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The EU's demand for selected critical raw materials used in the photovoltaic industry

Introduction

The European Union's (EU's) strategy aiming at preventing climate change has set ambitious targets in terms of energy from renewable sources. The first European Renewable Energy Directive, adopted as part of the EU climate and energy package, set an obligatory target of a 20% share of renewable energy in the total gross energy consumption in the EU by 2020 (Directive 2009/28/EC). The second directive, which entered into force in December 2018 as part of the packages for clean energy for all Europeans increased this limit to at least 32% by 2030 (Directive 2018/2001EC). The diversification of the energy sources towards those that are renewable is one of the leading tools of the EU's effective energy

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transformation (Musiał et al. 2021; Kochanek 2021; Liobikiene and Butkus 2017). The common goal of all the Member States is a reduction in the emission of greenhouse gases and achieving climate neutrality by 2050 to fulfil the commitment under the international Paris Agreement. In order to support these efforts, the EC launched the European Green Deal strategy (COM/2019/640) in December 2019 and in July 2021, the Fit for 55 (COM/2021/550) legislative package. The last of these documents highlighted the need to further increase the share of renewable energy sources in the overall energy mix to at least 40% in perspectives of 2030. Currently, the future policy framework is under discussion.

Among renewable energy sources, wind and solar power are expected to lead in the transformation of the electricity sector (EC 2020a). However, the development of these technologies is determined by the undisturbed supplies of the many required raw materials. Solar photovoltaic (PV) technology, which is investigated in this paper, is the cheapest form of electricity generation and one of nine technologies used in strategies for the EU sectors (besides renewable energy sector also e-mobility, defense and aerospace sectors; EC 2020a). Photovoltaic panel and module production requires over a dozen metals, such as: aluminum, copper, iron, lead, nickel, zinc, silver, cadmium, molybdenum, selenium, tin and tellurium (EC 2020a; Carrara et al. 2020). Furthermore, it generates demand for metals of high risk of supplies, identified as critical. These are silicon metal, gallium, germanium, indium, boron and phosphorus.

The purpose of this paper is to evaluate the EU's current demand for selected critical raw materials that are crucial for the development of photovoltaic technology with the indication of the most important consuming countries or net-importers in the EU. Taking into account the leading applications of analyzed raw materials and forecasted intensive growth in the solar-energy sector, major factors that may potentially influence future demand for these raw materials have been identified. Additionally, the major trends in the development of PV technology linked with the potential development of the demand for individual CRM has been traced. The paper is a part of a comprehensive study, including the analyses of demand in the first step and in the second step, analyses of the potential sources of supplies for the major critical raw materials suitable for the EU's solar photovoltaic industry. Part two of these works is planned to be published as separate paper.

1. Methodology

The analyses have been conducted for the raw materials included in the 2020 EU Critical Raw Material List (EC 2020b). This list contains thirty materials, namely: antimony, barite, beryllium, bismuth, borate, cobalt, coking coal, fluorspar, gallium, germanium, hafnium, rare earth elements (light and heavy), indium, magnesium, natural graphite, natural rubber, niobium, platinum group metals, phosphate rock, phosphorus, scandium, silicon metal, tantalum, tungsten, vanadium, bauxite, lithium, titanium, and strontium. Out of twenty-nine raw materials in this list (natural rubber is not included as it is not a mineral), six raw materials have been utilized in various quantities in photovoltaic technology. The list of these raw materials and their applications in solar energy systems are presented in Table 1. It includes silicon metal, gallium, germanium, indium, boron and phosphorus. However, boron and phosphorus have been added to silicon solar cells in very little amounts (admixture to the silicon), and both of them have been excluded from detailed analyses in the paper. Additionally, it is possible that in the near future, gallium doping instead of boron will become more popular in the production of solar cells (Wright et al. 2021).

The identification of specific applications of CRMs in photovoltaic technologies was the initial stage of work. Additionally, the current state of the art and the prospects for the development of energy production from solar sources were outlined. This has been described on the basis of scientific publications, data from the International Renewable Energy Agency (IRENA) as well as reports of various institutions.

The analyses of the EU's demand for selected CRMs concerned the period 2010–2020 and were based on statistics on trade reported by Eurostat. In the period 2010–2019, the analyses were carried out for twenty-eight EU Member States while in 2020, for twenty-seven of them, excluding the UK, which is no longer in the EU structures. Data on the EU's raw materials production have been compiled from statistics published by various institutions and geological surveys, including the British Geological Survey (subsequent editions of World Mineral Production with data up to 2019), the United States Geological Survey (Minerals Yearbook and Mineral Commodity Summaries with data up to 2020), and the Federal Ministry of Agriculture, Regions and Tourism of the Republic of Austria (World Mining Data with data up to 2019). In some cases, data in PRODCOM Eurostat has also been available, although up to 2018, they were mostly aggregated and reported together for beryllium, chromium, germanium, vanadium, gallium, hafnium, indium, niobium, rhenium and thallium or for total silicon (for grades containing <99.99% Si and ≥99.99% Si). The apparent consumption volume has been calculated as production volume + imports volume from outside-EU countries – exports to outside-EU countries. An important part of this stage of work was searching databases and afterwards data selection and verification based on research papers and information from institutions specializing in the studied issues. The volume of apparent consumption of analysed CRMs was also estimated in the EC report (EC 2020c); however, an average volume for the period 2012–2016 was exclusively presented and this data does not refer to any specific grades. The apparent consumption volume or net-imports volume for the individual Member States has been calculated, including data on total import and total export volume.

The EU's countries are small scale producers of selected CRMs in comparison to other global suppliers and some statistics are difficult to obtain. Among the analyzed raw materials, indium, gallium and germanium are obtained as a by-product of the processing of other metals. It causes statistics for these metals to be often incomplete and does not include all producers. Therefore, the production volume and list of countries that are included were verified on the basis of available elaborations and reports of scientific publications whenever it was possible (e.g. EC 2020c).

As crystalline silicon technologies dominate in the production of solar panels, silicon metal is the major component of individual solar cells required to convert sunlight into power. In order to use it for the production of photovoltaics cells, metallurgical grade silicon requires purification to obtain solar grade silicon (of purity of 99.9999%; Xakalashe and Tangstad 2011). High-purity silicon constitutes only a small part of the total silicon metal production and trade; however, the data on this metal grade has been reported separately.

The structure of the consumption of the analyzed raw materials with reference to their major end uses has been adopted from EC 2021 report (based on SCRREEN 2019a). The forecast on the future demand on CRMs in the photovoltaic energy sector prepared by various institutions and presented in, for example, EIT Raw Materials report (Carrara et al. 2020) as well as the SCRREEN project report (SCRREEN 2019b) has been compared. This data has been critically assessed taking into account the major trends in PV-panel-production technologies.

Table 1. The use of selected CRMs in solar PV technologies

Tabela 1. Wykorzystanie wybranych surowców krytycznych w technologiach fotowoltaicznych

Material	Solar PV applications
Silicon (Si)	c-Si wafer solar PV cells, a-Si thin-film solar PV cells, a-SiGe, and a-SiC thin-film solar PV cells
Gallium (Ga)	GaAs wafer solar PV technologies, and copper indium gallium diselenide (CIGS) in thin-film solar PV cells,
Germanium (Ge)	in amorphous silicon germanium (a-SiGe) alloys in thin-film solar PV cells
Indium (In)	copper indium gallium diselenide (CIGS) in thin-film solar PV cells, indium-tin oxide (ITO) for transparent conductive oxide (TCO) layer in thin-film technology
Boron (B)	boron doped (p-type) Si wafer silicon (c-Si) solar PV panels
Phosphorus (P)	phosphorus doped (n-type) Si wafer silicon (c-Si) solar PV panels

Sources: Carrara et al. 2020; Jean et al. 2015; Moss et al. 2011; Stryczewska ed. 2012; Nassar et al. 2016.

2. Results

2.1. The use of selected critical raw materials in PV technologies

There are two main types of photovoltaic cells: wafer-based and thin-film solar PV cells. A typical photovoltaic cell is a semiconductor wafer made of crystalline silicon (c-Si), either single-crystalline or multi-crystalline silicon, in which a potential barrier has been formed, for example, in the form of a p-n junction, by introducing atoms that are electron donors (e.g. phosphorus in n-type) into its structure or electron acceptors (e.g. boron in p-type). The thickness of the wafers ranges from 200–400 micrometers (Stryczewska ed. 2012). Phosphorus or boron is introduced into the wafer by diffusion most commonly using BBr_3 or $POCl_3$ compounds to form a p-n junction to produce a photovoltage, and current is conducted to the outer loop through an Ag, Al, or Cu electrode (Gallagher et al. 1986; Recart et al. 2007). The amount of boron consumed in this process ranges, depending on the degree of doping, from 1 boron atom per 1 billion silicon atoms (low degree – lightly-doped) to a ratio of 1 boron atom per 10 million atoms (high degree), which in terms of atomic weight, gives a boron content in the PV cell of a maximum of 0.385 ppb (0.000000385%) (Drózd 2006; Electronics Tutorials 2022). The optimal recommended boron doping concentration is obtained in the range of $1 \cdot 10^{19}$–$1 \cdot 10^{20}$ atoms/cm^3 i.e. $1.8 \cdot 10^{-4}$g/cm^3 to $1.8 \cdot 10^{-3}$ g/cm^3 (Kim and Kim 2013). With such a negligible boron content in silicon wafers used in PV panels, boron as a critical raw material used in PV was ignored in further analysis. Similarly, phosphorus was also not analyzed for consumption volume for photovoltaic applications due to fewer n-type cells in the silicon photovoltaic market.

P-type cells, which contain boron in their composition, have the largest share of the PV market in forty years. Currently, these types of cells account for 85% of all silicon solar cells manufactured (Kim and Kim 2013; Mihailetchi et al. 2008). It is worth mentioning that these cells significantly degrade during the first few hours of operation at ambient temperatures, and the process that occurs is commonly referred to as LID (light-induced degradation) (Vaqueiro-Contreras et al. 2019; Aleo-Solar 2022). Light-induced degradation does not occur if the acceptor is gallium instead of boron. However, for the past twenty years, the process of doping silicon with gallium was covered by a patent that finally expired in May 2020. Since then, the industry has been rapidly switching from boron to gallium to make p-type silicon cells. As early as the beginning of 2021, one of the leading manufacturers of solar-energy systems, Korea's Hanwha Q Cells, estimated that about 80% of all solar panels produced in 2021 will use gallium doping instead of boron (Wright et al. 2021).

In the group of wafer cells, in addition to commonly used silicon cells, there are also cells made of gallium arsenide (GaAs). These cells have the highest solar conversion efficiency (up to 30%), but they are the most expensive and are therefore used primarily in space technologies (Stryczewska ed. 2012).

Thin-film cells consist of thin layers with a thickness of 1 to 4 micrometers deposited on substrates such as glass, polymer or metal, which can significantly reduce the total cost of photovoltaic cell production (Klugman-Radziemska 2014). The most advanced thin-film cells are made of amorphous silicon (a-Si) and its alloys with germanium or carbon (a-SiGe – amorphous silicon-germanium alloys (a-SiGe), a-SiC – amorphous silicon-carbon alloy). Other materials used to make thin-film cells are cadmium telluride (CdTe) and CIS copper indium diselenide ($CuInSe_2$) or CIGS copper indium gallium diselenide ($CuInGaSe_2$). CIGS technology is preferred for specific ground-based applications in which flexibility is required (Butcher and Brown 2014; EC 2020b; Jean et al. 2015; Klugman-Radziemska 2014).

Crystalline silicon (c-Si) cells account for 94.5% of the current global cell market, while thin-film technologies account for 4.6% of the current market share (with CdTe accounting for 2.4%, CIGS 1.9%, and a-Si 0.3%). Within c-Si cells, 69.4% are monocrystalline cells, while 30.6% are polycrystalline technologies (Carrara et al. 2020; Photovoltaics Report 2022).

In the case of thin-film solar cells, where the manufacturing technology is still relatively new and most of the manufacturing processes are subject to trade secrets, especially in the case of CdTe and CIGS cells, it is difficult to determine the exact composition and quantities of materials used in their production. By contrast, it is worth noting that parallel to the expansion of solar development, there has been a downward trend in silicon consumption in c-Si panels in recent decades due to a reduction in absorber-layer thickness from about 200 μm to 500 nm by 2020 (Zuser and Rechberger 2011), resulting in a reduction of silicon consumption from 16 g/W in 2004 to less than 4 g/W (i.e., tonnes/MW) in 2018 and about 3 g/W (i.e., tonnes/MW) in 2020. This trend is likely to continue in the future, as silicon consumption is expected to drop to 2.1–3 g/W in 2028 and absorber-layer thickness may decrease to 100 nm in 2040 (Carrara et al. 2020; Photovoltaics Report 2022).

Thin-film technologies also each use a transparent conductive oxide (TCO) layer, which can consist of indium tin oxide (ITO), potentially requiring an additional 44.29 kg indium per MW for CIGS, 5.32 kg In/MW for a-Si, and 15.9 kg In/MW for CdTe (Nassar et al. 2016). However, since there is a real possibility of substitution of the indium-containing ITO layer by tin oxide (SnO_2), zinc oxide (ZnO), and aluminum-doped zinc oxide (AZO), it is difficult to estimate the future material requirements of indium demand for this PV technology application (Nassar et al. 2016).

2.2. Current state and prospects for the development of energy production from solar sources

According to the International Renewable Energy Agency (IRENA), the total generation capacity for renewable electricity reached more than 609 GW in Europe in 2020, of which more than 87% (528.5 GW) came from European Union countries. The wind, solar and hydro energy sectors accounted for the largest share in the EU countries (Figure 1a). Solar-power systems accounted for about 153 GW, or about 29% of the total capacity (Figure 1a). At the same time, this represents nearly 21% of the world's total solar-generation capacity (Figure 2). The sector has seen very rapid growth in new capacity over the past decade. In EU countries, they increased from 30 GW in 2010 to 153 GW in 2020, and globally from 39 GW to 714 GW, respectively (Figure 2). The greatest growth in PV technology has taken place in China (increase in installed capacity from 0.8 GW in 2010 to 254 GW in 2020), Japan (increase from 3.6 GW in 2010 to 67 GW in 2020) and South Korea (increase from 0.6 GW in 2010 to 15 GW in 2020). Of the new renewable energy systems launched in European Union countries in 2020 with a total capacity of about 30.6 GW, more than 61% were photovoltaic

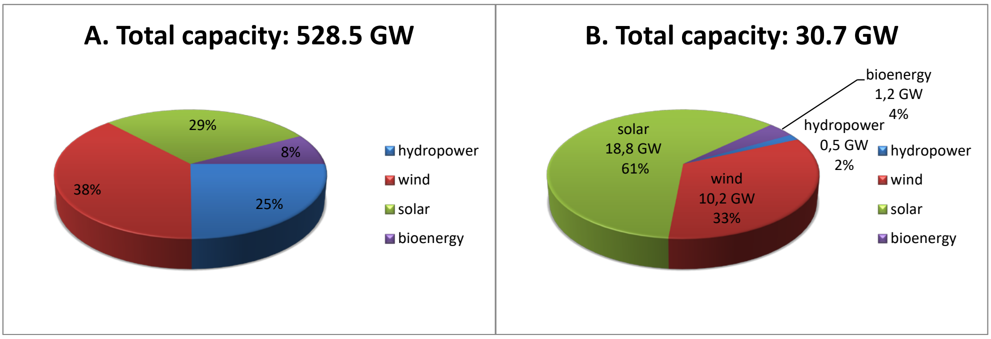


Fig. 1. A, B. The share of total renewable energy capacity (1A) and new installed capacity (1B) in the EU in 2020 (acc. to IRENA 2021)

Rys. 1. A, B. Struktura rodzajowa odnawialnych źródeł energii w krajach UE stan na koniec 2020 r. (1A) całkowite zdolności wytwórcze, (1B) nowo zainstalowane zdolności wytwórcze w 2020 r.

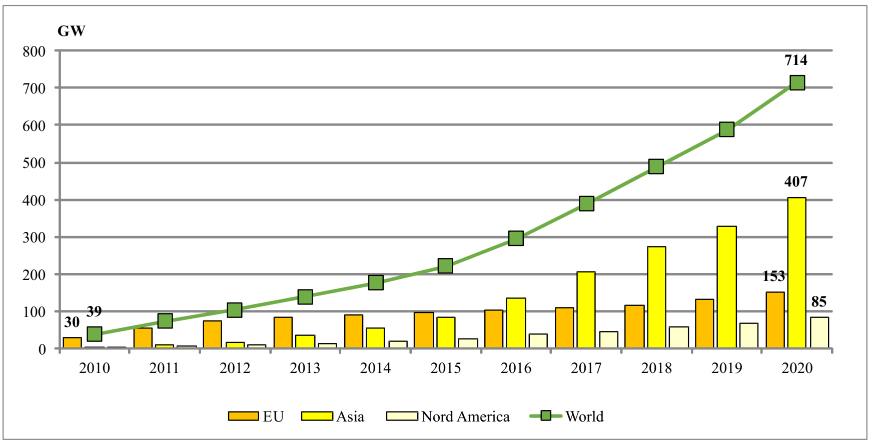


Fig. 2. PV solar cumulative energy capacity in EU and worldwide (acc. to IRENA 2021)

Rys. 2. Skumulowane zdolności wytwórcze energii ze źródeł fotowoltaicznych w krajach UE i na świecie

systems (Figure 1b). The four countries with the largest new production capacity are Germany (4.7 GW), Spain (2.8 GW), the Netherlands (3 GW) and Poland (2.4 GW) (Solar Power Europe 2020; IRENA 2021; IEO 2021).

According to the Solar Power Europe Report (2020), the share of energy from new PV systems in the total volume of energy derived from renewable sources is expected to further increase by 2024. The annual growth rate is projected to vary from 23% in 2021 to 13% in 2024, with a total of 35.1 GW of additional generating capacity expected over the entire period (Solar Power Europe 2020). The largest increase in capacity from new planned PV systems in the 2024 horizon is expected mainly in Germany (+26.9 GW), Spain (+15.8 GW),

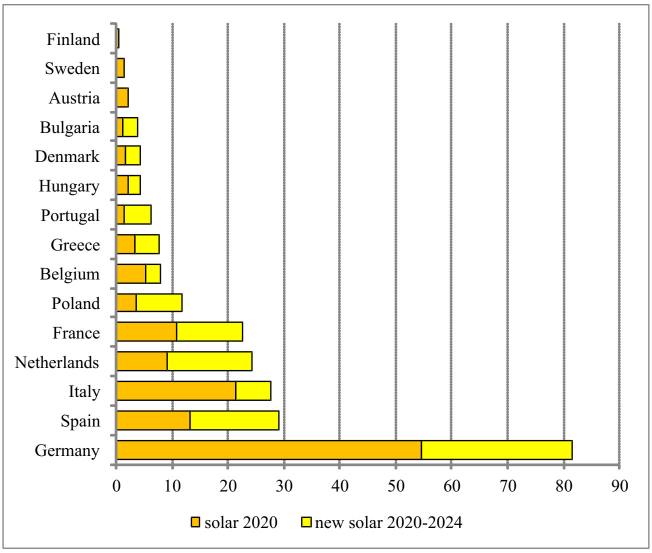


Fig. 3. Cumulative and perspective values for new solar energy capacity installations in the top EU countries (up to 2024 in medium scenario; prepared based on EU Market Outlook For Solar Power 2020–2024; Solar Power Europe 2020)

Rys. 3. Zdolności wytwórcze energii ze źródeł fotowoltaicznych w czołowych krajach UE – całkowite wg stanu na koniec 2020 r. i perspektywiczne do roku 2024 (wg scenariusza średniego tempa rozwoju do 2024 r. opracowane na podstawie EU Market Outlook For Solar Power 2020–2024; Solar Power Europe 2020)

the Netherlands (+15 GW), France (+11.8 GW) and Poland (+8.3 GW, Figure 3; Solar Power Europe 2020).

2.3. Assessment of the volume of demand for selected critical raw materials in the EU

2.3.1. Silicon

The volume of the silicon-metal consumption in the UE for the grade suitable for the photovoltaic cell production (with at least 99.99% silicon content) was not possible to calculate for the all analyzed period. This is due to the limited availability of data on silicon production for its two specific grades (metallurgical– with SiO_2 content by weight <99.99% and polysilicon – with SiO_2 content by weight not less than 99.99%). For the year 2019 and 2020, the volume of the apparent consumption of the polysilicon (used e.g. in photovoltaics systems) has been calculated on the basis of the Eurostat data on extra-EU imports and exports and PRODCOM Eurostat data on production. It reached almost 117,000 tonnes in 2019 and almost 6,000 tonnes in 2020 (Table 2). For the previous years (2010–2018), the data on silicon production have not been reported separately for two silicon grades either

Table 2. The EU's silicon consumption in the years 2010–2020 (in tonnes)

Tabela 2. Zużycie krzemu metalicznego w krajach UE w latach 2010–2020 (w tonach)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Silicon											
Production[1] (tonnes)	174,605	168,934	165,774	164,483	157,700	159,953	139,940	147,415	135,558	136,606	n/a
Imports extra-EU (tonnes)	397,116	387,126	365,125	405,489	426,682	417,698	405,386	389,153	449,724	411 182	325,908
Exports extra-EU (tonnes)	36,720	50,535	45,027	52,319	60,577	61,949	62,245	67,924	63,659	72,946	67,399
Import extra-EU – exports extra-EU	360,396	336,591	320,098	353,170	366,105	355,749	343,141	321,229	386,065	338,236	258,509
Consumption (tonnes)[3]	534,996	537,691	520,698	558,470	559,605	529,749	483,041	468,629	521,565	474,836	n/a
Silicon ≥ 99.99% Si											
Production[2] (tonnes)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	172,658	60,000
Imports outside-EU (tonnes)	10,178	11,431	5,368	2,402	8,950	4,521	4,042	4,418	2,048	7,061	5,561
Exports outside-EU (tonnes)	28,202	32,484	38,509	44,508	52,452	50,819	54,763	61,092	57,645	62,811	59,587
Import extra-EU – exports extra-EU	–18,024	–21,053	–33,141	–42,106	–43,502	–46,298	–50,721	–56,674	–55,597	–55,750	–54,026
Consumption (tonnes)[3]	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	116,908	5,974

[1] Total silicon metal production according to WMP 2015–2019 and previous editions.
[2] Data for grade ≥ 9999% Si from PRODCOM Eurostat – available for the years 2019 and 2020.
[3] Apparent.
n/a – data not available.
Sources: WMP 2015–2019 and previous editions (BGS 2021), EUROSTAT (CN 28046, CN 2804610), PRODCOM of Eurostat (20132160).

by Eurostat PRODCOM or by BGS in WMP 2015–2019 (and previous editions). During this period, it is only possible to present the net import volume of this type of silicon or the total volume of silicon consumption (regardless of its quality and applications). It has been calculated using data on production published by BGS in WMP 2015–2019 (and previous editions) as these data have also been included in market analysis for silicon metal in CRM Factsheets (EC 2020c). There is also some data reported by Eurostat PRODCOM but according to this source, the total amount of silicon metal production in the EU is significantly higher than in the official statistics of BGS, or USGS and the production volume for separate countries in the majority has not been revealed. The total volume of silicon consumption in the EU ranges from 468,629 to 559,605 tonnes/year in the years 2010–2019 and in 2019, it was more than fourfold higher than the grade of the higher purity (for the other years, data cannot be compared – Table 2). Germany and France have been the major silicon consumers in the EU (Figure 8).

According to WMP 2015–2019 and the previous edition, the total silicon-metal production in the EU amounted to 135,558–174,605 tonnes/year in the period 2010–2019 (Table 2). The major producers of the silicon metal in the EU have been France, Germany and Spain (WMP 2015–2019 and previous editions; BGS 2021). A higher level of total silicon metal production in the EU, between 235,000 and 309,000 tonnes/year, has been reported by

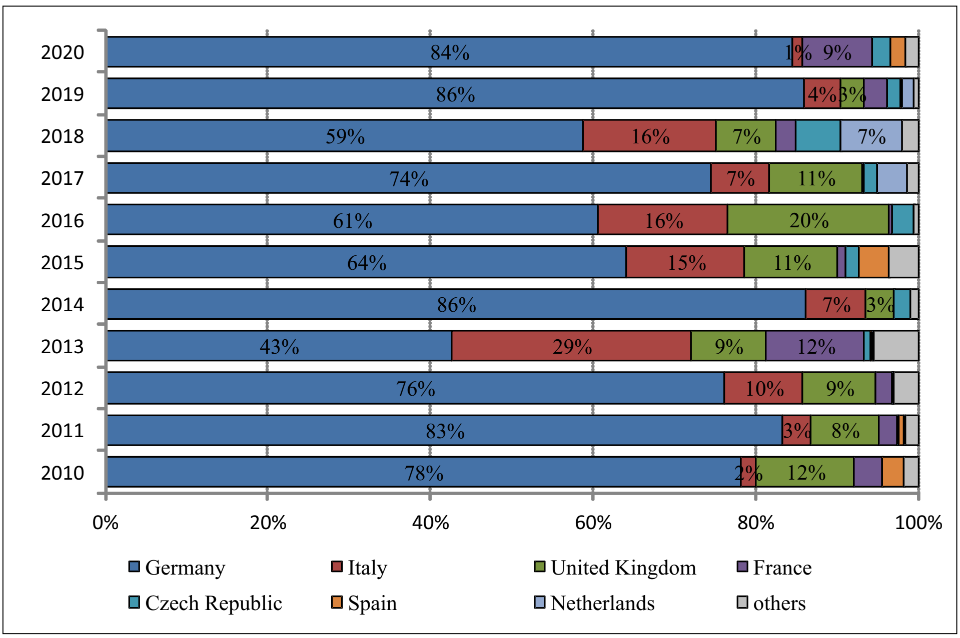


Fig. 4. The structure of the extra-EU imports of silicon containing by weight not less than 99.99% of Si (acc. to EUROSTAT)

Rys. 4. Struktura importu krzemu metalicznego o zawartości krzemu nie mniej niż 99,99% wag. Si do krajów UE (wg EUROSTAT)

PRODCOM Eurostat for the years 2010–2020. However, statistics for the separate Member States are mostly not available. The production volume of silicon metal grade containing by weight not less than 99.99 % of Si ranged from 60,000 to 173,000 tonnes/year but it has been reported in the EUROSTAT's statistics only since 2019 (Table 2).

Due to the low level of the domestic production, the EU is heavily dependent on imports of silicon metal. Its volume ranges from 325,908 to 449,724 tonnes/year in the years 2010––2020. The share of higher metal grade extra-EU imports (with content not lower than 99% by weight of Si) constitutes no more than 3% (2,048–11,431 tonnes/year), while the majority of supplies accounted for the lower grade of metallurgical silicon. The higher grade silicon has been imported predominantly to Germany, France and the Czech Republic, which accounted to 95% of supplies in 2020 (Figure 4). In recent years, substantial deliveries have also been directed to Italy (up to 29%) and to the United Kingdom (up to 20%; not included in statistics since 2020, Figure 4). The level of extra-EU exports reported for metal grade containing by weight not less than 99.99% Si considerably exceeded the imports level, ranging from 28 202 to 62 811 tonnes/year (Table 2).

In all analyzed periods, the EU was a net-importer of silicon metal. However, in the case of high grade metal (containing ≥ 99.99% by weight of Si), the situation differs and export dominated (Table 2). In 2020, the major net-importers of semiconductor grade silicon metal in the EU were the Czech Republic and Spain (Figure 8).

2.3.2. Gallium

The volume of the apparent consumption of gallium in the EU is difficult to precisely evaluate. The production of gallium from the primary sources has been reported by BGS (WMP 2015–2019 and previous editions) and USGS (MY 2021; MSC 2022). According to these sources, there was no primary gallium production in the EU from 2016. However, the Eurostat statistics on trade have been presented for unwrought gallium and gallium powders and in some cases they may also include gallium from secondary sources. In the PRODCOM's Eurostat, gallium production has been reported together with other metals (beryllium, chromium, germanium, vanadium, hafnium, indium, niobium, rhenium, thallium) and articles of these metals whereas data on unwrought gallium and gallium powders have been presented separately since 2019 (Table 3).

The production of gallium from primary sources was performed in the EU exclusively in Germany (BGS, USGS) and Hungary (USGS, EC 2020c) with the annual capacity being 25–40 tonnes/year and 6–8 tonnes/year, respectively (Rongguo et al. 2016). However, due to considerable oversupplies on the market and the reduction of the gallium prices caused by a strong Chinese competition, recovery of this metal from bauxite processing ceased in these countries in 2016 and 2013, respectively (EC 2020c). Recently, some plans for the resumption of production have been announced by Germany. The total volume of primary gallium production in the EU fluctuated between 11.0 and 39.7 tonnes/year in the years 2012–2016. Data for the years 2010–2011 and 2020 was not available.

Table 3. The EU's gallium consumption in the years 2010–2020 (in tonnes)

Tabela 3. Zużycie galu w krajach UE w latach 2010–2020 (w tonach)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Production[1]	n/a	n/a	n/a[4]	n/a[4]	n/a[4]	n/a[4]	n/a[4]	n/a[4]	n/a[4]	114.7	72.9
Imports extra-EU[2]	71.0	93.7	30.7	67.3	61.3	31.6	25.2	46.0	38.4	25.5	40.0
Exports extra-EU[2]	49.7	101.5	41.3	23.7	31.4	32.3	9.1	7.3	4.6	3.0	3.1
Import extra-EU – export extra EU[2]	21.3	–7.8	–10.6	43.6	29.9	–0.7	16.1	38.7	33.8	22.5	36.9
Consumption[3]	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	137.2	109.8

[1] Gallium metal.
[2] Unwrought gallium instead of germanium.
[3] Apparent.
[4] The volume of primary gallium production in the EU, available for the years 2012–2018 according to BSG and USGS statistics, amounted to 11.0–39.7 tonnes/year.

Sources: EUROSTAT (CN 81129289), PRODCOM of Eurostat.

Besides production from primary sources, gallium was also obtained in the EU from recycled material. The total volume of unwrought gallium and gallium powders production from both sources, reported by PRODCOM, amounted to 73–115 tonnes/year in the years 2019–2020. At the refining stage, the UK occupied a leading position in the EU, where refined gallium was obtained probably from German primary gallium, but production ceased in 2018 (EC 2020c). Slovakia and Germany were other producers of high purity gallium in the EU. These three countries also have the capacity to recycle gallium from new scraps (the UK up to 2018). In the EU, there are also numerous producers of gallium based products (EC 2017).

The volume of the EU's apparent consumption of unwrought gallium and gallium powders, calculated on the basis of PRODCOM's Eurostat data on production and Eurostat data on imports and exports, amounted to 110–137 tonnes/year in the years 2019–2020 (Table 3). Germany has been the major consumer of this metal in the EU (Figure 8). Taking exclusively data on the volume of primary gallium production in the EU into account (available for the years 2010–2019), it is estimated that the volume of the apparent consumption of this metal does not exceed a few dozen tonnes per year.

Due to the insufficient level of domestic production, the EU is heavily dependent on gallium imports. The volume of the extra-EU unwrought gallium and gallium-powder supplies in the years 2010–2020 changed in the range of 25.2–93.7 tonnes/year while the level of exports varied between 3.0 and 101.5 tonnes/year (Table 4). The gallium has been predominantly imported by Germany and the Netherlands, accounting for 92–100% of the total supplies in the last four years (Figure 5). Moreover, in the previous years substantial deliveries of this metal

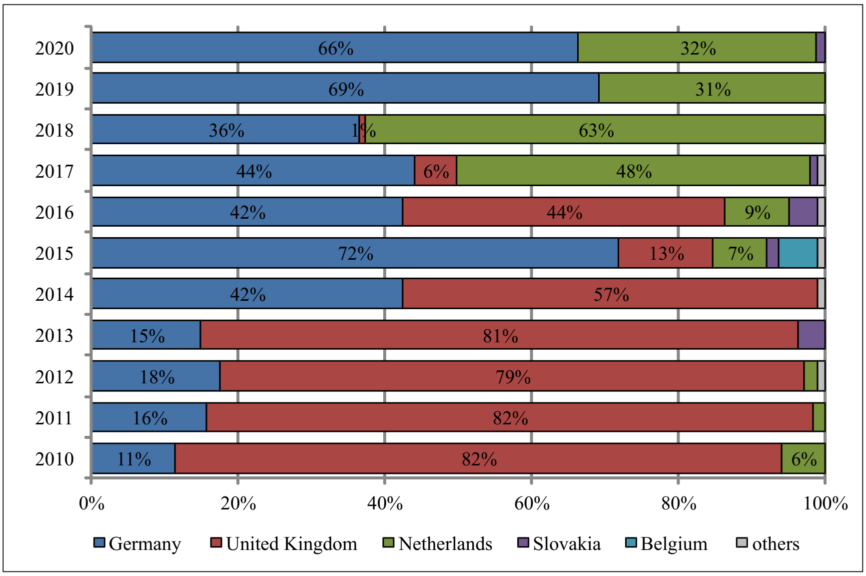


Fig. 5. The structure of the extra-EU imports of unwrought gallium and gallium powder (acc. to EUROSTAT)

Rys. 5. Struktura importu galu nieobrobionego i proszku galu do krajów UE (wg EUROSTAT)

have been directed to the UK (with the share of up to 82%, Figure 5), a significant European producer of high-purity refined gallium (up to 2018; EC 2020c; USGS 2021).

Recently, the EU has mostly been a net-importer of gallium metal with the exception of years 2011–2012 and 2015 when the export volume exceeded imports (Table 4). In 2020, the major net-importers of unwrought gallium and gallium powders in the EU were Germany and Slovakia (Figure 8).

2.3.3. Germanium

The volume of the EU's apparent germanium consumption is difficult to precisely evaluate due to considerable uncertainty regarding the quality of the source data. Germanium compounds and metal have been produced in some of the EU's states but the data concerning the volume of this production is only partially available. The basic germanium products, recovered through zinc ores or the leaching of coal fly ash, are germanium concentrates and crude germanium dioxide (GeO_2). In the course of further processing, tetrachloride (first usable product) and high purity oxide have been produced, and finally also various forms of germanium metal (USGS 2021).

The total average apparent consumption of various germanium processed materials, such as germanium unwrought, germanium dioxide and germanium tetrachloride, presented in the last EC report (2020c) for the period 2012–2016, has been estimated at 38.7 tonnes/year.

However, the data on trade in Eurostat statistics is exclusively available for unwrought germanium and germanium powder. The volume of germanium metal production has been reported by BGS (WMP 2015–2019 and previous editions) exclusively for Finland (Table 4), although it is believed that the recovery of this metal has also been performed in Belgium (from zinc residues imported from the USA; USGS 2021) and Germany (WMP 2015–2019, USGS 2021; EC 2020c). In Finland, germanium was obtained at an amount not exceeding 16 tonnes/year but in 2015, production ceased (EC 2020c). Recycling also formed a substantial source of germanium metal supplies (mostly of new scrap) that constitutes around 30% of its global production (USGS). Two large global recyclers and refiners of zinc with combined germanium had production facilities on the EU's territory (Umicore in Belgium and Recyclex in France with its subsidiary PPM Pure Metals Gmbh in Germany up to 2020 when the production ceased due to financial problems; EC 2020c). Belgium's Umicore has been a producer of germanium metal, germanium tetrachloride for fiber optics, germanium substrates, and germanium optical products (USGS 2021).

The calculated volume of the EU's apparent germanium metal consumption including the volume of extra-EU imports and extra-EU exports of unwrought germanium and germanium powder (reported by Eurostat) and the volume of metal production in Finland (according to BGS) changed in the range 3.1–31.9 tonnes in the years 2010–2019 (Table 4). However, as it was previously mentioned, this volume does not include figures for all production countries in the EU. The major germanium consumers have been Germany and France (Figure 8).

As a significant germanium metal consumer (according to EC 2020c accounting for 29% global processed material consumption), the EU is heavily dependent on germanium

Table 4. The EU's germanium consumption in the years 2010–2020 (in tonnes)

Tabela 4. Zużycie germanu w krajach UE w latach 2010–2020 (w tonach)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Production[1]	12.0	12.0	16.0	17.0	17.0	13.0	0.0	–	–	–	n/a
Imports extra-EU[2]	15.8	21.6	12.1	13.6	7.9	10.2	7.4	6.5	21.1	14.6	6.8
Exports extra-EU[2]	0.5	1.7	3.1	4.3	19.0	4.3	4.0	3.4	6.3	5.3	5.7
Import extra-EU – export extra EU[2]	15.3	19.9	9.0	9.3	–11.1	5.9	3.4	3.1	14.8	9.3	1.1
Consumption[3]	27.3	31.9	25.0	26.3	5.9	18.9	3.4	3.1	14.8	9.3	n/a

[1] Germanium metal.
[2] Unwrought germanium and germanium powder.
[3] Apparent.
Sources: Eurostat (CN 81129295), WMP 2015–2019 and previous editions (BGS 2021).

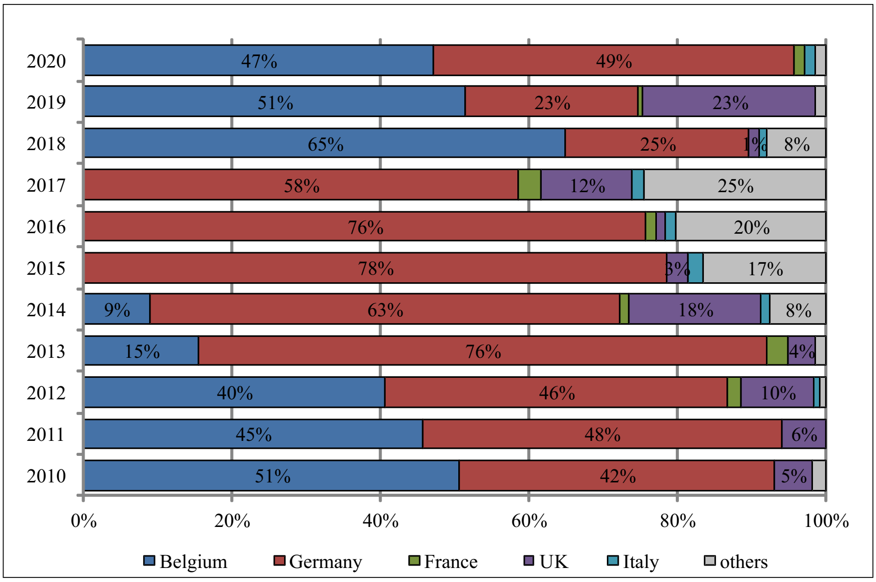


Fig. 6. The structure of the extra-EU imports of germanium unwrought and germanium powder (acc. to EUROSTAT)

Rys. 6. Struktura importu germanu nieobrobionego i proszku germanu do krajów UE (wg EUROSTAT)

imports. The volume of the unwrought germanium and germanium powders extra-EU supplies in the years 2010–2020 varied in the range of 6.5–21.6 tonnes/year while the level of the extra-EU exports changed from 0.5 to 19.0 tonnes/year (Table 5). Germanium metal has been imported predominantly by Germany and Belgium, together accounting for 96% of total supplies in 2020. Substantial deliveries were directed also to the UK (since 2020 no longer the EU Member State, Figure 6).

Recently, the EU has mostly been a net-importer of the germanium metal with the exception of 2014 when the export volume exceeded the imports (Table 5). In 2020, the major net-importers of unwrought germanium and germanium powders in the EU were Germany and France (Figure 8).

2.3.4. Indium

The volume of the apparent indium consumption in the EU reached the level of 51.5–104.9 tonnes/year in the years 2010–2019 with some high variation in the year 2011 and 2020 (Table 5). This has been calculated on the basis of the Eurostat's data on extra-EU imports and extra-EU exports of unwrought indium and indium powders as well as data for refined indium production published in WMP 2015–2019 (and previous editions; BGS 2021), World Mining Data 2021 (WMD 2021) and MCS (USGS 2022). The major indium consumers in the EU have been Belgium and Italy (Figure 8).

Table 5. The EU's indium consumption in the years 2010–2020 (in tonnes)

Tabela 5. Zużycie indu w krajach UE w latach 2010–2020 (w tonach)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Production[1]	50.0	50.0	63.0	83.0	88.0	81.0	35.0	65.0	70.0	65.0	63.0
Imports outside-EU[2]	129.6	225.0	65.3	61.2	63.5	52.1	44.9	64.4	37.3	29.1	29.3
Exports outside-EU[2]	105.7	389.3	58.7	52.8	67.3	40.2	20.1	24.5	53.6	42.6	52.9
Import extra-EU – export extra EU[2]	23.9	–164.3	6.6	8.4	–3.8	11.9	24.8	39.9	–16.3	–13.5	–23.6
Consumption[3]	73.9	–114.3	69.6	91.4	84.2	92.9	59.8	104.9	53.7	51.5	39.4

[1] Refined indium.
[2] Unwrought indium and indium powder.
[3] Apparent.
Sources: EUROSTAT (CN 81129295), WMP 2015–2019 and previous editions (BGS 2021), WMD 2021, MCS (USGS 2022).

The data concerning the EU indium production from zinc concentrates is not available and it is not clear if there has been any zinc recovery from domestic ores in recent years (although significant indium content occurs in ores extracted at Neves Corvo mine in Portugal). In spite of this fact, refined indium production in the amounts of 35-88 tonnes/year was reported in the years 2010–2020 (Table 8). According to the EC report (2017) there are two producers of refined indium from imported concentrates, residues and slags. The first of these is Nyrstar's plant at Auby in France (temporarily ceased production in 2015–2016 due to a fire in the plant) and the second is Umicore's Hoboken plant in Belgium. Among indium producing countries in the EU, Italy (WMP 2015–2019), the Netherlands (up to 2015; WMD 2021) and Germany (WMD 2021) have also been listed. However, the production capacity in Germany was related to very high purity indium that has been obtained in the course of the 4N indium metal upgrading. Besides, it is not clear if the production has recently been carried out. As far as semi-finished products are concerned, the ITO (indium-tin oxide for the flat panel devices) and CIS (cooper indium selenide for solar cells) seem to not be currently produced in the EU. The small production of CIS in Germany was moved to China in 2013 (EC 2017). Numerous indium base products have been manufactured e.g. in Germany (specially alloys, thin films).

The EU production of indium can to a substantial degree meet the demand for this metal. Most recently (in the years 2018–2020), the quantity of its production has even exceeded the consumption volume (mostly due to significant supplies in France). The remaining part of the demand has been covered by imports from outside-EU countries. Indium has been traded in the form of unwrought metal and powders. The volume of the extra-EU indium imports varied in the range of 29.1–225.0 tonnes/year while the volume of extra-EU export fluctuated between 20.0 and 389.3 tonnes/year in the period 2010–2017 (Table 5). The major importers of indium in the EU include the UK (up to 2019), Germany (4–55%), the Netherlands (up to 45%), Belgium (up to 13%) and Italy (up to 12% – Figure 7).

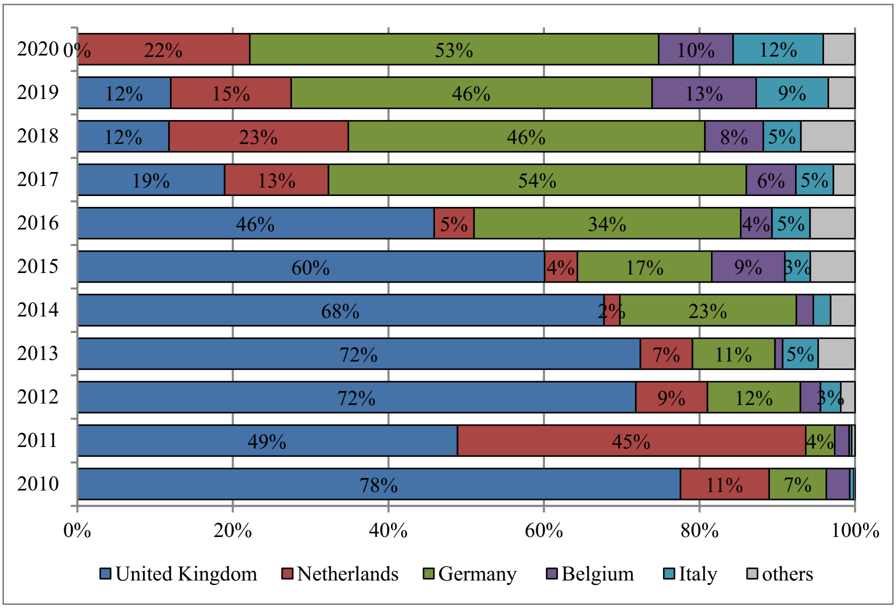


Fig. 7. The structure of indium unwrought and indium powder extra-EU imports (acc. to EUROSTAT)

Rys. 7. Struktura importu indu nieobrobionego i proszku indu do krajów UE (wg EUROSTAT)

The EU has been a net-importer of the indium metal in the years 2010, 2012–2014 and 2015–2017 while in 2011, 2014 and 2018–2020, the exports volume exceeded the imports (Table 5). In 2020, the major net-importers of unwrought indium and indium powders in the EU were Germany and Italy (Figure 8).

2.4. Structure of consumption of selected CRMs in the EU

Apart from photovoltaic technologies, the CRMs analyzed in this paper have a wide range of other industrial applications that compete for the same raw material (Table 6). Currently, PV systems represent only a small proportion of the total use of silicon metal, gallium, niobium and indium (mostly no more than a few percent, Table 6 – SCRREEN 2019a).

Silicon metal has been primarily used in the EU in chemical industry (the production of silicones and silanes) and the aluminum industry (casting alloys and wrought alloy pro-

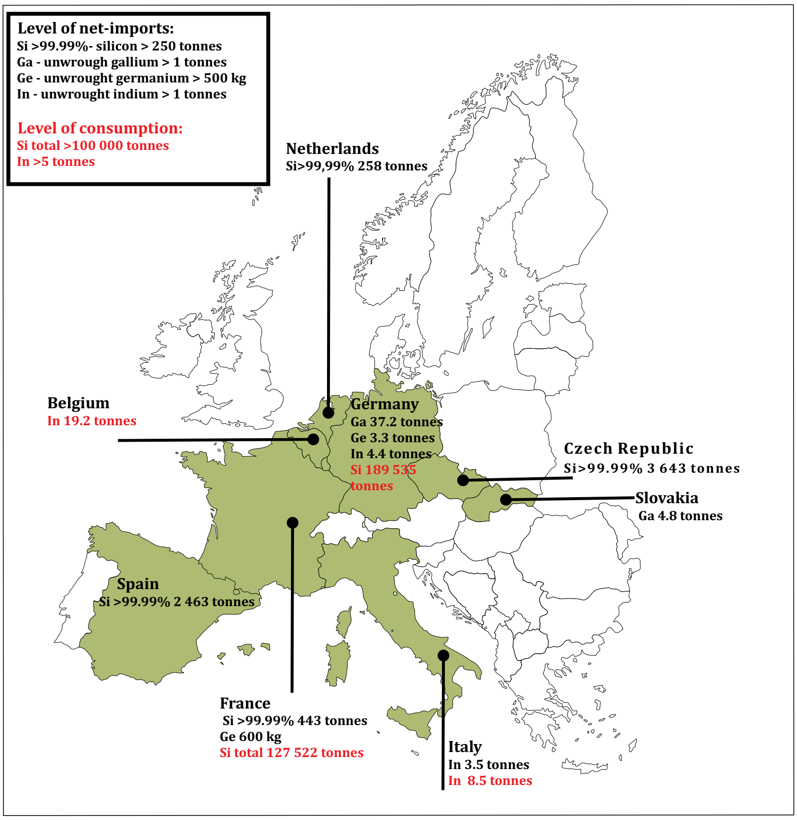


Fig. 8. The major consumers and net-importers of selected CRMs for PV energy sector in the EU in 2020 (own calculations based on EUROSTAT; BGS 2021; USGS 2022)

Rys. 8. Główni użytkownicy i importerzy netto wybranych surowców krytycznych dla sektora fotowoltaiki w krajach UE w 2020 r. (obliczenia własne na podstawie danych EUROSTAT, BGS 2021; USGS 2022)

Table 6. The major applications of selected CRMs in the EU

Tabela 6. Główne zastosowania wybranych surowców krytycznych w UE

CRM	1st application	% 1st	2nd application	% 2nd	3rd application	% 3rd
silicon metal	chemical applications	54	aluminum alloys	38	solar applications	6
gallium	integrated circuits	70	lighting	25	CIGS solar cells	5
germanium	infrared optics	47	optical fibres	40	satelite solar cells	13
indium	flat panel displays	60	solders	11	PV cells	9

Sources: EC 2020c, SCRREEN 2019a.

duction). These two applications account for more than 90% of the total consumption of this metal while the remaining 8% has been divided between solar applications (6%) and electronic applications (2% – Table 6, SCRREEN 2019a). The ultra-high purity grade of silicon (polysilicon) is required for the manufacturing of semiconductors for photovoltaic technology (Euroalliages 2022). This includes silicon of Si content above 99.9999% for solar silicon and above 99.999999% for polycrystalline solar-grade silicon (Xakalashe and Tangstad 2011). Other applications of polysilicon have been electronics (electronic grade silicon of purity >99.99999999%), including devices such as silicon semiconductors, transistors, printed circuit boards and circuits merged. Particularly, semiconductor-grade silicon metal that is crucial for computer chips manufacturing presents significant importance for modern technologies development (EC 2017; Euroalliages 2022).

The vast majority of gallium consumption in the EU accounted for semiconductor materials (in microchips, laser diodes, photodetectors and solar cells). The most common gallium compound utilized in this application is gallium arsenide (GaAs) with subordinate importance of gallium nitride (GaN; EC 2020c). The first of these is used in integrated circuits (70% of the EU gallium consumption) that are crucial components of electronic devices such as cell phones, wireless communications system, and in military applications. The second is used in LED lighting and laser diodes for BlueTray DVD devices (25% of the EUs consumption). The remaining 5% of the gallium end-uses include copper-indium-gallium diselenide (CIGS) in the thin-film solar cells for photovoltaic technology (Table 6). Other gallium applications include high-temperature thermometers to create high-quality mirrors and some dental applications, where it is utilized as a mercury substitute.

Germanium has been used mostly in the form of germanium tetrachloride, germanium dioxide and germanium metal. Germanium tetrachloride has been suitable for fiber-optic cable production whereas germanium dioxide for the manufacturing of certain types of optical lenses and as catalysts in the production of PET resin. Germanium metal has been used as a semiconductor and for the infrared optical device (manufacturing of lenses or window blanks; USGS 2021). The major germanium consuming sectors in the EU have been infrared optics (47%) and optical fibers (40%; Table 6; SCRREEN 2019a). Satellite solar production for military reasons has a subordinate share in the total volume of germanium consumption (13%). In the world market, germanium has also been consumed in PET catalyst and IT applications, but they are not among end-uses in the EU.

The majority of metallic indium utilized in the EU is in the form of indium tin oxide (ITO) thin films for various display technologies (FPDs – flat panel displays, including LCDs – liquid crystal displays, PDPs – plasma display panels, OLED – organic light emitting diodes). After application on glass or clear plastics, they function as a transparent electrode and because of this, they are widely applied in the electronic-equipment sector and subordinately also in high-efficiency glass manufacturing (e.g. for architectural and automotive purposes). The widespread use of LCD technology in televisions, computers and handheld electronic devices has driven a rapid growth for indium demand worldwide in the last twenty years (Lokanc et al. 2015). Flat panel displays are the most important indium application in the EU (60%), followed by low temperature and lead-free solders (11%). PV cells sector accounted only for 8% of indium end-uses (Table 6; SCRREEN 2019a). In this application, indium semiconductor compounds have been utilized as light absorber material in CIGS and CIS (without gallium) thin film solar cells. Other applications, such as thermal interface material for electronic devices (7%), batteries (6%), alloys/compounds (4%), semiconductor and LEDs (3%), have a significantly lower share. In infrared technologies, indium antimonide (InSb) and InGaAs (indium gallium arsenide) are utilized in laser diodes InP (indium phosphide). However, according to the last EC report (2021), all of the flat panel display production has been carried out outside the EU (in Japan, South Korea and China). As a result, non-ITO applications, such as production of solders, alloys and compounds dominate outside of Asia.

3. Discussion and conclusion

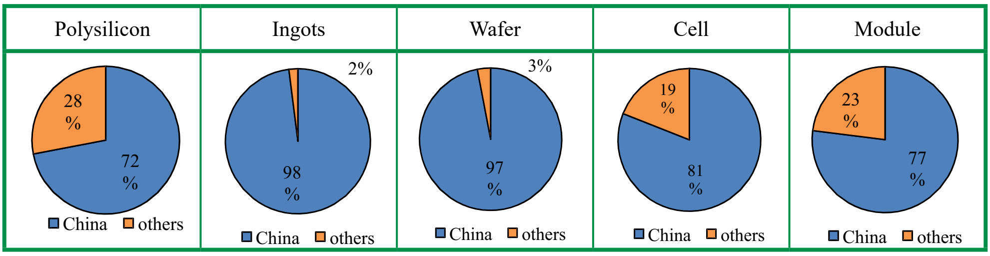
3.1. CRMs as part of the PV value chain in the EU

The EU ranks second in the world in terms of cumulative installed photovoltaic energy capacity. Simultaneously, according to the European Solar Manufacturing Council (EMSC) a strong dependency of the EU on external supplies has been reported for all key components for photovoltaic panel production. This is reported along the entire value chain from upstream to downstream, starting from the production of polysilicon, through ingots, wafers and cells, up to modules. It is estimated that in 2020, Europe's share in the total world's production of PV grade of silicon amounted to 11%, the ingots and wafers did not exceed 1%, while the share for cells was as low as 0.4% (ESMC 2021a). With regards to module, Europe accounted for only 4% global supplies. The global PV market was dominated by China, which in 2021 controlled ca. 80% of the total production of cells and modules, over 90% of ingots and wafers and 72% of polysilicon (Table 7; U.S. Department of Energy 2022). In comparison to data for 2019 published by Bernreuter (Bernreuter 2022), in almost each of these applications, China increased the market share by a few percentage. Other important but much smaller producers of PV systems include Japan and South Korea (ESMC 2021b). As a result of strong production concentration in Asia, the EU is significantly dependent on photovoltaic panel imports and China's share in supplies is very high. The negative balance in trade in these materials exceeded 6 billion Euro (common value for all photosensitive semiconductor devices, including photovoltaic cells whether or not assembled in modules or made up into panels; light emitting diodes (excl. photovoltaic generators) in 2020 (Eurostat).

With regard to photovoltaic value chain in the EU, several metallic silicon producers can be identified. The largest is the German company Wacker Chemie AG (up to 2019 also the top silicon global producer) with plants in Burghausen and Nünchritz in Gemany (and

Table 7. China's share in production volumes along the PV solar value chain in 2021

Table 7. Udział Chin w wielkości produkcji sektora fotowoltaiki w 2021 r. na poszczególnych etapach w łańcuchu dostaw



Sources: own study, based on report: Solar Photovoltaics Supply Chain Review Report (US Department of Energy 2022).

also in Charleston in the US). Metallurgical-grade silicon, which is subsequently used for ultra-purity silicon production, is supplied to both of these plants from smelter at Holla in Norway (also owned by Wacker; Saur Energy International 2021; Wacker 2022).

The production of ingots is performed in the EU by a division of the MEMC Electronic Materials SpA company with a plant in Merano in Italy while the production of wafers is conducted by the plant in Novara in Italy, which is also owned by the same company (MEMC Electronics 2022).

The production of photovoltaic panels is performed only by the French RECOM with manufacturing facilities in France, Italy and Poland. Other companies that operate on European market include Japanese Sharp Solar (plant in Germany), Swiss Meyer Burger (plant in Germany) and the American Sunflare (plant in Sweden). It is worth mentioning that a number of European companies have moved their plants outside the European continent (e.g. German companies AE Solar and Axitec that operates in China; Solar Power World 2022). The production of photovoltaic panels in the EU is also conducted by QCells, the company that was originally established in Germany but in 2012 was acquired by the Korean Hanwha concern (with its production plants in Germany and Malaysia; Fotowoltaikaonline 2022).

To sum up, the production of PV panels was dominated by developed countries, such as the USA, Japan and Germany twenty year ago. However, fierce competition on the market and significant reduction of prices caused it to move to China (Carvalho et al. 2017). Currently, the solar photovoltaic value chain in Europe is poorly developed and even if there is production of some CRMs needed in PV technology, they are to a significant extent exported to third countries. An example is presented in Table 2 with regard to high grade silicon that has been directed in the overwhelming majority to China. A similar situation concerns indium that is believed to be recovered by, for example, the Umicore plant in Belgium (probably from Bolivian zinc ores) and then might be exported to another company's factory in the USA (where ITO is produced; Ronsse 2020). The volume of indium export from the EU, presented in Table 7, constitutes a substantial part of the reported volume of domestic production. It has been directed primarily to the USA, China and most recently also to Great Britain (EUROSTAT).

Funds from the EU Recovery and the Resilience Facility, which is part of the European Union's support measures undertaken as a response to the coronavirus pandemic, present an opportunity to strengthen the PV value chain. European manufacturers of solar energy associated in European Solar Manufacturing Council (ESMC 2021b) postulate to use these funds in order to significantly increase European PV manufacturing capacity by 2026 to be able to cover 75% of the domestic demand for new systems from own sources (ESMC 2021b). This could result in reducing a deficit in trade on each stage of the PV value chain and create ca. 178,000 new jobs (ESMC 2021b). The new projects in Europe concern, for example, the expansion of PV module manufacturing capacity by companies from Italy (3 Sun factory) Germany (several suppliers) and France (Carbon start-up). However, it is highlighted that the facilities for ingots and wafer production are more complex to establish than PV module plants (Reuters Events 2022). Besides, competition with low-cost Chinese manufacturers of PV components and panels might be difficult to deal with for European companies. Because of this, one of the considered options is to build the plants with very large production capacity with the availability of material supplies on site to reduce transport costs.

3.2. Trends in the demand for selected CRMs in the solar-PV sector

The conducted studies revealed that the total amounts of silicon metal that has been utilized in the EU in the analyzed period amounts to 0.4–0.6 million tonnes/year. However, in case of the metal grade of high purity (containing ≥99.99% Si) the volume of consumption was substantially lower (up to 0.1 million tonnes in the years 2019–2020). Other analyzed CRMs, namely gallium, germanium and indium have been utilized in the EU in significantly smaller quantities (for gallium and indium, the values do not usually exceed a hundred tonnes/year and for germanium, this amounts to several dozen tonnes/year). The major net-importers of analyzed CRMs were Germany (gallium, germanium, indium), France (high purity silicon metal, germanium), Spain, the Czech Republic and the Netherlands (high purity silicon metal), Slovakia (gallium) and Italy (indium). The most important polysilicon and germanium consumers have been Germany and France, Belgium and Italy for indium – and Germany and Slovakia for gallium (in the case of gallium and germanium, there is no reported data on production from primary sources in the EU).

The total production capacity of PV panels is expected to increase from 153 GW in 2020 to 188.1 GW in 2024 (by 23%). A spectacular growth of volume of the installed capacity is forecasted in perspective of the nearest and more distant future both in Europe (up to 291 GW in 2030 and nearly 900 GW in 2050) as well as globally (from 714 GW in 2020 up to nearly 3000 GW in 2030 and over 8000 GW in 2050; IRENA 2019). This means that the development of the PV technology will require a substantial increase in raw materials use, in particular CRMs. Although some of them have already been extracted in the EU, the volume of this production certainly is not enough in comparison to the expected future demand.

According to the Report on Raw Materials and the Circular Economy (EC 2018) the projected demand for Ga, In and Si in the EU in solar PV sector will significantly increase in perspective of 2030. In high deployment scenarios, it is expected to increase six-fold for Ga (up to 6.5 tonnes/year) and In (up to 45 tonnes/year) and seven-fold for Si (up to 234,962 tonnes/year) from the basic year 2015.

The forecast of demand for gallium presented in the SCRREEN report assumes growing trends in all major applications of this metal up to 2035, particularly in electronic appliances (e.g. smart phones). The future use of indium will be mainly dependent on ITO applications in liquid crystal displays (LCDs) and PV technologies. It is expected to steadily increase; however, it is assumed that the share of CIGS thin-film solar cells in indium consumption will remain small up to 2030. Conversely, CRMs such as silicon, indium and gallium in the PV applications should become less critical by 2035, especially owing to improvement in material efficiency (SCRREEN 2020b).

According to a JRC report on raw material demand for wind and solar PV technologies, the authors considered three scenarios with various assumptions on the development of specific PV sub-technologies and their market share (Carrara et al. 2020). The medium scenario includes the growth of the share of thin-film technologies up to 10% in 2050, the high scenario being up to 23% (and c-Si decrease to 77%) while in the low scenario, these applications constitute barely 1% (remaining 99% accounts for c-Si applications). As a consequence, in the medium scenario the demand for germanium is expected to increase 7.5 times, for indium 6–7 times, for gallium 6 times and for silicon 3–4 times. In the high scenario, demand will increase 86 times for germanium, 36–40 times for indium and gallium and 13 times for silicon (Carrara et al. 2020).

The significant differences between forecasts prepared by various institutions revealed that the precise evaluation of future demand for analysed CRMs in PV sector is very difficult. The authors of the paper have not performed a typical trend analyses that would verify these estimations as obtained result could be considerably uncertain, particularly in the current geopolitical situation in Europe. Instead of this, major factors that could influence the future demand for the analyzed CRMs in the PV sector have been identified. There is strong pressure on PV-panel prices resulting in searching paths to raw material efficiency as well as the development of individual PV sub-technologies with various requirements in terms of CRM type as well as quantities.

On the basis of the conducted analyses, it seems that the crystalline silicon technology (c-Si) that currently accounted for over 90% of global PV market is expected to remain in the nearest future on the leading position. These kinds of panels are still more efficient that the commercial thin-film versions (Carrara et al. 2020). From this perspective, access to sustainable and diversified supplies of silicon metal is a key factor that enables development along the whole value chain. Most recently, the PV-panel production sector has experienced significant growth of polysilicon prices that has been to a substantial part absorbed by solar wafers, cells and module manufacturers (Reuters Events 2022). However, it should be highlighted that due to a decreasing trend in the volume of silicon metal utilized for wafer-based crystalline silicon cell production, the growth of demand for this metal might not be as spectacular as was forecasted. With respected to wafer cells, it is also expected that the use of boron in the production will become less popular due to possible substitution with gallium that simultaneously allows the obtaining of higher performance.

Thin-film solar cells technologies (a-SiGe, a-SiC, CdTe, $CuInSe_2$, $CuInGaSe_2$), with their currently subordinate share in the solar PV panels production, require a wide range of CRMs, such as amorphous silicon, germanium, gallium and indium. Among these technologies, in most forecasts, CIGS cell production is expected to increase, resulting in rising needs for gallium and indium. A indium has a particularly significant importance in thin-film applications. The largest volume of this metal is required for CIGS production (with no commercially available substitutes; EC 2020c), while in CdTe and a-Si technologies, it has been utilized in smaller amounts. Indium has also been utilized in thin-film technologies in the form of ITO in amorphous silicon and CdTe PV cells. However, in this application, substitution with tin oxide (SnO_2), zinc oxide (ZnO), and aluminum-doped zinc oxide (AZO) is possible and the future increase of demand for indium will be probably highly dependent on metal prices. Among thin-film technologies, the production of a-SiGe and a-SiC panels has a decreasing tendency due to its low efficiency.

Besides the mature solar PV technologies analyzed in the paper, there are some promising innovations, such as copper zinc tin sulphide, perovskite solar cell, organic PV, or others that might increase the share in the market (more so in the distant than in the near future).

In summary, the analyzes of reports of IRENA and Solar Power Europe indicate that the growing trend in the development of production capacity of new PV installations in most EU countries can be expected and that the domination of solar PV technologies based on metallic silicon will be continued. However, it is much more difficult to predict the impact of technology advancement on the volume of the consumption of analyzed CRMs. As the conducted analyses revealed, the systematic reduction for all analyzed CRMs used in PV technology is observed and this tendency is expected to be continued in the future (Table 8).

Table 8. The estimated use of selected CRMs in solar PV technology (in t/GW)

Tabela 8. Szacunkowe zużycie wybranych surowców krytycznych w technologii fotowoltaicznej (t/GW)

CRM	2010[2]	2018[1]	2020[2]	2030[1]	2040[2]	2050[1]
Silicon (Si) (c-Si)	n/a	4,000	n/a	2,200–3,500	n/a	1,000–3,000
Silicon (Si) (a-Si)	n/a	n/a	n/a	75–130	n/a	40–110
Gallium (Ga)	6–11	3–7	2–6	2–4.5	1–3	1–2.5
Germanium (Ge)	73	48	36–48	22–32	14–24	10–20
Indium (In)	23–43	10–27	8–22	8–17	6–12	5–10

[1] Carrara et al. 2020; [2] Nassar et al. 2016.

In this context, it may be concluded that there is high probability that the volume of future demand based on forecasts that do not take into account these technological advancement will be overestimated. It is without doubt that we can expect a substantial growth of silicon consumption in all PV sub-technologies.

Despite the above, in order to achieve the goals outlined in the European Green Deal and to meet future energy demand through renewable sources, including solar PV sources, a strong growth of demand for analyzed raw materials in the coming decades is expected, despite improvements in material intensities. The volume of these future demands will be strictly related to the trends of development in PV-panel production technologies. Simultaneously, there is a number of other applications that compete for the same raw materials and the solar energy sector at the moment constitutes a marginal share of the EU total end-uses (10% of silicon metal, 5% of gallium, 13% of germanium and 9% of indium). The analyzed CRMs have a significant importance for modern technologies development, particularly for electronic equipment manufacturing (computers, laptops, mobile phones; EC 2017; Euroalliages 2022), which is also important factor driving a future demand.

In conclusion, it is particularly important to highlight that the lack of own sources of CRMs in the EU is crucial for PV-panel production would result in a significant increase of imports of these raw materials and would deepen the already negative trade balance. Taking into account the plans of China to double renewable energy capacity by 2030 and the USA's ambitions for clean energy deployment it raises a concern of material supply shortage. This could be a factor that would limit the development of the photovoltaic technology in the EU and would make difficult to hit the decarbonization target.

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THE EU'S DEMAND FOR SELECTED CRITICAL RAW MATERIALS USED IN THE PHOTOVOLTAIC INDUSTRY

Keywords

critical raw materials (CRMs), renewable energy, photovoltaic (PV) power sector, raw materials demand

Abstract

This paper presents the results of analyses of structure, volume and trends of demand for selected major critical raw materials (CRMs) suitable for the EU's photovoltaic industry (PV). In order to achieve the EU's goals in terms of the reduction of greenhouse gas emission and climate neutrality by 2050, the deployment of energy from renewable sources is of key importance. As a result, a substantial development of wind and solar technologies is expected. It is forecasted that increasing the production of PV panels will cause a significant growth in the demand for raw materials, including

CRMs. Among these, silicon metal, gallium, germanium and indium were selected for detailed analyses while boron and phosphorus were excluded owing to small quantities being utilized in the PV sector. The estimated volume of the apparent consumption in the EU does not usually exceed 0.1 million tonnes for high purity silicon metal, a hundred tonnes for gallium and indium and several dozen tonnes for germanium. The major net-importers of analyzed CRMs were Germany, France, Spain, Czech Republic, the Netherlands, Slovakia and Italy. The largest quantities of these metals have been utilized by Germany, France, Belgium, Slovakia and Italy. The PV applications constitute a marginal share in the total volume of analyzed metal total end-uses in the EU (10% for silicon metal, 5% for gallium, 13% for germanium and 9% for indium). As a result, there is a number of applications that compete for the same raw materials, particularly including the production of electronic equipment. The volume of the future demand for individual CRMs in PV sector will be strictly related to trends in the development of PV-panel production with crystalline silicon technology currently strongly dominating the global market.

ZAPOTRZEBOWANIE UE NA WYBRANE SUROWCE KRYTYCZNE WYKORZYSTYWANE W FOTOWOLTAICE

Słowa kluczowe

surowce krytyczne, energia odnawialna, fotowoltaika, popyt na surowce mineralne

Streszczenie

W artykule przedstawiono wyniki analizy struktury, wielkości i trendów zapotrzebowania Unii Europejskiej (UE) na wybrane surowce krytyczne wykorzystywane w technologiach fotowoltaicznych. Dla osiągnięcia celów UE w zakresie ograniczenia emisji gazów cieplarnianych i uzyskania neutralności klimatycznej w perspektywie 2050 r. kluczowe znaczenie ma wykorzystanie energii ze źródeł odnawialnych. W efekcie prognozowany jest znaczny rozwój energetyki wiatrowej i słonecznej. Przewidywany wzrost produkcji paneli fotowoltaicznych skutkował będzie zwiększonym zapotrzebowaniem na surowce, w tym zaliczane do grupy krytycznych dla UE. Spośród nich do szczegółowych analiz wybrano krzem metaliczny, gal, german i ind, jednocześnie pomijając bor i fosfor, wykorzystywane w zastosowaniach fotowoltaicznych w niewielkich ilościach. Szacunkowe zużycie pozorne tych surowców w UE w ostatnich latach zwykle nie przekraczało 0,1 mln ton dla krzemu metalicznego o wysokiej czystości, 100 ton dla galu i indu oraz kilkadziesiąt ton w przypadku germanu. Głównymi ich importerami netto były Niemcy, Francja, Hiszpania, Czechy, Holandia, Słowacja i Włochy. Największe ilości analizowanych metali zużywane były przez Niemcy, Francję, Belgię, Słowację i Włochy. Produkcja paneli fotowoltaicznych stanowi niewielki udział w łącznych zastosowaniach końcowych krzemu (10%), galu (5%), germanu (13%) i indu (9%). W związku z tym wiele sektorów przemysłu, w tym m.in. sprzętu elektronicznego, konkuruje o dostawy tego samego materiału. Wielkość przyszłego zapotrzebowania na poszczególne surowce krytyczne w sektorze energii fotowoltaicznej będzie ściśle uzależniona od trendów rozwoju poszczególnych technologii produkcji paneli, z silnie dominującą obecnie na rynku technologią wykorzystującą krzem krystaliczny.