metal in the EU is estimated at 63%, which is not an unexpected figure considering the relatively small EU production, high import and low exports figures.

An end-of-life recycling plant for PV waste exists in France. In 2017, Rousset in Bouches-du-Rhône, Veolia, PV CYCLE and the Syndicat des Énergies Renouvelables opened the first line in France and in Europe dedicated to recycling end-of-life photovoltaic panels. The plant was planned to process 1,800 tonnes of material in 2017 pear year that will gradually increase to 4,000 tonnes by 2021 (Veolia, 2018).

The flows of silicon metal through the EU economy are demonstrated in Figure 13.

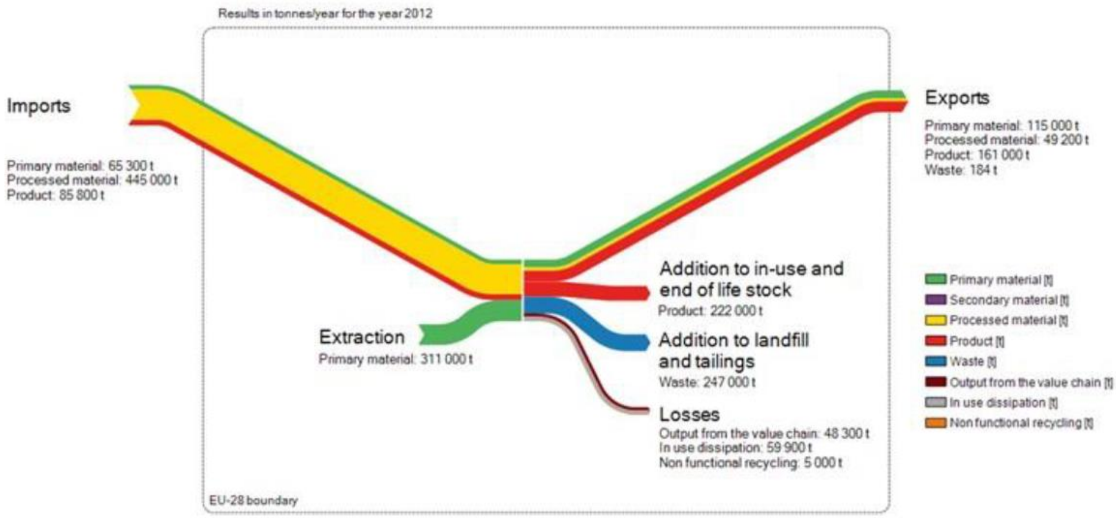

Figure 13: Material system analysis of silicon metal, reference year 2012 (simplified for EU-27 and the UK)(BioIntelligence Service, 2015)

In 2019, BRGM published a MSA of silicon metal, at the global level (Boubault, 2019) ()

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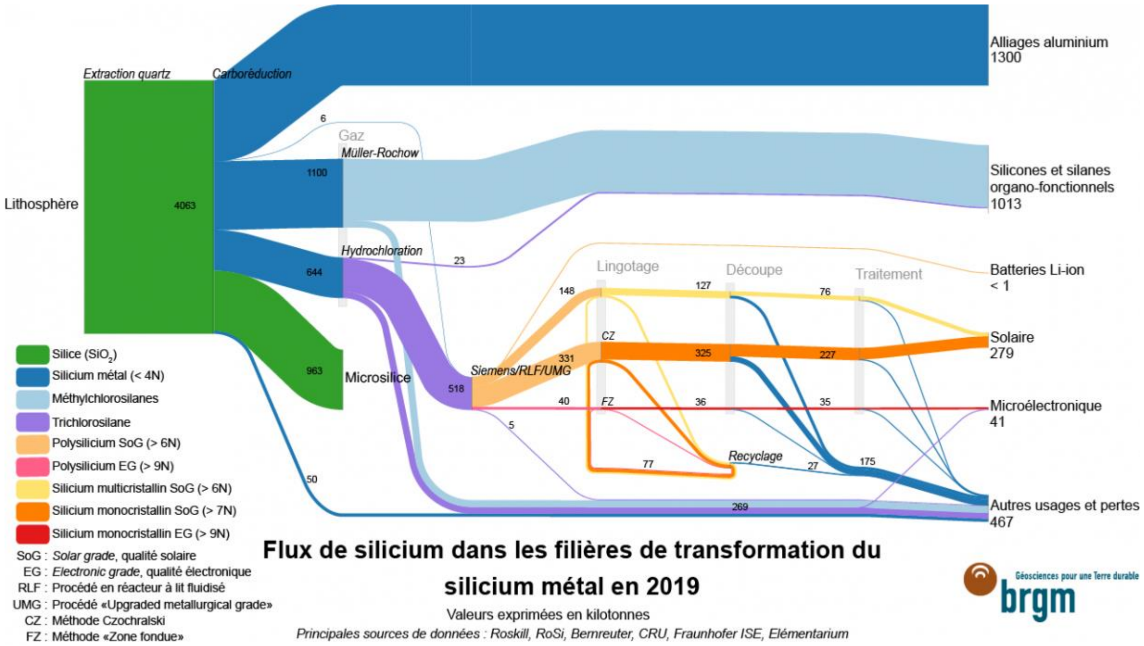

Figure 14. MSA of silicon metal at teh global level (Boubault, 2019)

SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF SILICON METAL

GEOLOGICAL OCCURRENCE:

Quartz makes up approximately 12% by weight of the lithosphere, making it the second most common mineral in the Earth's crust. SiO2 accounts for 66.62% of the mass of the upper crust (Rudnick, 2003). Quartz is found in magmatic, metamorphic and sedimentary rocks and may be distinguished between numerous quartz types, depending on its genesis and specific properties.

Quartz occurs in many different settings throughout the geological record; however, only very few deposits are suitable in volume, quality and amenability to tailored refining methods for speciality high purity applications, which require extreme qualities, with specific low-ppm or sub-ppm requirements for maximum concentrations of certain trace metals (European Commission, 2014).

Magmatic SiO2 rocks represent more than 90% of quartz and other SiO2 minerals of the lithosphere, however this share is not representative of the materials used to process silicon metal. The majority of quartz in SiO2-rich igneous and volcanic rocks (granite, rhyolite) is intergrown with other rock-forming silicates. Therefore, quartz from these rocks does not play an important role as raw material. In contrast, pegmatite bodies and hydrothermal veins Quartz makes up approximately 12% by weight of the lithosphere, making it the second most common mineral in the Earth's crust. SiO2 accounts for 66.62% of the mass of the upper crust (Rudnick, 2003). Quartz is found in magmatic, metamorphic and sedimentary rocks – and may be distinguished between numerous quartz types, depending on its genesis and specific properties.

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Quartz from metamorphic rocks represents only about 3% of the whole quartz in the lithosphere (Rösler, 1981) and are not usable as high-quality SiO2 raw material. However, metamorphic quartzites of high chemical purity (98% SiO2) can sometimes be used as raw materials for high-technology industries. Moreover, metamorphogenic quartz mobilisates often represent a high-purity SiO2 material that can be used e.g. as raw material for single-crystal growth (Haus, 2012).

Finally, sedimentary SiO2 rocks represent the majority of the high-purity quartz volumes supplied to the industry worldwide. However, quartz in sedimentary rocks (mostly under the form of quartz sands, quartz gravel or sedimentary quartzite) is used in silica sands or ferrosilicon value chains, but its purity does not rank high enough for any use as silicon metal (Haus, 2012).

GLOBAL RESOURCES AND RESERVES OF HIGH PURITY QUARTS[6][261]:

Information on high purity quartz from the Minerals4EU platform (2014) is available in the silica sands factsheet, but is not displayed here as only a small – and unknown – share or it is part of the silicon metal value chain.

It is acknowledged that reserves of high purity quartz are large enough to meet the worldwide consumption needs for the next decades.

EU RESOURCES AND RESERVES[7][262]:

In the EU, a number of quartz mines and resources have been reported. However, it is not clear if any of these has high-purity quartz necessary for silicon metal production. In Austria, Bulgaria, Greece, and Italy, some deposits were identified with no information on their resource. In Austria and Portugal, there were some

[6] 261 There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of silicon metal in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template. which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

[7] 262 For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for silicon metal. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for silicon metal, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for silicon metal the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU 2019).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However, a very solid estimation can be done by experts.

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deposits and production of quartz in the past. In Finland, there are two active quartz mines with a production quantity of 93 kt of quartz in 2016, some of which may be categorised to medium to high-purity quartz. There are 52 quartz deposits in Sweden, including three active mines producing 100 kt of quartz per year used in the ferro-alloy industry.

There are also known unexploited occurrences in Sweden, containing medium to high quality quartz (Lauri, L. et. al., 2018).

The H2020 GREENPEG project is aimed at overcoming the lack of exploration for pegmatite ore deposits by developing new toolsets for the exploration of small volume, high-quality ores of European pegmatites. These small volume deposits have been calculated by means of new genetic models at 0.01–5 million m3, corresponding to an estimated resource target size of 0.025–12.5 million tonnes (Müller et al., 2022).

MINING OF HIGH PURITY QUARTZ AND PROCESSING OF SILICON METAL

Quartz extraction occurs by drilling and blasting operations from veins deposits (vein quartz) as well as from fluvial deposits (quartz pebbles), by simple excavation methods. The major deposits of high purity quartz currently mined for silicon metal processing are located in Turkey, Egypt and Spain, among others (Euroalliages, 2016). Others include the USA, Norway and Russia. High purity quartz for the silicon metal industry is extracted as main product; most of the quartz processed in the EU into silicon originates from European countries, namely Spain and France (BGS, 2016). There is no reliable worldwide data.

Once mined, quartz is reduced to silicon metal by carbothermic reduction. This takes place in a submerged electric arc furnace containing quartz and carbon materials, such as coke and charcoal. Electric energy is supplied by electrodes submerged in the charge – with temperatures from 800 to 1,300°C at the top of the furnace, and exceeding 2,000°C at the bottom, near the electrodes (Aasly, 2008). Molten silicon metal is produced at the bottom of the furnace. The silicon produced has a purity of approximately 98.5%; the main impurities are iron, aluminium and calcium. Most silicon applications require further refining to reach 99% purity; this is done by treating the molten silica with oxidative gas and slag forming additives. Silicon of this purity is known as metallurgical grade silicon and is used in the aluminium, chemical and polysilicon industries. Semiconductor and solar grade silicon (polysilicon) must be of ultra-high purity (between 6N and 11N) to ensure semiconducting properties; this is commonly done through the Siemens process (European Commission, 2014). In this process, the metallurgical grade silicon is converted to a volatile compound that is condensed and refined by fractional distillation. Ultra-pure silicon is then extracted from this refined product.

The quartz raw material follows specific requirements from the industry to be used in silicon metal processing, among which: chemistry (specifications on impurities), lump size; as well as mechanical and thermal strength, and softening properties. These characteristics may influence the process itself or the purity of the silicon metal processed (Aasly, 2008).

The processing of silicon also generates silica fumes which have been successfully transformed by the silicon (and ferro-silicon) industry from waste to a by-product.

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Main research efforts are focused on the reduction of both the energy and CO2 footprints of refining process. However, there are researchers trying to reduce the consume of raw materials as the SisAl Pilot Project. This project utilizes secondary raw materials such as aluminium (Al) EoL scrap and dross, as replacements for carbon reductants used today in Submerged Arc Furnace (SAF) process (SisAl 2022).

23.4.2.3 WORLD AND EU PRODUCTION OF SILICON METAL

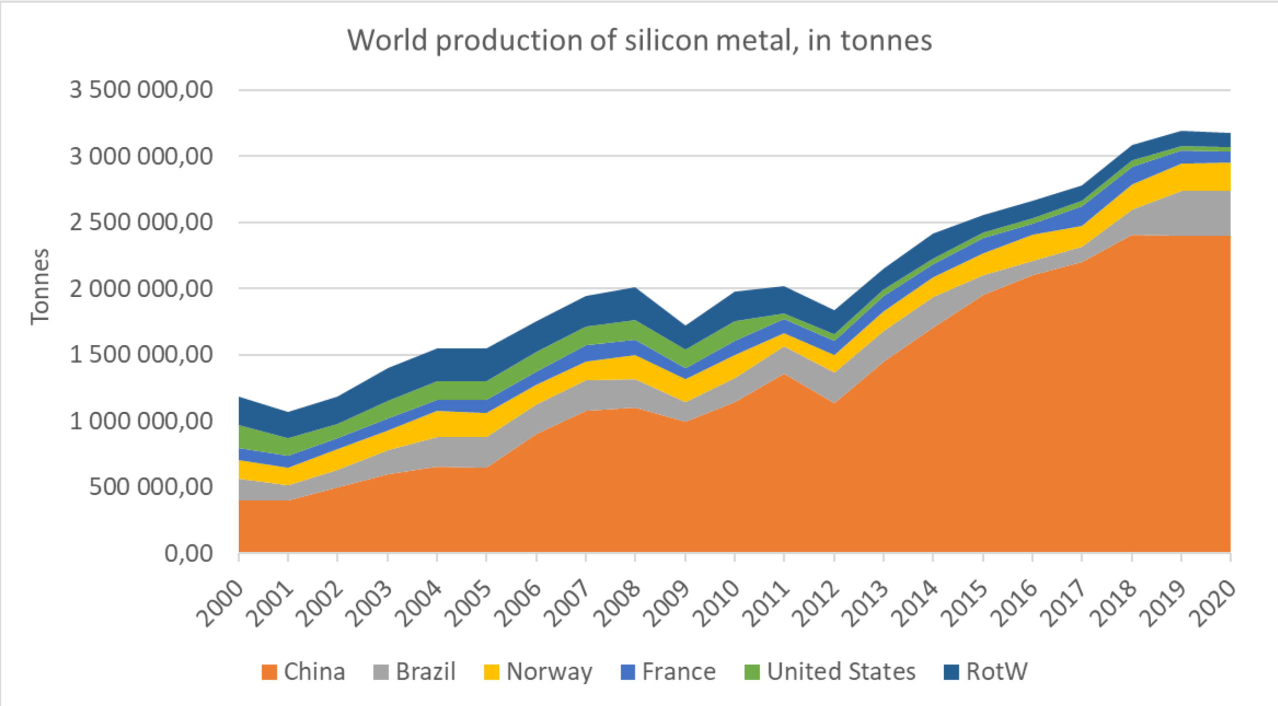

Figure 15 .World production of silicon metal (USGS 2022)

Production share of refined silicon metal by country since 2000 is presented in Figure 15 and the average 2016-2020) is presented in Figure 16. The production in this period reached an average of 3,215 kt per year. Global supply of silicon metal is dominated by China with about 2,224 kt per year equivalent to 72% of the global annual production over the years 2016-2020. Brazil, accounting for 190 kt (6% of global supply), was the second largest producing country, followed by Norway, accounting for 148 kt (5% of global supply).

The overcapacity built in China in the past decades is equivalent to more than twice the world consumption (2,9 million tonnes) in 2019 (Euroalliages, 2020). Chinese production capacity of silicon metal increased from 4 million tonnes in 2014 to 6-7 million tonnes in 2019. This expansion of more than 2 million tonnes is concentrated in the Xinjiang province. This region is able on its own to almost supply the worldwide consumption of silicon. It is important to note that almost 100% of power generation in this region is coal based.

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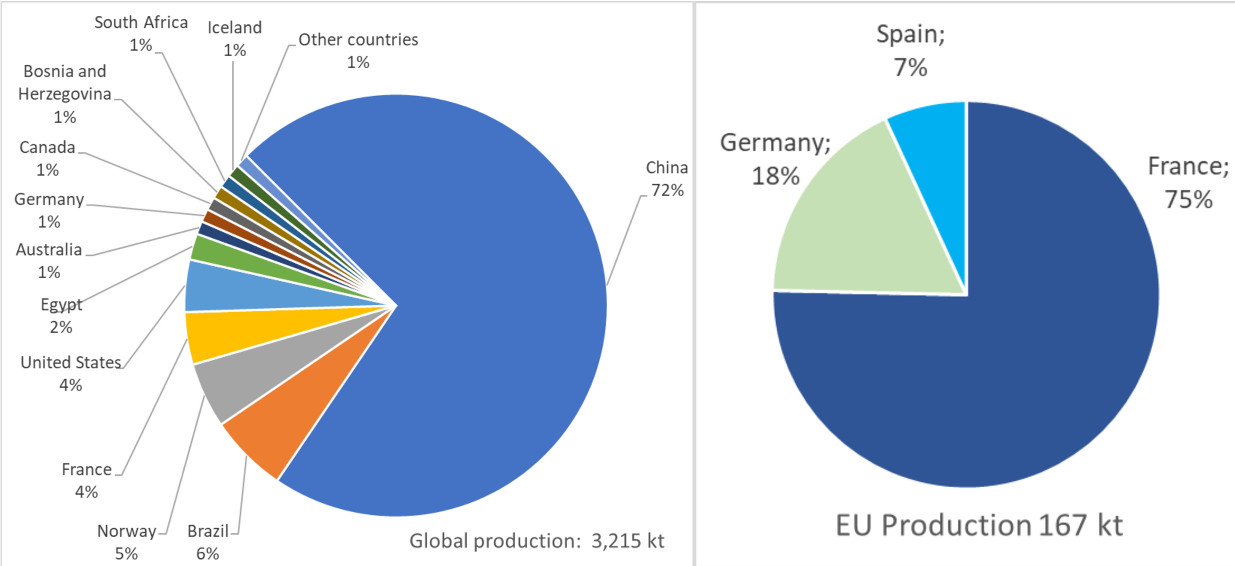

Figure 16: Global (eft) and EU (right) refined production of silicon metal, average 2016-2020 (Data from USGS Minerals Yearbook Silicon 2022)

Over the historical period of 2016 to 2020, the global market for metallurgical grade silicon registered a CAGR of 2.7%. Worldwide demand for MG Si is projected to increase at 4.1% CAGR from 2022 to 2032 (Fact.MR 2022). The increasing production will be supported by robust demand in the sectors of silicones, aluminium and semiconductors (solar and electronics). In addition, other uses such as silicon-rich anodes for Li-ion batteries can also reinforce demand. The main obstacles to an increase in Si metal production are a high energy demand (11-14 kWh/kg Si) and raw materials' cost. (BRGM 2019, Ferroglobe 2022, IEA 2022, Elkem 2022)

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

Most chemical applications of silicon metal are dispersive, thus not allowing for any recovery. In recent years there have been functional recycling plants of Si scrap from wafers and from photovoltaic panels, such as:

- Resitec in Norway that recycles wafers generated in the production of photovoltaic materials (PV). ReSiTec produces more than 500 tons of recycled, high-purity silicon metal powder per year (Moen, et. al., 2017)
- The recycling plant Veolia in France that treats end-of-life solar panel

European companies are trying to improve the recycling of these materials, with examples such as the ICARUS or Reprosolar projects. ICARUS aims to demonstrate modular processing solutions at industrial scale to retrieve 95% of high-value raw materials from silicon ingot and wafer manufacturing (ICARUS 2022). Reprosolar project will demonstrate new technologies to recover silicon, silver, and glass from PV panels, with a nominal annual capacity of 5,000 ton of decommissioned PV modules (EIT RawMaterials, 2021).

Silicon metal used in the electronic industry is of higher quality than for other applications. Most of the silicon scrap generated during crystal ingot and wafer production for electronic applications can therefore be used in the photovoltaic industry (Woditsch and Koch, 2002).

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There is no functional recycling of silicon metal in aluminium alloys.

In the industry buying metallurgical grade silicon, for economic and environmental reasons, recycling streams exist as well as separate or specialised processes for utilisation of any side streams. However, very little material is sold back into the market by metallurgical silicon users (Euroalliages, 2016).

Although there were new functional recycling plants for silicon metal, it has not been possible to quantify the precise updated end of life recycling input rate for silicon metal. The recycling input rate, was estimated to remain low. According to the MSA study of silicon metal, the end of life recycling input rate for silicon metal is 0% (Bio Intelligence Service, 2015).

Table 7. Material flows relevant to the EOF-RIR of silicon metal

MSA Flow	Value (t)
B.1.1 Production of primary material as main product in EU sent to processing in EU	180,719
B.1.2 Production of primary material as by product in EU sent to processing in EU	0
C.1.3 Imports to EU of primary material	65,254
C.1.4 Imports to EU of secondary material	0
D.1.3 Imports to EU of processed material	444,806
E.1.6 Products at end of life in EU collected for treatment	206,619
F.1.1 Exports from EU of manufactured products at end-of-life	183
F.1.2 Imports to EU of manufactured products at end-of-life	0
G.1.1 Production of secondary material from post consumer functional recycling in EU sent to processing in EU	0
G.1.2 Production of secondary material from post consumer functional recycling in EU sent to manufacture in EU	0

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

No specific issues identified.

ENVIRONMENTAL ISSUES

In their LCA study, Heidari and Anctil (2022) calculate that the cradle-to-gate production of metallurgical grade silicon potentially generates from 12 to 16.5 kg CO_2-eq/kg silicon metal, while its Cumulative Energy Demand (CED) ranges from 186 to 286 MJ/kg silicon metal, depending on the producing country/mine and the level of purity of the silica sand used as input to the process.

Through a hotspot assessment considering 18 impacts categories, Zhang et al. (2023) identify that, overall, the environmental impacts of silicon metal are essentially driven by: i) the important energy consumption from the production process; ii) the use of graphite anodes in the process; and iii) the use of coal.

NORMATIVE REQUIREMENTS

During transport, silicon metal must be kept away from moisture (OFZ 2019).

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The EU and the USA restrict the international trade of silicon metal. Europe sets an antidumping import tax on silicon metal coming from China; the USA as well, but their rules are very dynamic and may change from one administration to another. Some taxes are also set in the EU and in the US on photovoltaics components containing crystalline silicon coming from Asian countries (BRGM 2019).

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF THE SILICON METAL FOR EXPORTING COUNTRIES

Table 8 lists the countries for which the economic value of silicon metal product exports represents more than 0.1 % in the total value of their exports.

Table 8: Countries with highest economic shares of silicon metal Exports in their total exports

Country	Export value (USD)	Share in total exports (%)
Bosnia Herzegovina	38,046,197	0.62
Norway	425,540,486	0.53
Iceland	23,110,419	0.51
Brazil	356,691,257	0.17
Croatia	27,990,005	0.16
Malaysia	66,112,241	0.12

Source: COMTRADE (2022), based on data for 2020

Bosnia Herzegovina has the largest share of exports (0.62 %) of silicon metal out of its total exports. For Norway and Iceland, it is around 0.5 % and for rest of exporting countries countries such as Brazil, Croatia and Malaysia this share is close to 0.1 %.

SOCIAL AND ETHICAL ASPECTS

Chinese imports are being heavily dumped in the European Union market. The EU calcium silicon industry is primarily based in France and Slovakia. Ferroalloys such as calcium silicon are crucial in the production of special steels and are therefore a vital component of the steel production chain and the EU's economic independence. This can also affect EU's commitment to fully utilizing trade defence instruments to protect the ferroalloy industry from unfair trade practices that endanger their competitiveness. (EC,2022)

RESEARCH AND DEVELOPMENT TRENDS

The below projects are a small selection of a very large number of recent research papers and projects related to silicon (metal) in semiconductors, photovoltaics and other applications. More information is available on the Internet.[8]

[8] See for example on Sciencegate (https://www.sciencegate.app/keyword/3138535 and https://www.sciencegate.app/keyword/776214), and on the EU CORDIS database (https://cordis.europa.eu/search?q=startDate%3D2016-01-01-2049-12-01%20AND%20(%27silicon%27%20AND%20%27metal%27)&p=1&num=10&srt=Relevance:decreasing).

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- DISC[9] project: Double side contacted cells with innovative carrier-selective contacts (EU, 2016 – 2019)

The DISC project addresses the need to reduce the consumption of fossil fuels by developing key technologies for the next generation of high-performance photovoltaic (PV) solar cells and modules, allowing ultra-low solar electricity costs with minimum environmental impact.

DISC focuses on the only way to fully exploit the potential of silicon to its maximum: through the use of carrier selective junctions, i.e. contacts which allow charge carriers to be extracted without recombination. Such contacts allow for simple device architecture as considered in DISC - non-patterned double-side contacted cells – which can be fabricated within a lean process flow, either by upgrading existing or within future production lines. In DISC, a unique consortium of experienced industrial actors will collaborate with a set of institutes with demonstrated record devices and worldwide exceptional experience in the R&D field of carrier selective contacts. DISC will target efficiencies >25.5 % on large area cell and > 22 % at module level while demonstrating pilot manufacturing readiness at competitive costs.

Together with a reduction of non-abundant material consumption (Ag, In), with an enhancement of the energy yield, with modern module design ensuring outstanding durability, DISC will provide the key elements for achieving in Europe very low Levelized Costs of Electricity between 0.04 – 0.07$/kWh (depending on the irradiation), with mid-term potential for further reduction, making solar one of the cheapest electricity source. The high efficient PV modules developed in DISC are predestined for rooftop installations, i.e. neutral with respect to land use aspects. A life cycle approach applied in DISC prevents the shifting of environmental or social burdens between impact categories.
DISC has a chance to contribute towards mitigating the impacts of climate change, improving energy access and towards bringing Europe back at the forefront of solar cell science, technology and manufacturing

- Research and development priorities for silicon photovoltaic module recycling to support a circular economy (Heath et al. 2020)

Large-scale deployment of photovoltaic (PV) modules has considerably increased in recent decades. Given an estimated lifetime of 30 years, the challenge of how to handle large volumes of end-of-life PV modules is starting to emerge. In this perspective, we assess the global status of practice and knowledge for end-of-life management for crystalline silicon PV modules. We focus in particular on module recycling, a key aspect in the circular economy of photovoltaic panels. We recommend research and development to reduce recycling costs and environmental impacts compared to disposal while maximizing material recovery. We suggest that the recovery of high-value silicon is more advantageous than the recovery of intact silicon wafers. This approach requires the identification of contaminants and the design of purification processes for recovered silicon. The environmental and economic impacts of recycling practices should be explored with techno–economic analyses and life-cycle assessments to optimize solutions and minimize trade-offs. As photovoltaic technology advances rapidly, it is important for the recycling industry to plan adaptable recycling infrastructure.

[9] CORDIS EU research results, https://cordis.europa.eu/project/id/727529

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- Recycling of silicon metal powder from industrial powder waste streams (Moen et al. 2016)

Industries that are cutting and grinding silicon metal, such as the photovoltaic and semi-conductor industry, are depositing valuable metal powder materials. ReSiTec has worked on research projects for several years and developed new technology for recycling and purification of valuable metal powders. The focus has been silicon metal powder from cutting and grinding production. The process has been developed to collect fine particles, with a size range of 0–150 µm, from highly diluted waste water. Furthermore, known separation and classification techniques for metal powder processing have been adapted with the purpose of purifying and upgrading silicon metal powder from waste to new products. The tests performed were successful and the results showed an increase in purity level from 50 % to > 99 % metallic silicon and an acceptable yield. It is believed that this new technology can be suitable for similar types of industrial metal powder waste streams. Today, ReSiTec is supporting the process industry with R&D services and is producing more than 500 tons per year of recycled, high-purity silicon metal powder.

- Preparation of $TiSi_2$ Powders with Enhanced Lithium-Ion Storage via Chemical Oven Self-Propagating High-Temperature Synthesis (Xu et al. 2021)

Although silicon has highest specific capacity as anode for lithium-ion battery (LIB), its large volume change during the charge/discharge process becomes a great inevitable hindrance before commercialization. Metal silicides may be an alternative choice because they have the ability to accommodate the volume change by dispersing Si in the metal matrix as well as very good electrical conductivity. Herein we report on the suitability of lithium-ion uptake in C54 $TiSi_2$ prepared by the “chemical oven” self-propagating high-temperature synthesis from the element reactants, which was known as an inactive metal silicide in lithium-ion storage previously. After being wrapped by graphene, the agglomeration of TiSi2 particles has been efficiently prevented, resulting in an enhanced lithium-ion storage performance when using as an anode for LIB. The as-received $TiSi_2$/RGO hybrid exhibits considerable activities in the reversible lithiation and delithiation process, showing a high reversible capacity of 358 mAh/g at a current density of 50 mA/g. Specially, both $TiSi_2$ and $TiSi_2$/RGO electrodes show a remarkable enhanced electrochemical performance along with the cycle number, indicating the promising potential in lithium-ion storage of this silicide. Ex-situ XRD during charge/discharge process reveals alloying reaction may contribute to the capacity of $TiSi_2$. This work suggests that $TiSi_2$ and other inactive transition metal silicides are potential promising anode materials for Li-ion battery and capacitor.

- Infrared spectrum tailoring based on refractory transition-metal silicides disordered metamaterials (Li et al. 2021)

Broadband and spectrally selective absorbers/emitters are realized based on refractory transition-metal silicides disordered metamaterials, which give a simple way to tailor infrared spectrum. The proposed disordered metamaterials provide a promising and low cost absorber/emitter for thermophotovoltaics and many other applications.

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- Dye-sensitized solar cells as promising candidates for underwater photovoltaic applications (Enaganti et al. 2022)

Harvesting solar energy using photovoltaic (PV) cells is the simplest, efficient, and reliable approach to power marine electronics. Installing PV above or under water provides cooling and cleaning to sustain the power conversion efficiency. Previous work on commercially available silicon-based PV quantified the performance of PV with different submerged environments and showed promising results in harvesting available underwater solar energy. Subsequent, theoretical studies point to enormous potential of using wide-band-gap PV in underwater conditions. With this motivation, herein for the first time, a dye-sensitized solar cells (DSSCs) employing wide-bandgap ruthenium sensitizers (1.8 eV) have been tested under submerged conditions. The DSSCs were characterized under submerged conditions up to 20 cm. Four replicates provided data detailing DSSCs potential for underwater PV applications when compared with the previously collected data for monocrystalline, polycrystalline, and amorphous silicon PV. Although the light intensity under water decreases with an increase in depths, the rate of decrease in power output for DSSCs was only 40.68%, which was less than the traditional monocrystalline and polycrystalline silicon PV by approximately 20–25 %. Also, compared with amorphous silicon PV, DSSCs showed a slightly better performance by 2– 3%, clearly displaying the capability of DSSCs to harvest indirect/diffused lights in comparison with the conventional PVs. Compared with the conventional PVs, indigenously fabricated DSSCs showed tremendous relative increase in performance in underwater conditions. Further work is underway to further optimize DSSCs even though it can be concluded that with added advantages of simple fabrication process and cost-effectiveness, DSSCs have enormous future potential for underwater PV applications.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- UFSD:[10] Ultra-Fast Silicon Detectors: Enabling Discoveries (2016 – 2021, EU)

The goal of the project is to empower a broad range of research fields with a completely new particle detector, able to concurrently deliver time resolutions of the order of ~10 picoseconds and position resolutions of ~30 microns. This will remove the constrains that many applications such as particle tracking, medical PET, mass spectroscopy, and beam monitoring have due to the lack of precise information on all 4 dimensions.

Analysis of state-of-the-art particle detectors show a dichotomy: specialized sensors measure very accurately either time or position, but not both: the ambitious goal of UFSD is to create a new family of detectors, based on controlled charge multiplication in silicon, which will remove this limitation. Significant challenges will be tackled along this research path, but the simulations and prototypes indicate that this approach has the potentiality to radically transform present detectors and to enable many applications to reach their peak performances.

The ultimate goal – a highly segmented detector with a space resolution of ~30 microns and a time resolution of ~10 picoseconds – can be achieved only by developing full custom Very Large Scale Integrated chips that,

[10] C.f. CORDIS, https://cordis.europa.eu/project/id/669529

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matching the size of the read-out to the area of each pixel sensor, will deliver unprecedented timing resolution at the pixel level.

- ICY-LAB[11] project: Isotope CYcling in the LABrador Sea (EU, 2016 – 2021)

The high-latitude regions are experiencing polar temperatures rising twice as fast as the global mean and there are concerns about the impact of sea-ice and glacier retreat on global oceans and climate. The high-latitude North Atlantic is also a key region for ecologically and economically important natural resources such as fisheries. How these resources will change in the future depends strongly on the response of marine biogeochemical cycling of essential nutrients to increasing anthropogenic stress.

Diatoms are photosynthetic algae responsible for nearly half of the export of carbon from the sea surface to the seafloor. They are a sensitive indication of the state of nutrient cycling. Diatoms are one of many organisms that precipitate biogenic opal, an amorphous glass made of silica (hydrated SiO_2), to form protective skeletons, and one of the essential nutrients is therefore dissolved silicon (Si) in the form of silicic acid. The response of the silicon cycle to changing environmental conditions is critical for both carbon and nutrient cycling and it can now be addressed through high precision silicon isotopes, which is the focus of ICY-LAB.

The approach will be to capture the whole silicon cycle system in areas of marked environmental change using careful field sampling strategies coupled with cutting-edge analytical methods. The results will lead to a cross-disciplinary view of nutrient cycling, biomineralisation, and the taxonomy and biogeography of siliceous organisms in an ecologically important region of the North Atlantic.

ICY-LAB develops a new method for looking at modern biogeochemical processes, adding to existing palaeoclimate and biochemical expertise.

- Drain-Engineered Reconfigurable Transistor Exhibiting Complementary Operation (Ehteshamuddin et al. 2021)

A multifunctional transistor is proposed and simluated that exhibits device reconfigurability and realizes both nFET and pFET electrical characteristics when adequately biased. The use of this device will significantly reduce the transistor count in realizing sequential and combinational circuits and will result in highly compact design. The device uses a dual fin structure having a single mid-gap workfunction gate (~4.65 eV) alongside dual metal (metal-silicide) drain regions. It employs n + / p + - i junctions at the source-channel interface along with the Schottky junctions at the channel-drain interface. In practice, metal-silicides such as erbium/ytterbium silicide (ErSi x /YbSi x) for the n -drain and platinum silicide (PtSi) for the p -drain can be used as they provide smallest electron and hole Schottkybarrier heights (SBHs). Simulations carried out using calibrated parameters show better drive current (≈ 10 −2 −10 −3 A/ µ m) compared to the quantum tunnelling current in simulated state-of-the-art multifunctional devices (≈ 10 −4 − 10 −5 A/ µ m). In addition, butterfly curves show symmetric high (NM H) and low (NM L) noise margins of 0.43V and 0.29V for zero and finite SBHs, respectively. The switching characteristics is shown to have an overshoot of ~0.15 V for realistic SBHs which is then eliminated for the

[11] CORDIS EU research results, https://cordis.europa.eu/project/id/678371

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case of zero SBHs. In the last section, it is also demonstrated that a simplified structure having single mid-gap work function (~4.65 eV) drain of Nickel silicide (NiSi) does not hamper the reconfigurability of the device.

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