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MATERIALS DEPENDENCIES FOR DUAL-USE TECHNOLOGIES RELEVANT TO EUROPE'S DEFENCE SECTOR

Summary Report

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Contents

Abstract

In order to support the European Commission in the preparation of future initiatives fostering the sustainability of strategic supply chains, this study was commissioned to assess bottlenecks in the supply of materials needed for the development of technologies important to Europe's defence and civil industries. The study focuses on five dual-use technology areas, namely advanced batteries, fuel cells, robotics, unmanned vehicles and additive manufacturing (3D printing). The technologies are preselected on the basis of a previous study (EASME, 2017) that explored the dual-use potential of key enabling technologies in which Europe should strategically invest. In addition, this report examines how these technologies could address specific military needs and their differences in relation to civil needs, and identified opportunities for future defence research areas that could potentially serve as a basis for the design of research initiatives to be funded under the future European Defence Fund. Moreover, potential opportunities for common policy actions are also identified, notably: to strengthen Europe's position in the selected technologies' supply chains; to facilitate collaboration between stakeholders; to increase industry involvement, with special emphasis on small and medium-sized enterprises; to improve existing legislation; and to increase synergies between civil and defence sectors to speed up progress in promising research areas.

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1. Executive summary

There has been growing concern throughout the EU in recent years about the security of supply of strategic raw and advanced materials that are critical for both civil and defence applications. The European defence action plan was launched to tackle such issues and to make the defence and security sectors more competitive and efficient via the European Defence Fund and other actions to support Member States with more efficient spending on joint defence.

In order to support the European Commission in the preparation of future initiatives to foster the sustainability of strategic supply chains, a study was commissioned to assess bottlenecks in the supply of materials needed for the development of technologies that are important to Europe's defence and civil industries. The report also identifies common dual-use research needs that would benefit from support from the European Defence Fund.

This report focuses on five dual-use technology areas: advanced batteries, fuel cells, robotics, unmanned vehicles (UVs) and additive manufacturing (3D printing — 3DP). The technologies were preselected on the basis of a study (EASME, 2017) that explored the dual-use potential of key enabling technologies in which Europe should strategically invest. These technology areas were selected for their high relevance to the European defence technological and industrial base and their contribution to:

— the strategic independence of the civilian and defence supply chains;

— the economic impact on EU growth and job creation;

— the EU's knowledge base (impact on R & D capital stock).

The five selected technology areas were thoroughly analysed with regard to their geopolitical supply chain dependencies, accompanied by a comprehensive overview of the corresponding key players (countries and companies). Other bottlenecks were also examined, such as the availability of a skilled work force, cost, quality issues, regulation, certification and legislation. Standardisation matters and intellectual property rights (IPR) issues have also been identified.

The report also examined how these technologies could address specific military needs and how these differ from civil needs. In light of the above, the study identified opportunities for future defence research areas that could potentially serve as a basis for the design of research initiatives to be funded under the European Defence Fund. Potential opportunities for common policy actions were also identified, notably: to strengthen Europe's position in the selected technologies' supply chains; to facilitate collaboration between stakeholders; to increase industry involvement, with special emphasis on small and medium-sized enterprises (SMEs); to improve current legislation; and to increase synergies between civil and defence sectors to speed up progress in promising research areas.

A dedicated methodology, relying on several key parameters, was developed to identify forthcoming bottlenecks (supply risks) in the supply chains of the selected five technologies, from raw materials to final assemblies (e.g. lithium-ion (Li-ion) cells, fuel cells, robots, drones, 3D printers). Such parameters reflect the concentration of supply, the availability of domestic production in Europe, import reliance on specific raw materials, the use of critical raw materials (CRMs) in the technologies in question and the substitution and recycling potential of the raw materials required for these technologies. Potential bottlenecks are then visualised using a traffic-light colour matrix, in which red, yellow and green mean respectively supply issues of high, medium and low risk.

Key findings

The technologies

Advanced batteries: Li-ion

Li-ion battery technology has improved recently, and has now become a real emerging technology across a wide range of civil and defence applications. Li-ion batteries offer improved power and energy performance compared to the currently used lead-acid batteries. Li-ion batteries are now used for portable applications such as tactical radios, thermal imagers and portable computing. In the next 5 years Li-ion batteries will further expand to heavy-duty platforms, such as military vehicles, boats, shelter applications, aircraft and missiles. Military land applications represent the largest fraction of the military battery market, followed by military naval ships and electric drone applications. While Li-ion batteries are crucial for defence applications, their development and future uptake are primarily driven by the civilian demand for portable electronic devices and, most recently, electric vehicles.

Fuel cells

Fuel cells are providing operational advantages to different mobile, stationary and portable defence applications as a power solution. Fuel cells require less maintenance and zero lubricants, increase endurance and ensure a high specific energy and power density beyond that which can be achieved using conventional battery power. In addition they have the potential to reduce sound and thermal signatures, which is an essential advantage for defence applications. The defence sector could gain noticeably from the unique features of fuel cells, which can provide tactical benefits to and increase the efficiency of the army. There is strong military interest in fuel cells as a means of reducing the logistics burden: fuel cells allow military forces to generate power in the operational theatre using local fuels or other sources, reducing the need to transport fuel with the associated high logistics costs and levels of risk.

Robotics and exoskeletons

Robotics is an emerging field of technology offering enormous potential for many civil and defence applications. Robots can perform military operations considered too risky, too complex or even impossible for humans. Military robots are autonomous or remote-controlled mobile robots designed for military applications, from transport, to search and rescue, to attack. Robots are used in the military on all three fronts — ground, water and sky — for rescue operations, disaster management, surveillance and security. Major tasks performed by robots include bomb disarmament, mine clearance, surveillance and help in search and rescue operations. Wearable robotics for the military is the most dynamic subset of the exoskeleton industry. Exoskeletons can be used by the army to support strength and endurance and protect soldiers from strain injury.

Unmanned vehicles

UVs are an evolving technology with enormous growth potential. The defence industry has recently witnessed growing application in unmanned aerial vehicles (UAVs), as well as in unmanned ground vehicles (UGVs) and unmanned underwater vehicles (UUVs). The potential for market discontinuity is particularly evident for UAVs, as this branch is further developed in terms of market volumes than the UGV and UUV subsectors.

UVs are expected to make significant changes to army, navy and air force operations in the 2021-2040 time frame up to the global scale. They will be crucial for mixed manned and unmanned arms operations. Increased load capabilities, in particular of UGVs and UAVs, will enable the soldier load to be reduced and will thus extend the soldier's active area. UAVs in particular show the potential to provide key support in military operations such as remote sensing; reconnaissance; surveillance; target and decoy; the delivery of military cargo to and near combat zones, including lethal and non-lethal payloads; and armed attacks. Eventually, the application of UVs has the potential to reduce human exposure to hazards, reduce costs, extend application ranges and generally give commanders more options for action.

3D printing

3DP is a new technology, which will disrupt the aerospace supply chain significantly by eliminating multiple manufacturing stages. It allows for reduction, substitution, recycling and mitigation in the use of CRMs and traditionally manufactured components. This is particularly relevant to defence in resource-constraint situations and/or remote locations in order to keep aerospace platforms operational. Currently, the use of 3DP in the defence sector is both very promising and merely anecdotal. The sector is not yet thoroughly incorporating 3DP, and thus is not yet exploiting the full technical potential offered by reducing weight and creating stronger and more efficient components.

Raw materials supply risks

Access to raw materials, and in particular to CRMs, is of great importance for the successful and smooth deployment of established and emerging technologies in Europe. This applies in particular to the five investigated technologies, which show massive growth potential. Several factors play a role when defining the risk of supply disruptions for Europe. One factor is the limited production of raw materials in Europe. Another factor is the high geographic concentration of the supply for some materials. The supply of certain strategic materials is dominated by only a few countries, several of which have politically instable governments. These factors, coupled with a rapid increase in demand, are risk factors for a potential supply shortage.

The study confirmed the supposition that Europe currently produces only a small proportion of the raw materials required overall for Li-ion batteries, fuel cells, robotics, drones and 3DP technologies. The study has revealed Europe's extremely high dependence on the supply of raw materials for all five technologies, supplying between 2 % of the raw materials (for Li-ion) and 5 % (for fuel cells). China dominates global production of the raw materials required for these five technologies, supplying between 22 % and 32 % across the five technologies. Other key suppliers of raw materials are South Africa, Russia and Brazil for all five technologies except Li-ion batteries, for which Australia and Chile are the major suppliers after China.

Critical raw materials supply risks

As regards the supply of CRMs for the five technologies, drones require the most at 23 CRMs, followed by robotics (19 CRMs), fuel cells (11 CRMs), 3DP (8 CRMs) and Li-ion batteries (5 CRMs). Europe provides only 1 % of the CRMs required for its research and industrial needs. The major supplier of CRMs is China, with a share of almost 40 %, followed by South Africa, Russia, the Democratic Republic of the Congo and Brazil. China is the major supplier of 13 of the 23 CRMs, namely Sb, Bi, F, Ga, In, Mg, C, P, rare earth elements (REEs), Sc, Si, W and V. Around 40 % of the CRMs are provided by many small suppliers, with a < 1 % production share. Altogether, Li-ion batteries, fuel cells, robotics, UVs and additive manufacturing rely on 23 CRMs ([1]). The most used critical material in all five selected technologies is cobalt. The demand for cobalt is expected to rise sharply, especially with the market launch of electromobility, which may create supply shortages. Another bottleneck or supply risk is linked to the geopolitical stability of the main producing country. Currently, 54 % of cobalt mine production comes from the Democratic Republic of the Congo, a country experiencing situations of violence and political instability. An additional bottleneck for cobalt is the refining stage: the majority is refined in China. China is also the major producer of magnesium, natural graphite, silicon metal and vanadium (CRMs used in four of the five technologies). Most of the other critical materials are used in three of the five technologies.

The CRMs used in the selected technologies are listed below.

— **Li-ion batteries.** Cobalt, fluorspar, natural graphite, phosphorus and silicon metal.

— **Fuel cells and hydrogen-related technologies.** Boron, cobalt, magnesium, natural graphite, palladium, platinum, REEs, rhodium, ruthenium, silicon metal, vanadium.

— **Robotics.** Antimony, bismuth, gallium, indium, tantalum and tungsten, in addition to the CRMs required in Li-ion batteries and fuel cells.

([1]) Platinum group metals (PGMs) are considered to be separate materials, while REEs were considered as a single material in the assessment.

— **Unmanned (aerial) vehicles.** Beryllium, niobium, hafnium and scandium, in addition to the CRMs needed in robotics.

— **3DP.** Cobalt, hafnium, magnesium, niobium, scandium, silicon metal, tungsten and vanadium. Of the non-critical materials, titanium is particularly relevant to metal-based 3DP for aerospace.

Processed materials supply risks

By the term 'processed materials' we mean manufactured materials such as composites, ceramics, steels and special alloys, along with advanced materials such as nanomaterials, graphene and carbon nanotubes. With the exception of Li-ion batteries, Europe is a strong supplier, globally, of the processed materials required for the five selected technologies. In general, Europe produces around 30 % of the processed materials required for Li-ion batteries, fuel cells, robotics, drones and 3DP technologies.

Although a strong player in the field of processed materials production, Europe is highly dependent on the supply of some specific materials such as aramid fibre and semiconductors (main supplier United States; used in robotics and UAVs); ferroniobium (main supplier Brazil; used in UAVs and 3DP) and processed materials for Li-ion batteries (main supplier China). Such dependencies apply to both the civil and the defence sectors. To a lesser degree, Europe also relies on the supply of nanomaterials, specific Al alloys and speciality steels.

The key suppliers of processed materials resulting from the analysis are:

— China, Japan and South Korea for Li-ion batteries;

— United States, China and Japan for fuel cells;

— United States, China and India for robotics and drones;

— United States, Canada and Japan for 3DP.

The United States is a major supplier of the processed materials used in fuel cells, robotics and drones such as fibres (carbon and Kevlar), semiconductors, polymers, yttria-stabilised zirconia, nanomaterials and carbon nanotubes. Japan is among the key suppliers of processed materials for Li-ion batteries (nickel cobalt aluminium (NCA) cathode material) and is an important supplier of carbon fibre composites (CFCs), used in robotics and drones. China is a key supplier of processed materials for Li-ion batteries and is an important supplier of Mg and Ni-Ti alloys, along with magnetic alloys/powders for robotics and drones. South Korea is an important supplier of semiconductors and cathode and anode materials for Li-ion batteries. India is an important supplier of the steels and special alloys (Al, Ni, Ni-Ti) required in robotics and drones, while Canada is an important supplier of processed materials for fuel cells.

Europe is relatively strong in processing capacities of materials for 3DP, with 40 % to 60 % of the suppliers of Ti alloys, Al/Mg alloys, Ni alloys, stainless steel alloys and special alloys being located in Europe. With only a small number of metal (aluminium and titanium) powder suppliers identified globally so far, the supply risk for metal-based 3DP for aerospace is still evaluated as high. Europe also appears to have a gap in the supply chain of all metal wire products. The analysis identified only two main suppliers with headquarters located in Europe. Most of the suppliers (at least 10) are located in China, and two suppliers in the United States. This may cause a significant lack of customisation capabilities between processed materials and the specific 3DP technologies that have been developed.

Specific processed materials for military applications are those used in low-signature (low observable) applications. However, country production shares for such materials could not be assessed due to a lack of data.

Components supply risks

By the term 'components' [2] we mean finished parts ready to be used in certain applications, such as cathodes for batteries or fuel cells, motors and gears for robots and sensors for drones. With the exception of

[2] Components step for 3DP was not considered (explanation given in the 3DP chapter).

fuel cell technology, Europe is home to a relatively low rate of domestic production of components. A key issue for batteries is the lack of EU capacity in Li-ion cell component manufacturing (cathodes, anodes, electrolytes and separators) and in cell manufacturing itself, for each of which there is a high level of dependence on China. Although the European share of the production of Li-ion cells is expected to increase — following the European strategic action plan on batteries adopted in 2018 — Li-ion batteries for common military applications are still assembled from commercial cells manufactured in Asia. China is also a major supplier (80 %) of the REE magnets used in robots and drones for both civil and defence applications.

A high level of dependency is also observed in robotics and UAVs: one of the main concerns of the EU industry is the lack of EU component manufacturers, with the United States leading the supply of actuators, controllers (processors), graphics processing units (GPUs) and inertial measurement units (IMUs), while Japan dominates the supply of high-precision gears. The key suppliers of components shown in the analysis are:

— China, Japan and South Korea for Li-ion batteries;

— North America, Japan and Europe for fuel cells;

— United States, China and Japan for robotics and drones.

Overall, Europe produces around 12 % of the components required for Li-ion batteries, fuel cells, robotics, drones and 3DP technologies. More specifically, Europe produces around 8 % of the components for Li-ion batteries, 25 % for fuel cells, 4 % for robotics and 13 % for drones. It can be assumed that such dependencies are basically valid for both civil and defence applications.

Assembly supply risks

By the term 'assembly' we mean finished products such as Li-ion cells, fuel cells, robots, drones and 3DP systems. Overall, Europe produces around 0.2 % of Li-ion batteries, 1 % of fuel cells, 41 % of robots, 9 % of UAVs and 34 % of 3D metal systems globally.

Europe is still a strong player in the production of robots (mainly service but also industrial) and 3D metal systems. Europe provides around 40 % of robots and supplies 34 % of additive manufacturing metal systems globally. However such leadership is being strongly challenged by China for both technologies; the picture may change drastically in the coming years — by 2025 — reflecting the ambitious 'Made in China 2025' initiative. Europe has some production of drones, though certainly not enough to satisfy its needs. Europe is very weak in the supply of Li-batteries and fuel cells, which are predominantly provided by Asia (China, Japan and South Korea) and North America (United States and Canada).

Japanese manufacturers dominate industrial robotics, while US manufacturers dominate non-industrial robotics (e.g. surgical, defence and rescue), UVs and artificial intelligence. China dominates the manufacture of UAVs for civil purposes. The United States is the key player in military drones, along with military UGVs and UUVs, of which Europe is the second-biggest producer. Europe leads the exoskeleton market (based on the number of companies producing exoskeletons), followed by the United States, Japan, Canada and several other countries. The main use of exoskeletons is currently in the medical sector for rehabilitation purposes. Defence represents only 8 % of the exoskeleton market, in which US companies are the key players. Requirements for military exoskeletons are more stringent than for their civil counterparts: they need more strength and less weight, in addition to smaller, optimised power units allowing troops to be more independent. As the use of fibres (Kevlar and carbon) is critical for military exoskeletons, Europe faces a high level of dependence on the United States for the supply of such materials.

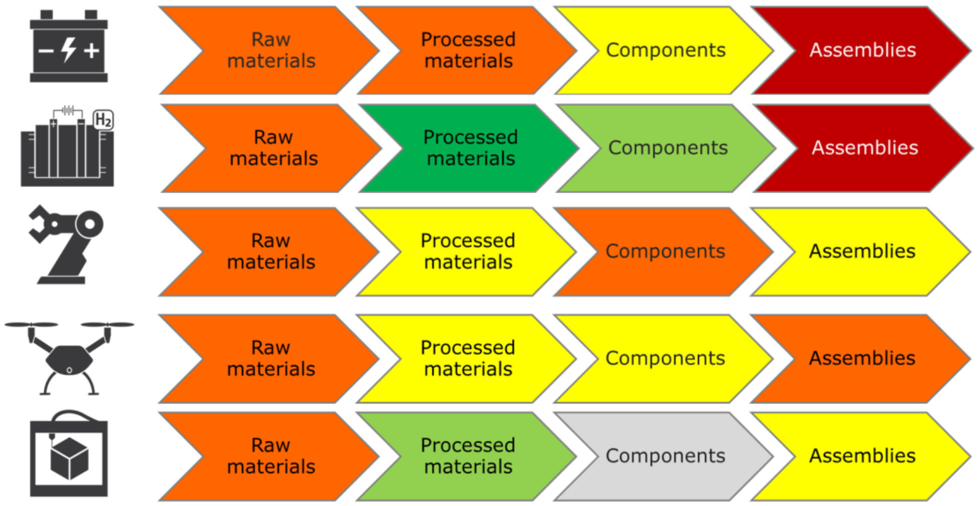
Regarding 3D printers for industrial use, the United States leads in polymer-based technologies, with Europe strongly present in metal additive manufacturing (AM), which is more relevant to aerospace. On the basis of total units sold, Europe has about 20 % of the market share and the United States and Israel represent over 71 % of supply. Europe's share in the number of suppliers is 25 % and 21 % respectively for the two key sub-technologies: powder bed fusion (PBF) and directed energy deposition (DED). China has a high and fast-growing number of individual suppliers, albeit with a relatively low number of unit shipments so far. For aerospace applications, the United States and the EU are equally present in the top 15 system integrators such as Airbus and Boeing, driving the development of 3DP on a large scale in their own way, in their respective supply chains.

Policy recommendations

This report stresses the importance of utilising the synergies between the civil and defence sectors in order to increase interest in common, dual-use research and investment opportunities. For some technologies, such as Li-ion batteries and fuel cells, supporting such synergies is even more crucial where volumes for defence are small and Europe has a weak position globally.

The analysis has shown that the weakest step in the supply chain, for the five technologies under the spotlight, is the supply of raw materials. Furthermore, the supply of assemblies appears to be very critical for three of the technologies, namely Li-ion batteries, fuel cells and drones. The supply of processed materials is shown to be critical for Li-ion batteries, though some supply risks are also detected for robotics and drones. At the components level, though some supply risks are detected for Li-ion batteries and drones, robotics seems to be the most vulnerable of the technologies (Figure 1).

Figure 1. Identified supply risks for Europe in the supply chains of Li-ion batteries, fuel cells, robotics, drones and 3D printing



Source: JRC

Europe should therefore introduce mitigation strategies throughout the whole supply chain as soon as possible. At the level of raw materials, such strategies could include **supply diversification, increased recycling volumes** and the **substitution of critical materials**, for example the substitution of cobalt and PGMs, needed in Li-ion batteries and fuel cells and relevant also for robotics and UVs. Cobalt is also one of the CRMs for 3DP technology. Recycling is of particular importance for Li-ion batteries as a feasible way to secure access to raw materials. The role of China as a key supplier in the supply chains examined here is noteworthy. China has acquired, and continues to expand its dominant position in the Li-ion battery and drone supply chains, and has ambitious plans in the fields of robotics, fuel cells and 3DP.

In addition, **stockpiling could be considered to secure access to raw materials** in the event of a crisis. A dedicated study needs to be commissioned to evaluate and analyse in more depth the potential of stockpiling materials essential to the development of certain technologies, looking at the environmental and economic impact and taking into account the expected technological developments in the future.

Tailored, competitive awards-based programmes could be initiated to encourage European companies, in particular small businesses, to engage in European defence R & D with the potential for commercialisation, i.e. high technology readiness level. The European Defence Fund could notably fund collaborative cross-border defence R & D to increase its attractiveness and to encourage SMEs to get involved. Such programmes, with a primary focus on defence, would lead to the procurement and development of new industrial capabilities addressing raw and processed materials criticalities with additional civil potential.

The report also calls for support to **increase manufacturing opportunities in Europe** by creating an attractive investment environment for European companies.

Further key policy actions identified in the report include fostering **international collaboration** (e.g. for fuel cells); **supporting standardisation activities** (e.g. 3DP, fuel cells, robotics and drones); and promoting the **cyber physical security** of robotics systems (including UVs).

Research needs relevant to defence applications

Besides the dual-use research needs identified in this study, important defence-related research areas should also be explored as potential topics for future reserach.

Li-ion batteries

— **Research on system management to address specific military requirements** such as thermal management, electromagnetic compatibility and battery safety.

— **Research on Li-ion batteries** with lithium iron phosphate as a cathode material and lithium titanate replacing the graphite in the anode to improve the specific energy (3) and reduce discharging and costs. Such battery types are of interest to the naval and land defence sectors, especially for military vehicle applications in relation to providing 'silent-watch' conditions.

— **Research on emerging advanced batteries such as lithium-sulfur (Li-S) and lithium-air (Li-air)**, with high potential for military applications, as they are both characterised by a very high specific energy density. Li-air batteries represent an emerging and promising chemistry for soldier-portable batteries and aviation. Li-S batteries also show great potential, especially for high-energy military applications, as they can offer a theoretical energy density more than five times that of Li-ion batteries. Li-S batteries also have the advantage of not containing any environmentally harmful fluorine, but research on new manufacturing processes is needed to make this technology commercially viable and usable for the defence sector.

Fuel cells

For military purposes, operating fuel cell systems independently from a hydrogen infrastructure is an essential point. The hydrogen needs to be produced on-site. This aspect is especially important for mobile fuel cell applications, including defence applications. The most feasible way to produce hydrogen for military purposes is reforming of diesel fuel or kerosene, as both fuels are readily available in the armed forces and logistics are available for these types of fuel. However, logistic fuels contain some amount of sulfur, which is detrimental for fuel cells — it poisons the noble metal catalysts. Desulfurisation is therefore considered to be a very important step in fuel-processing technologies for military purposes. Consequently, the following research areas should be explored.

— **Development of systems that can operate on logistic fuels as well as fuel cell systems, capable of operating in harsh environmental conditions** (e.g. Arctic or desert) and giving an advantage to the army. Fuel cells tolerating sulfur could greatly facilitate military operations.

(3) The specific energy of a battery is defined as the battery capacity in weight (Wh/kg), or the energy that can be stored in 1 kg of active material.

— **Research on portable on-site fuel reformers and desulfurisation methods applicable directly to logistic fuels.** This includes innovative materials for on-site hydrogen purification — for example, materials based on noble metals such as silver, gold and palladium seem to be a promising solution for the desulfurisation of logistic fuels.

— **Development of reliable stack-sealing concepts** ([4]), which could be more challenging for defence applications, especially mobile ones, due to more stringent requirements regarding vibrations and shock.

— Fuel cells such as direct-methanol fuel cells (DMFCs) can save energy and reduce the operating costs associated with dependence on foreign oil. These fuel cells are relevant to defence applications when used in remote locations to ensure electric power for battery charging, auxiliary power for surveillance and regular power for communication equipment. **Research actions aiming at replacing methanol with ethanol in DMFCs could be relevant due to the toxicity of methanol.**

Robotics and unmanned vehicles

— **Development of advanced, lightweight, high-strength, structural materials** (e.g. based on Al, Mg, Ti-alloys, composites) for robotics (including exoskeletons) and large UAVs.

— **Development of innovative smart** ([5]) and **multifunctional materials** ([6]) for special applications such as: multifunctional actuators ([7]) and artificial muscles (e.g. vanadium-based materials); **electronic skin** ([8]) (e.g. composites of soft materials with conductive fillers, polymer-based materials, which could also incorporate metallic (e.g. Ni) microparticles into a polymer network, flexible and porous graphene foams); **materials, paints and textiles to mitigate and reduce signatures** (e.g. foams, plastics, elastomers, low-emissivity paints, multispectral patterned textile netting); and **materials for soft robotics** (e.g. printed liquid metals, metallic glass, liquid silicone rubber).

— Development of **smaller, more powerful, high-speed and precision electronics for military applications**: complex military systems require efficient power electronics. High-density power electronics with high efficiencies (> 90 %) are becoming a requirement for high-end mission-critical military platforms, including UAVs, for which size, weight and power are limited. Gallium nitride-based radio-frequency components are beginning to populate military radio-frequency applications.

— Energy storage is a major bottleneck for mobile robotics. The **development of smaller and more efficient power/energy sources** (batteries, fuel cells or other alternative sources) and electric motors specifically important for exoskeletons and UAVs is another challenge to be faced by robotics and UAVs.

— Development of **armour with high ballistic performance** and increased blast and shrapnel protection (e.g. complex composite materials, steel-alloys, Ti-alloys etc.).

— **Cyber physical security of electronics systems** (such as controllers) for military robotics applications, including UAVs: methods to protect military systems (and critical civil infrastructure) against cyber supply-chain attacks.

([4]) Each individual fuel cell needs to be securely sealed in order to be protected from the environment and neighbouring cells. Stack sealing is therefore decisive for the cell's lifespan. Sealing materials should be reliable (resist thermal and mechanical shocks and vibrations), should not react with the other fuel cell components and also should not be expensive.

([5]) Smart materials are materials that can change their stiffness and shape, for example.

([6]) Multifunctional materials, integrating processes like sensing, movement, energy harvesting or energy storage (e.g. materials that can change over time to adapt or heal). Smart materials can be considered to be multifunctional materials that have the ability to react upon an external stimulus, thus simulating the behaviour of nature's materials.

([7]) Actuators can be considered to be a robot's muscles.

([8]) Electronic skin refers to flexible, stretchable and self-healing electronics that are able to mimic the functionalities of human or animal skin.

— Technology advancements to develop **more autonomous, smaller, more economical and more efficient military UAVs.**

— Research on **counter drone systems** will secure the data link and support shielding for emissions security (e.g. silver plating).

3D printing

Targeted investment in 3DP R & D for defence will enhance capabilities related to mobility, sustainability, repair and maintenance. More investment is needed to keep up with the pace of development in the United States and China. The potential of 3DP for defence capabilities is crucial for the smooth operation of combat and peacekeeping missions. It is recommended that R & D focus specifically on the following.

— The **development of new sustainable materials and processes**, and related characterisation in the field of multifunctional materials, multi-materials and materials with highly improved functionality for aerospace applications, special alloys used for defence and space purposes and incorporating such elements as niobium, hafnium/zirconium and scandium.

— **REACH** (registration, evaluation, authorisation and restriction of chemicals) **related issues** to be further investigated to ensure safe handling and proper removal and recycling from powder beds (9).

— The **standardisation and certification of metal powders and wire recipes for AM**, which would aid EU companies in particular, considering that EU companies, and SMEs in particular, are relatively well positioned to produce high-quality components. The preference of the aerospace industry itself is to have a stable and international standardisation process involving European and international bodies (AM-motion, 2018; DefenceIQ, 2016). With regard to the Chinese research and development pace, which is seemingly much faster than that of the EU, it is recommended that targeted research and innovation actions be funded in this technical domain.

— An improved **strategic assessment of the resilience of the military supply chains**. The (future) supply chain of the critical sectors of aerospace and defence will inevitably rely more and more on 3DP in the near future. This warrants a careful reconsideration of specific strategies to mitigate supply risk. As a supporting strategy, **creating strategic stockpiles for the manufacturing** of the main 3DP powders can be reconsidered (RPA, 2012). Here, the most relevant 3DP powders identified in the background report include titanium grade 2, grade 5 and grade 23, Al-10Si-Mg, Al07Si-0.6Mg, nickel alloys 316L and 625, stainless steel alloy 718; CoCr and possibly specific zirconium and niobium alloys.

— The use of **3DP for the repair and maintenance of equipment used in operations at remote locations**.

— Address the current **lack of customisation capabilities between the processed materials and the specific 3DP technology**, as well as the availability of high-quality, environmentally friendly and cost-effective materials.

— Comprehensive assessment of aspects related to **sustainability, responsible sourcing, skills and workforce, IPR protection and digital security**.

Cross-cutting research topics identified in this study include **the maintenance of a knowledge base and skilled workforce in Europe**, including **software development skills** — a key enabler for the development of robotic and autonomous systems for both European military forces and civil applications. **Sensors are another cross-cutting element**, becoming ever more important; their development and the processing of their data should receive close attention.

(9) Nickel is restricted for certain uses related to skin contact. Cobalt, magnesium, niobium and tungsten are registered as well. In this case, their specific properties will likely lead to more demand rather than restricted use in the future.

Policy context

Raw materials are crucial for the trade and competitiveness of EU industry, as highlighted in various policies such as the renewed industry policy strategy (COM(2017) 479 final), the raw material initiative (COM(2008) 699) and the circular economy action plan (COM(2015) 614). Secure and sustainable access to raw materials is vital for strategic value chains such as batteries, e-mobility, renewable energy and defence. Following communication COM(2013) 542 and the European defence action plan (COM(2016) 950), this report analyses raw materials supply risks for the value chains of five dual-use technologies considered both strategically important for resilience in the defence sectors and fundamental for competitiveness in relation to their civil use.

Main findings

This study identifies bottlenecks and supply risks linked to raw materials and processed materials needed for the development of key defence capabilities by Europe's defence industry. **The dependence of Europe on the supply of raw materials for the five analysed technologies is extremely high.** Europe produces on average around 3 % of the overall raw materials required in Li-ion batteries, fuel cells, robotics, drones and 3DP technology. China dominates global production, supplying around one third of the raw materials. Other key suppliers are South Africa (7 %) and Russia (4 %). **With regard to the supply of CRMs required in these five technologies, Europe provides only 1 % of them.** The major supplier is China, with a share of almost 40 %, followed by South Africa (9 %) and Russia (6 %).

With the exception of Li-ion batteries, in general Europe is an important supplier of processed materials for these technologies, providing on average about one third of the materials. Other key suppliers are United States (20 %), China (19 %) and Japan (8 %). Canada, India and South Korea are also key suppliers for 3DP, robotics and Li ion batteries.

With regard to the supply of components, with the exception of fuel cell technology **Europe has a relatively low level of domestic production of components**. On average Europe produces around 12 % of the components required in Li-ion batteries, fuel cells, robotics and drones. Most of the components are supplied by Asia (46 %) and North America (31 %).

Europe is very weak with regard to the supply of Li-ion, LiPo batteries and fuel cells, which is predominantly covered by Asia (China, Japan and South Korea) and North America (United States and Canada).

Europe is a major player in the production of robots. Japanese manufacturers dominate industrial robotics, while US manufacturers dominate non-industrial robotics, robotics for the military, UVs and artificial intelligence. Europe is the leader in the production of exoskeletons for medical and industrial purposes. Other key manufacturers are the United States and Japan. Manufacturers in the United States are also the key players for military exoskeletons.

Europe has some drone production capability, though not enough to satisfy its needs. The United States and China dominate UAV assembly and manufacturing for civil applications. The United States is the leader in the production of UGVs and UMVs. Europe is the second-biggest manufacturer of UGVs and UMVs.

Regarding 3D printers for industrial use, the United States leads in polymer-based technologies, with Europe strongly present in metal additive manufacturing. However, more R & D investment is needed to keep pace with the speed of development observed in the United States and China.

Key conclusions

It is important for Europe to secure the supply throughout the whole supply chain for important emerging dual-use technologies such as Li-ion batteries, fuel cells, robotics/exoskeletons, unmanned systems and 3DP technology. The analysis has shown that **the weakest step in the supply chain for the five investigated technologies is the supply of raw materials.** Furthermore, the supply of assemblies appears to be very critical for three of the technologies, namely Li-ion batteries, fuel cells and drones. The supply of processed materials is critical for Li-ion batteries, though some supply risks are detected for robotics and drones. At the components level, though some supply risks are detected for Li-ion batteries and drones, robotics seems to be the most vulnerable technology.

The extremely high dependency of Europe on the supply of raw materials required for these technologies should be mitigated via various measures. China has the dominant position in the supply of raw materials, including CRMs used in the five technologies. The other two major suppliers are South Africa and Russia. Yet a large amount of the materials are provided by numerous small suppliers, which gives good perspectives for **supply diversification**. The same is also true for the supply of processed materials and components required in those dual-use technologies for which Europe has no or insufficient production. In addition, **stockpiling** could be another way to secure access to raw or processed materials and components in the event of a crisis. A comprehensive analysis is needed to evaluate the potential and the feasibility of stockpiling for each of the technologies in question. Securing sustainable access to the right quantity and quality of raw materials is also a key element for future responsible developments in EU industry.

Tailored, **competitive awards-based programmes** could be initiated to encourage domestic small businesses to engage in European defence R & D with the potential for commercialisation, i.e. a high technology-readiness level. The European Defence Fund could fund collaborative cross-border defence research to increase its attractiveness and encourage SMEs to get involved. Such programmes, with a primary focus on defence, would lead to the procurement and development of new industrial capabilities with additional civil potential.

The report also calls for the provision of support to **increase manufacturing opportunities in Europe** by creating an attractive investment environment for European companies.

Further key policy actions identified in the report include **fostering international collaboration** (e.g. for fuel cells); **supporting standardisation activities** (e.g. 3DP, fuel cells, robotics and drones); and **promoting the cyber physical security of robotics systems** (including UVs).

Cross-cutting research topics identified in this study include the maintenance of a knowledge base and a skilled workforce in Europe, including software development skills — a key enabler for the development of robotic and autonomous systems for both European military forces and civil applications. Sensors are another cross-cutting element that is becoming ever more important; their development and the processing of their data should receive close attention.

Lastly, it is recommended that **more outreaching, strategic and comprehensive discussions on the role and future competitiveness of these emerging technologies be organised**, in particular on the aspects of material availability, sustainability, IPR protection, software development and digital security for key military and civil supply chains.

Related and future JRC work

This study is a part of the JRC raw materials project, which aims at supporting various EU policies by building the knowledge base (e.g. data, indicators, analysis, models and methodologies) required to ensure a secure and sustainable supply of primary and secondary raw materials across a wide range of value chains and sectors. The study is a follow-up to the 2016 study *Raw Materials in the European Defence Industry*, which identified a list of raw materials that are important for European defence. The present study analyses in more detail the specific supply risks in the entire value chain for five key technologies, with a focus on the early stage of extraction and refining of raw materials, and processed materials available for manufacturing.

The outcomes of this report support the further development of the EU's knowledge base on raw materials and the JRC Raw Materials Information System. It also provides valuable insights into individual materials to update the list of CRMs to be published in 2020. Finally, the results feed into ongoing research on the supply of primary and secondary raw materials, supporting in particular the implementation of the strategic action plan on batteries (COM(2018) 293).

Quick guide

This document is a summary report of the JRC technical background report '*Materials dependencies for dual-use technologies relevant to Europe's defence sector*', EUR 29889 EN, referenced here as MatDual (2019).

A comprehensive analysis, all data and information sources used to perform the analysis can be found in the JRC background report. In this summary the main facts and findings for the five investigated technologies are briefly summarised.

2. Introduction

Materials are important assets that contribute to the prosperity and power of nations. They are seen as powerful weapons in economic warfare. Ensuring a sustainable supply of materials is, therefore, of crucial importance for Europe. And when they are needed for defence applications, materials assume strategic importance. The supply of raw materials is, however, just one side of the coin. The processing of raw materials and their transformation into advanced industrial products, in the context of growing scarcity and an increasing world population, is equally important. The need to obtain more with less is even greater, considering the relatively low or even non-existent potential for recycling of some of the materials used in many modern products. The potential for material substitution is often weak and is limited in many fields, amplifying yet further the need to secure our supplies. The processing of raw materials must therefore become smarter and more effective, producing high-quality products with as little of the raw material as possible. Using advanced manufacturing methods such as additive manufacturing is just one way to deal with such a challenge. Applying innovative methods to achieve higher recovery rates during the recycling of products is another. Reuse and remanufacturing approaches, part of a circular economic policy, are mitigating measures that can further reduce the demand for primary materials.

Various measures can be introduced to mitigate the supply risk, but they will not be sufficient to cope with rapidly increasing demand. The supply of primary raw materials will continue to be a key factor in the vulnerability of Europe and its deployment of emerging technologies. Europe is highly dependent on the supply of raw materials. Ensuring sustainable access to them is crucial for the processing and manufacturing industries, in both the civil sector and the defence sector. The present study aims to identify bottlenecks in the supply of materials needed for the development of several dual-use emerging technologies important to Europe's defence and civil industries. The ultimate goals of the study are to: (1) identify possible opportunities for targeted policy actions to support the sustainable supply of such materials; (2) support DG Internal Market, Industry, Entrepreneurship and SMEs in the preparation of future research programmes at EU level; and (3) raise awareness among companies, in particular SMEs, about possible supply-chain issues related to materials.

Five emerging dual-use technologies have been selected for this study, namely: (1) batteries; (2) fuel cells and hydrogen storage; (3) robotics; (4) UVs; and (5) additive manufacturing (3DP). All five technologies are part of a wider list of technologies of high relevance to the European defence technological and industrial base in terms of strategic independence, economic impact, and knowledge and innovation. The list was established by a recent study (KET4Dual, 2017), where 38 technology areas were identified as innovation areas of common interest for both the civil sector and the military sector in which Europe should invest strategically.

The five selected technologies are thoroughly examined with regard to pertinence to specific civil and defence applications, future demand trends, material requirements, supply of materials and key players in the supply chain, along with specific bottlenecks beyond material supply issues, including the necessity of a skilled workforce, know-how, regulation and legislation matters and the involvement of industry. There is a special focus on technology supply-chain issues, from raw materials to assembly, identifying key players at specific levels of the supply chain. Four supply-chain levels were chosen for the analysis, namely: level 1 — raw materials; level 2 — processed materials; level 3 — components; and level 4 — assemblies. The specificities of these five technologies with regard to defence applications are analysed, as military requirements are often more challenging than civil ones.

A dedicated methodology, relying on several key parameters, has been developed to identify forthcoming bottlenecks in the supply chains of the selected five technologies, from raw materials to final assemblies (e.g. Li-ion cells, fuel cells, robots). Such parameters reflect the concentration of supply, the availability of domestic production in Europe, the import reliance on specific raw materials, the use of CRMs in the analysed technologies and the substitution and recycling potential of raw materials required in these technologies. The expected demand trends for each technology are also taken into consideration as a factor that could challenge the adequate, continued and sustainable supply of materials, components and assemblies. Potential bottlenecks are then visualised using a traffic-light colour matrix in which red, yellow and green respectively mean a high, medium and low risk of supply issues.

This study also provides an overview of ongoing research in Europe in relation to the selected five technologies. A dedicated patent analysis covering worldwide patent activities has also been carried out, following a methodology developed specifically for this analysis. A comparison between Europe and other leading countries has been made, and the top patenting companies listed for each technology. Details can be found in the related JRC technical background report (MatDual, 2019).

Finally, opportunities for research activities and policy actions were proposed, based on the analysis described above.

3. Advanced (Li-ion) battery technology

3.1. Applications of and demand for Li-ion batteries

The chapter describes the importance to military users of advanced Li-ion batteries and intelligent battery-powered solutions, which can give operational advantages in various applications, from military land vehicles to anti-tank guided-missile systems or soldiers' equipment.

Traditional lead-acid batteries have been used by mechanised military forces since World War One, going through a major modernisation phase in the 1970s with the introduction of sealed lead-acid batteries. Lead-acid batteries are still used in the majority of military land vehicles, and they are expected to remain in use in the immediate future since they are reliable and low cost. However, the low energy capabilities of lead-acid batteries, combined with their long charging times, has significantly restricted the silent-watch performance of military land vehicles.

Today there is a strong need for **intelligent battery-powered solutions** to power modern defence applications such as wearable computers, night-vision systems, satellite communication systems, lasers, acoustics, magnetic and seismic sensors, drones, land missiles and other types of electronic equipment. **Advanced military batteries must be secure and safe, with high operational quality and long-term security of supply, and must have the highest possible energy densities.**

Taking the example of batteries for military land vehicles, the report stresses the need for the latter to **deliver high energy** (requested for **silent watch**), to deliver **high power levels for engine starting and load levelling** and to **withstand harsh environmental conditions**. Batteries for military land vehicles need to be **fast charged to minimise engine-on time during silent-watch operations, to reduce the noise of the vehicle and its heat signature**, to lower the **risk of detection and to reduce fuel consumption**. Insufficient electrical energy storage can also inhibit the operational performance of military land vehicles.

Against this backdrop, Li-ion battery technology has improved recently, and has now become a real emerging technology across a wide range of civil and defence applications. **Li-ion batteries offer improved power and energy performance compared to the currently used lead-acid batteries.** Over the last decade, **Li-ion batteries have being used in the defence sector** for portable man applications such as tactical radios, thermal imagers and portable computing. In the next 5 years, Li-ion batteries will further expand to heavy-duty platforms, such as military vehicles, boats, shelter applications, aircraft and missiles. Military land applications represent the largest fraction of the military battery market, followed by military naval ships and electric-drone applications. Although **defence applications currently represent less than 1 % of the total Li-ion battery demand, the demand for batteries in these three defence applications is expected to increase about fourfold between 2018 and 2028** (IDTechEx, 2018). While Li-ion batteries are crucial for defence applications, their development and future uptake are primarily driven by the civilian demand for portable electronic devices and, most recently, electric vehicles.

3.2. Technological challenges for Li-ion batteries

The developments in the field of lithium batteries are very dynamic, and essentially driven by civilian applications, which can be a challenge for the military. If a battery type is not of interest to the civil sector, its adoption by the defence sector will be strongly challenged. Two **recent promising technologies that can meet the specific military requirements for mobile applications (land vehicles)** are lithium iron phosphate and lithium titanate batteries (Sims and Crase, 2017). They can offer greater energy capabilities and are able to be charged quickly. Other benefits of these batteries can be seen in their compatible voltage window, especially in case of lithium titanate, allowing them to immediately replace lead-acid batteries, and their improved safety properties, thus reducing the risk of catching fire when damaged. However, the higher upfront cost of lithium iron phosphate compared to lead-acid batteries remains a challenge to their wider adoption.

Lithium metal oxide batteries use various different metals, such as nickel, cobalt, aluminium and manganese. Lithium metal represents the best alternative to the graphite anode, able to produce a higher energy density compared to the Li-ion batteries used currently. However, lithium metal is still an immature technology, and many issues still need to be addressed, such as dendrite growth, instability of lithium metal, low coulombic efficiency, poor life cycle and safety, and the high flammability of the liquid electrolyte.

By using these types of lithium ion-batteries, it is expected that **the silent-watch endurance of military land vehicles will increase**, but further research is needed before these battery types can be integrated to military land applications in terms of battery management systems.

Li-ion batteries using ionic liquid electrolytes or **molten salts** are also of interest for defence applications, as they show great potential to improve battery safety by decreasing the flammability of organic electrolyte solvents. However, **the development of viable ionic liquid electrolytes remains a challenge that needs to be addressed by appropriate research actions**. For example, suitable combinations of different ionic liquids with synergic physicochemical properties that are also stable against reduction still need to be found in order to meet the requirements for operative conditions of practical devices.

Solid polymer electrolytes could be a key solution to overcome safety issues associated with liquid electrolytes. Indeed, **solid-state batteries** are considered to be an emerging option for next-generation batteries, promising high energy density, high levels of safety, low costs and a long life cycle. However, the current poor ionic conductivity at room temperature and the loss of mechanical properties in the conductive molten state at higher temperatures limit their spread in the battery market.

Research actions also need to be launched on Li-S batteries (a subset of lithium-metal batteries), with regard to their potential to **increase batteries energy capability at a low cost.** Despite a series of characteristics problems such as poor stability and low cycle life, Li-S batteries **show great potential, especially for high-energy applications**, as they can offer a theoretical energy density more than five times that of Li-ion batteries. Li-S batteries also have the advantage of not containing any environmentally harmful fluorine, but on the other hand **new manufacturing processes will be needed to make them commercially viable**.

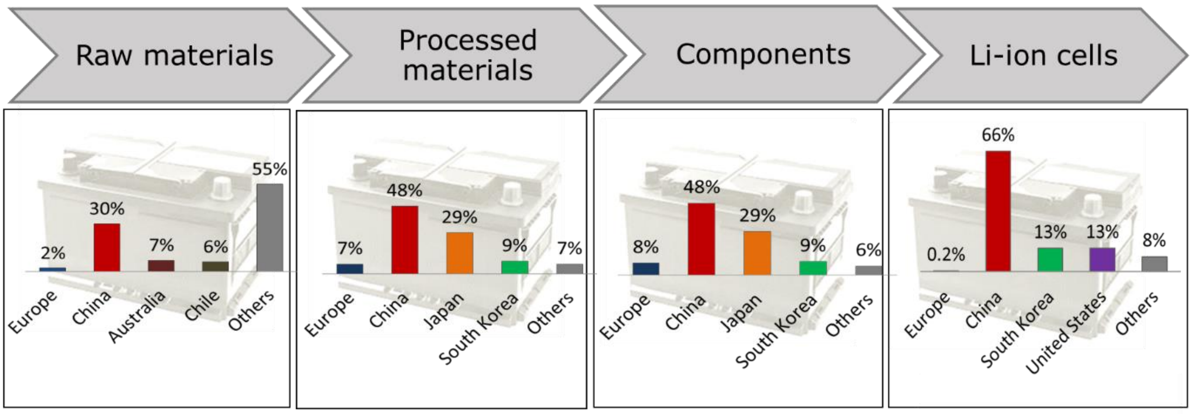
It should be noted, however, that Li-ion batteries using ionic liquid electrolytes and Li-S batteries are immature technologies, and therefore they are not expected to be immediately relevant to military land vehicles. Eventual research on them could, however, provide advantages for the defence sector in the longer term.

Li-ion batteries are also important for powering soldier-portable devices. Performance requests for batteries will increase in the future, for example due to remote wireless devices ensuring more efficient communications, monitoring military equipment and providing instant access to strategic information. **Batteries with a higher gravimetric/volumetric energy density are highly desirable to reduce the weight and volume of the batteries to be carried by each soldier.** In this regard, **lithium carbon monofluoride (Li-CFx) and Li-air represent two emerging and promising chemistries for soldier-portable batteries**, as they both are characterised by a very high specific energy density. Li-CFx batteries have one of the highest energy densities of all commercial lithium primary batteries known to date. However, due to typically limited current, the Li-CFx battery is not used in high-power applications. Li-air batteries have a theoretical specific energy even higher than Li-CFx cells, being considered by specialists as the next revolutionary step in battery power. In practice such a high specific energy has not yet been achieved due to cell-construction considerations. As such, Li-air batteries are still far away from commercial applications, and research still needs to be conducted to fix the issues related to this battery chemistry, especially with regard to improving the cycling stability (expected to reach market by 2040). The construction of an electrochemical cell that takes advantage of both the Li-CFx and the Li-air chemistries is also under consideration.

3.3. Key players in the Li-ion battery supply chain

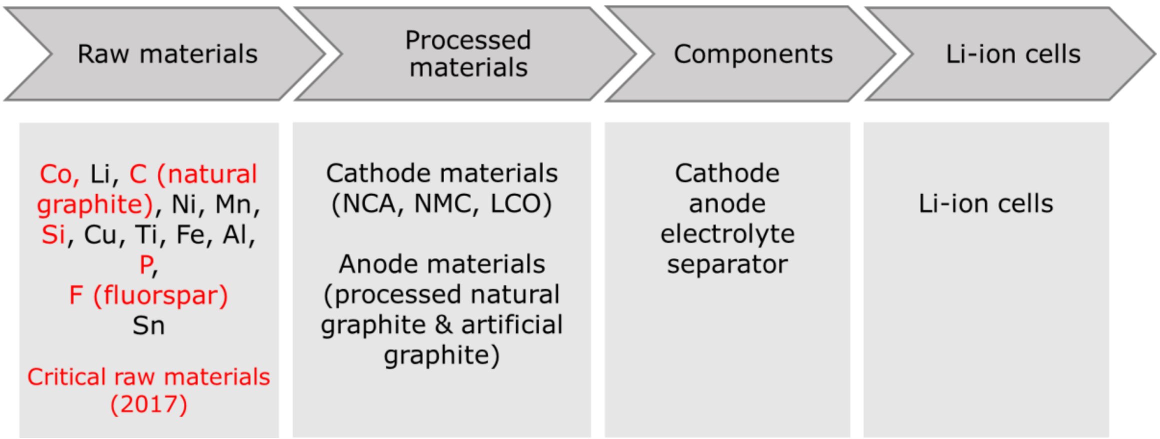
The key players in the Li-ion cell supply chain are shown in Figure 2. **Europe produces only 2 % of the raw materials, and the current Europe contribution to global manufacturing of cell components in Li-ion battery is negligible (< 1 %). China is the major supplier in the whole Li-ion cell supply chain — from raw materials to battery cells.** Other key players in the supply chain are Japan and South Korea for processed materials and components, and South Korea and the United States for the production of Li-ion cells. In Figure 3, an overview is given of the raw materials, processed materials and components required in Li-ion technology that have been considered in the analysis. The country (region) shares shown in Figure 2 are estimated correspondingly.

Figure 2. Li-ion batteries: key players in the supply chain



Source: JRC

Figure 3. Li-ion batteries: an overview of raw materials, processed materials and components considered in the analysis

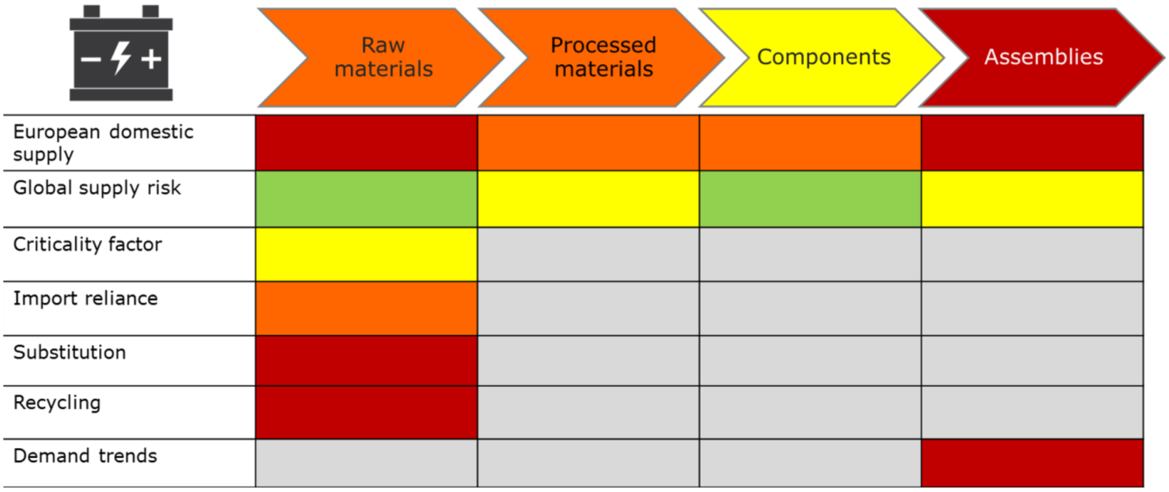


Source: JRC

3.4. Overview of supply risks for the Li-ion battery supply chain

An overview of the various supply risks (issues) and bottlenecks for Li-ion batteries is shown in Figure 4. **Very high supply risk is observed for the last step of the supply chain — Li ion cells production. A high risk of bottlenecks is also detected for the supply of raw and processed materials, while a medium level of risk is estimated for the supply of components.**

Figure 4. Overview of supply risks and bottlenecks in the supply chain of Li-ion cells/batteries

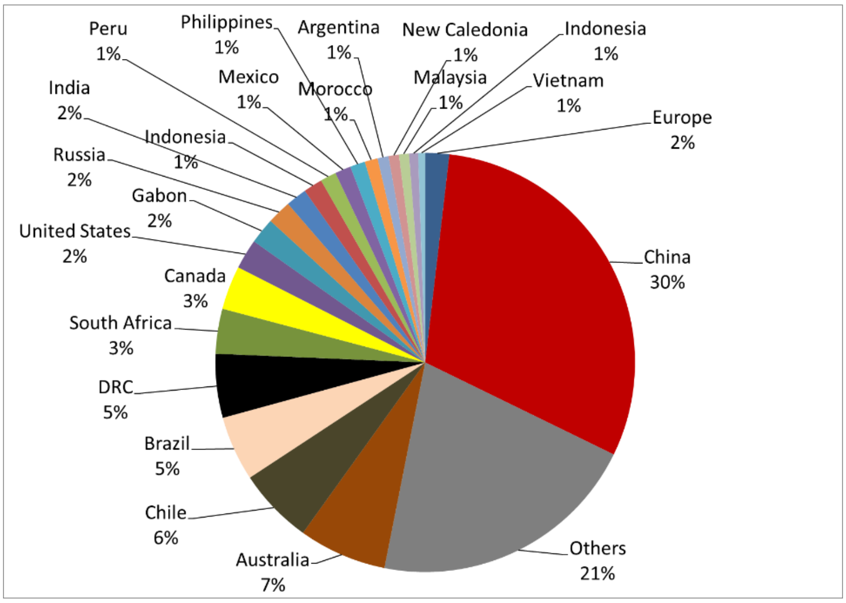


Source: JRC

3.4.1. Supply risks for Li-ion battery raw materials

China delivers one third of the raw materials required in Li-ion batteries and is the major supplier of eight of the 13 raw materials selected as being relevant to Li-ion batteries in this study. Other key suppliers are Australia (7 %) and Chile (6 %). Europe is fully dependent on the supply of 11 raw materials. More than half of the raw materials are supplied by numerous smaller suppliers, providing an opportunity for supply diversification. An overview of the raw materials suppliers for Li-ion batteries is shown in Figure 5.

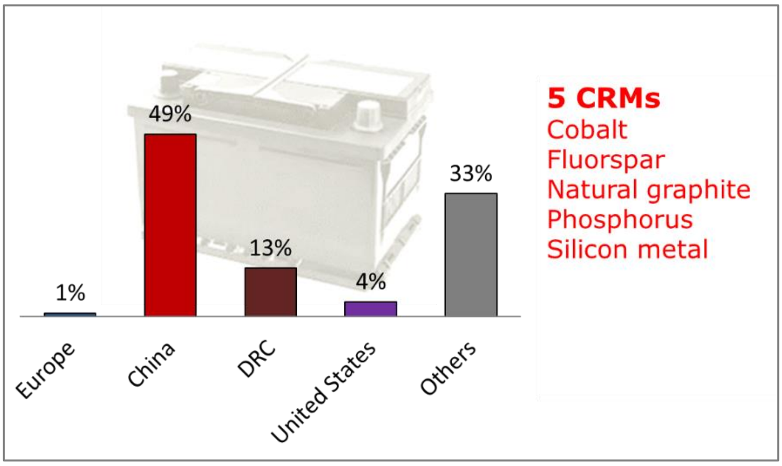
Figure 5. Raw materials suppliers for Li-ion batteries: overview



Source: European Commission, 2017.

The materials of particular importance are Co, C (natural graphite), Si, F and P, which are flagged as critical to the EU economy in the 2017 CRM list. Around half of the CRMs in Li-ion batteries are provided by China. The second key supplier of CRMs for batteries is the Democratic Republic of the Congo (13 %) (Figure 6). Another key material receiving global attention and anticipated to become critical for batteries is lithium. The production and processing of Li will have to be strongly upscaled (possibly more than 10 times according to some scenarios) to match future demand. This might create severe shortages in the supply of Li in future over the longer term (2050 and beyond) (Engineering and Technology, 2018).

Figure 6. Supply of CRMs for Li-ion batteries: key players



Source: European Commission, 2017.

In view of the large quantities of raw materials needed to address the exponential growth of Li-ion battery demand globally, some insights are provided further for three particular materials, which have the potential to become a bottleneck for Li-ion batteries.

The demand for **cobalt** is expected to rise sharply, especially with the market launch of electromobility and the Li-ion batteries required for this purpose. The second supply risk is linked to the geopolitical stability of the producing country. Currently, 54 % of cobalt mine production comes from the Democratic Republic of the Congo, which is associated with unstable political conditions and difficulties in doing business. Cobalt refineries are rarely located near the source mine sites. Instead, major refiners purchase cobalt concentrate from various mines, ship to their own locations and refine cobalt into a usable form for cathode production. **Based on the huge investments made in this sector, the majority of cobalt refining now takes place in China.**

Around 90 % of **lithium** is produced in Australia, Chile and Argentina, mostly from brine and spodumene sources. Despite the recent fears of shortages and price spikes **the supply of lithium is not expected to be an issue for the battery supply chain in the short or medium term** (Jaffe, 2017). In the longer term, however (2050 and beyond), shortages in the supply of lithium could be expected globally, depending of course on the deployment scenario (Engineering and Technology, 2018).

China supplies around 70 % of the global production of natural graphite, with the iron and steel industry being the main driver for its demand. About 10 % of natural graphite demand currently goes into battery applications to manufacture anodes (Dougher, 2018). Although more expensive, synthetic graphite is a viable substitute for natural graphite. In these conditions, **the supply risk for graphite can be considered moderate**.

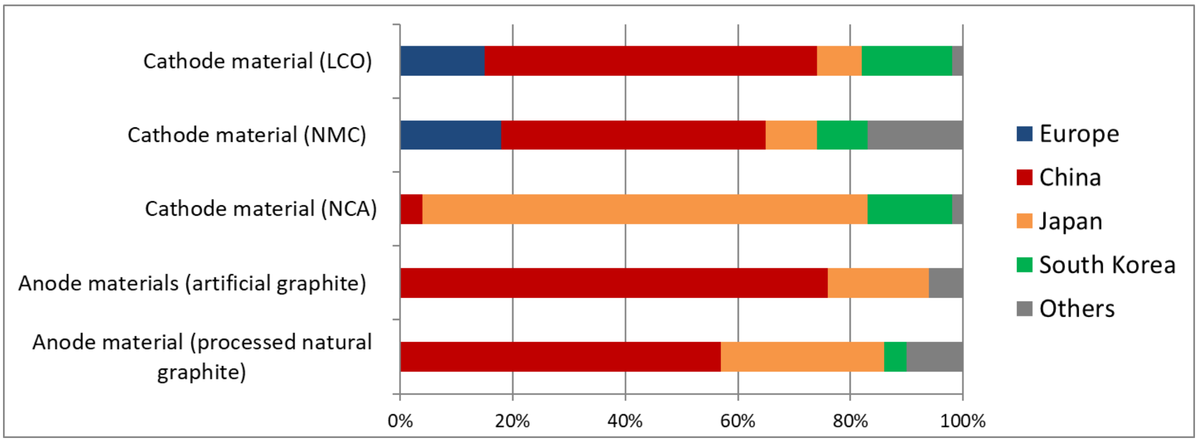
Overall, **China is the major supplier of around half of these three raw materials used in Li-ion batteries**.

3.4.2. Supply risks for Li-ion cell processed materials

Asia, represented by China, Japan and South Korea, delivers 86 % of the processed materials and components for Li-ion batteries globally, with China alone providing 48 %, followed by Japan and South Korea. Europe has a relatively small share of the supply, at 7-8 %. Other countries deliver only 6-7 %, which gives very little margin for supply diversification. In particular, Europe is fully dependent on the supply of processed natural graphite, artificial graphite, NCA cathode material, anode and separators.

Two anode materials (processed natural graphite and artificial graphite) and three cathode materials (NCA, nickel manganese cobalt oxide (NMC) and lithium cobalt oxide (LCO)) are analysed in this study. China is the major supplier of anode materials, as well as NMC and LCO processed materials, while Japan is the key supplier of NCA cathode material. Europe is fully dependent on anode materials and NCA cathode material supply, and delivers around 18 % of NMC materials and 15 % of LCO materials (Figure 7).

Figure 7. Country production shares of processed materials relevant to Li-ion batteries



Source: JRC, BNEF, 2019.

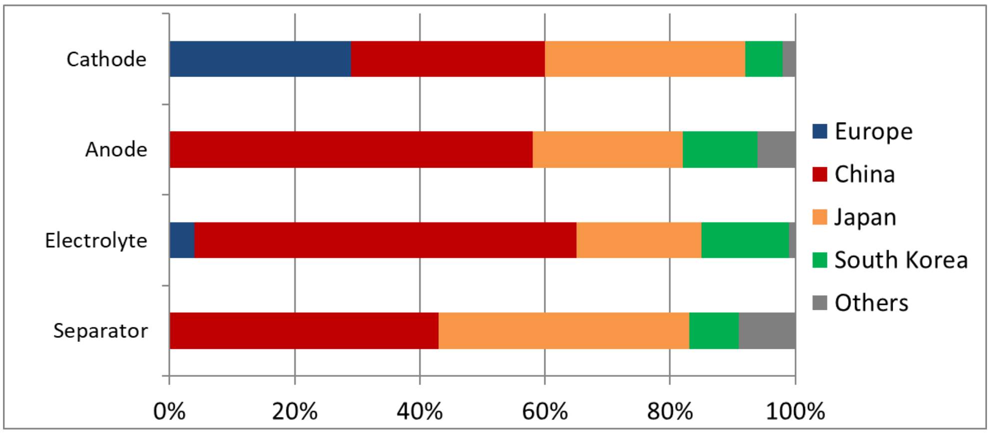
A critical aspect for Europe is the lack of European capacity to produce important processed materials for Li-ion batteries, such as anode materials and NCA cathode material. European companies produce less than 20 % of NMC and LCO materials globally, but this might not be enough to satisfy the European demand for Li-ion batteries.

Even if Europe were able to manufacture the required anode and cathode materials, the supply of appropriate **'battery'-grade raw materials is another critical aspect**. For example, not all nickel in the global supply chain is suited for Li-ion battery production. High-grade nickel products are required to produce nickel sulphate, which represents a principal ingredient in NMC and NCA cathode batteries.

3.4.3. Supply risks for Li-ion cell components

The major supplier of components for Li-ion batteries is again China (48 %), followed by Japan and South Korea. European companies supply around 30 % of overall cathode production and 4 % of electrolytes globally. There is no European production of anodes and separators. The country production shares of Li-ion battery components are shown in Figure 8.

Figure 8. Country production shares of components relevant to Li-ion batteries



Source: JRC, BNEF, 2019.

3.4.4. Supply risks for Li-ion cells

Europe is almost fully dependant on imports of both battery cells and their constituting raw and processed materials, exposing the industry to supply uncertainties and potential high costs. China is definitely the major player in manufacturing Li-ion cells — 66 % of global cell production. Other suppliers are South Korea and United States, with 13 % each. Europe has very marginal production, with 0.2 % of Li-ion cells [10]. Other suppliers provide around 8 % of the global supply, therefore the margin for supply diversification is also limited in this case.

In the short term, a large increase in the production capacity of Li-ion cells is expected to be realised by Chinese companies, which will guarantee the dominance of China in the battery market into the near future. It is also expected that global original equipment manufacturers, cell manufacturers and suppliers will compete with each other to secure their battery supply chains and to secure access to the five essential battery raw materials — lithium, cobalt, nickel, graphite and manganese.

3.5. Civil versus military battery supply chains

While Li-ion batteries are crucial for defence applications, their development and future uptake is primarily driven by the civilian demand for portable electronic devices and, more recently, electric vehicles. Many Li-ion batteries for common military applications are currently assembled from commercial cells manufactured in Asia, meaning that in times of crisis there is no guarantee of logistical availability, military storage capability or interchangeability.

As for civil applications, the defence battery supply chain starts with the raw materials used to produce battery components and covers all other stages of cell manufacturing up to the assembly of the final military product. **The first steps in the battery supply chain, namely the supply of raw materials, their processing and the manufacturing of electrodes, are mostly common to both the civil sector and the defence sector.**

However, batteries need to be more resistant to physical damage and stable in extreme working conditions specific to military operations (e.g. explosive decompression, submersion, thermal and mechanical shock, sand and dust storms). For weapons or support systems in particular, the battery's dimensions, capability and storability need to be specifically designed to meet military requirements. **Consequently, more emphasis must be put upon pack design and assembly, including control systems, electronics and thermal management.**

(10) It should be noted that using company headquarters has its limitations. For example, if the geographical location of companies is considered, Europe would appear to be the supplier of around 5 % of Li-ion cells globally.

By taking into account the **ongoing shift in military preferences towards secondary rechargeable batteries** and an increasing demand for them in coming years, a secure supply chain will be required, in particular for rechargeable Li-ion batteries. There are three major concerns regarding the supply of Li-ion batteries that are also applicable to the defence sector.

1. The security and surge ([11]) **capability** of the supply chain for the manufacturing of battery cells: all required materials and battery components need to be obtained from secure sources alongside the creation of new battery production capacity throughout the supply chain.

2. The very high cost of establishing new manufacturing facilities for battery cells outside Asia (e.g. the total investment cost for a battery gigafactory is estimated at between USD 7.5 billion and USD 10 billion (CleanTechnica, 2019).

3. The possible incompatibility of the dimensions, design standards, safety risks, testing protocols and reliability requirements of batteries, as well as long procurement times for specialised military purposes in comparison to the commercial production of the component cells ([12]).

The rechargeable batteries used in defence applications, in particular Li-ion, are almost entirely assembled from processed materials and cell components manufactured outside the EU, especially in Asia. Defence ministries typically limit their risks by contracting with national battery manufacturing integrators that are aware of 'defence'-related requirements. These companies procure cells from outside (primarily Asian) suppliers, integrate them into batteries together with supporting electronics, which they also procure, and provide the battery management system to manage the power needs required for the military system the battery is designed to fit in. In the same way, **defence ministries fund the development and production of defence-specific application-specific integrated circuits** (which use electronic materials sourced internationally) **by trusted suppliers to meet military specifications for sensitive military high-performance applications** (e.g. electronic warfare systems).

As the **defence sector needs smaller volumes of batteries** than civil markets, **defence battery requirements are not a major driver for the R & D investments of battery companies**.

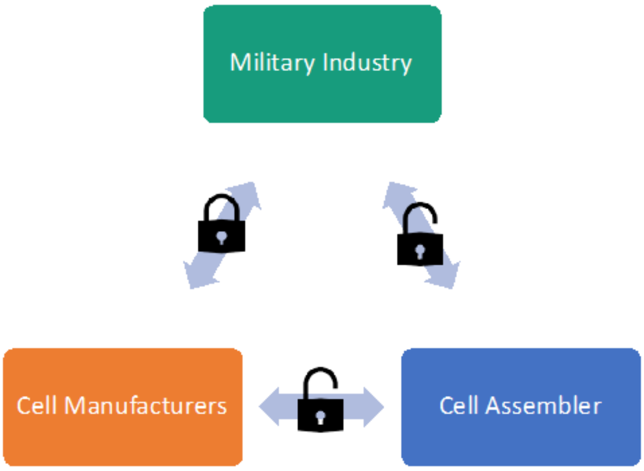
Consequently, European MoDs need to invest (as is currently done, for example, by the United States Defence Logistics Agency for advanced batteries for armoured vehicles) **in advanced Li-ion battery manufacturing capabilities, to foster the development of European battery power systems that meet their needs.** Indeed, as the integration of Li-ion technology into military applications increases, the absence of a major manufacturer in Europe should be addressed to ensure, in times of crisis, the logistical availability, military storage capability and interchangeability of military batteries.

In the meantime, as cell manufacturers are unlikely to respond to the specific needs of the military industry, the defence sector could influence the latter through modules and battery assemblers, which procure large amounts of cells and therefore have the negotiating power to convey specific military requirements (Figure 9). The battery procurement timescales for military applications are typically quite long, with equipment often used for decades.

([11]) The potential for upscaling manufacturing capabilities adequately in order to meet the demand.

([12]) For instance, the voltage window of batteries employed in military land vehicles or other military applications might be different from the voltage window of those used in civil applications. As such, batteries used in military vehicles must be compatible with the right voltages, otherwise the electrical equipment on the vehicle could be damaged or the battery may never be fully charged. In this case a conversion device will be needed or additional changes to the vehicle's electrical system will be necessary, which can introduce higher costs, increased complexity and additional inefficiencies into the system.

Figure 9. Procurement pathway of Li-ion batteries for the defence sector



Source: JRC, private communication with experts

3.6. Recommendations for policy actions and research to reduce bottlenecks in the Li-ion battery supply chain

3.6.1. Recommendations at the level of raw materials for advanced Li-ion batteries

Two main policy actions could be identified as potential mitigation measures at the level of raw materials, namely **diversifying the supply** and **boosting recycling activities in Europe**. More than 50 % of the raw materials used in Li-ion batteries for civil and defence applications are supplied by various smaller suppliers, which provides an opportunity for supply diversification. Securing trade agreements with such suppliers could be a way out in the event of a crisis or war that leads to potential supply interruptions. The overall suppliers of raw materials for Li-ion batteries are shown in Figure 5. **Boosting the recycling of Li-ion batteries in Europe** is seen as a no-regret solution that allows key materials such as cobalt, lithium, manganese and nickel to be recovered and reused in the production of new batteries. The recycling of military batteries inside the EU or their reuse in stationary energy storage applications also needs to be encouraged.

3.6.2. Recommendations at the assembly level (Li-ion cells and battery systems)

In general, building manufacturing capacity for domestic Li-ion cells will make Europe more resilient in relation to the supply of Li-ion batteries for both the civil sector and the defence sector. Providing an attractive investment environment for European companies to invest in Europe rather than outside Europe, which is the current situation, is part of this effort.

Specific defence-related recommendations at assembly level can be also identified as follows.

— Establish **European production capacity for Li-ion batteries throughout the supply chain**, with complete electronics and packaging suitable for both civil and military applications.

— Create **targeted funding programmes and cooperation** between companies for initiating and scaling-up production of Li-ion cells addressing specific military requirements.

— Launch **innovation programmes to support collaborative R & D**, involving co-investment from the military industry on the specific research topics listed below.

3.6.3. Other policy and R & D recommendations for Li-ion batteries

The following **'dual-use' research topics** can be identified from the analysis performed.

— Further research **to reduce the amount of critical materials (such as cobalt) in Li-ion cells**. The potential consequences of the substitution of one material with another (e.g. cobalt with nickel) should also be carefully examined in order to avoid a bottleneck somewhere else.

— Research on **alternative advanced cathode materials**, i.e. so-called conversion materials such as transition metal oxides (MnxOy, NiO, FexOy, CuO, Cu_2O, MoO_2, etc.) representing a valid alternative for cathode materials in future Li-ion batteries. Manganese and iron are of particular interest from a resources point of view. Technologically, however, the developments are not yet sufficiently far advanced. **Specific problems include the volume changes, the high potential differences and the resulting stability of the cycles and their number, all of which represent topics for future research.** If the transition from research to concrete applications is successful, the recycling potential of such batteries is expected to be greater than for the current Li-ion batteries. For instance, graphite is usually lost in the recovery process, as it is burned and used as an energy source.

— Further research in the field of **alternative anode materials** in order **to increase the energy density of a battery and prolong the battery life**. The ongoing research efforts also need to be sustained at the industrial level to substitute carbon anodes with anode composed largely of silicon (so-called Si/C composite). Indeed, materials bottlenecks relating to the use of silicon are not expected. Although silicon anodes are generally viewed as being the next development in Li-ion battery technology, **further research is required to understand and quantify silicon expansion in batteries, which can cause them to malfunction**.

— Research in the field of **innovative electrolytes** is also an ongoing effort to make batteries better performing and safer, and further developments are needed. The use of solid electrolytes, for example based on polymers with lithium ion-conducting electrolyte salts, is a promising direction to make batteries safer and improve the energy density. Work is also underway to produce composite electrolytes using ceramic or metal-organic nanoparticles (Chen and Vereecken, 2019). Another possibility is the development of fully ceramic electrolytes.

— Further research on **emerging advanced batteries** such as Li-S and Li-air. Both batteries display the potential to be used in both civil and defence applications. Li-air is believed to deliver great potential for use in military applications, including soldier-portable batteries and aviation. The key advantage of a Li-air battery is that the active cathode, oxygen, is not carried inside but extracted from the surrounding air. This results in a great advantage in specific energy (Wh/kg), which is important for applications that are very sensitive to weight, such as soldier equipment and aircraft. Li-S batteries are a subset of lithium-metal batteries, and have the potential to increase the energy capability and safety of batteries at low cost. Li-S batteries are seen as the potential successors to Li-ion batteries, and are of high interest to both the civil sector (for mobile, including automotive, and/or static energy storage) and the defence sector (e.g. for military vehicles and as single portable batteries for soldiers). For military applications, Li-S batteries could provide advantages in terms of safety in case of electrical and physical abuse or punctures.

— Research on **Li-ion cell components**, in particular related to materials development, optimisation and processing in order to enhance battery performance, reduce costs and improve safety, specifically for harsh military environmental conditions.

— Further research on **supercapacitors** to make this technology more competitive with existing options for high-performance energy storage applications. Supercapacitors can be used as ‘energy reservoirs’ that smooth out power supplies to electrical and electronic equipment. They can also **complement or replace batteries when high power delivery or uptake, intermittent energy with variable power demands and/or long cycling stability are required**. This is mainly the case for electric vehicles. Supercapacitors can regulate the power they supply and prolong the service life of battery systems. The development of supercapacitors can also contribute to the rapid growth of low-power electronics (wearable, portable electronic devices, etc.) and high-power military applications (e.g. guided missile technology, highly sensitive naval warheads) (W. Raza et al., 2018). Moreover, supercapacitors can offer better power systems for soldier-based applications, enabling improved design of the electronic equipment.

With regard to specific **'defence'-related research needs**, the following topics have been identified.

— **Research on system management** should be considered to address specific military requirements such as thermal management, electromagnetic compatibility and safety of the battery. This will facilitate the integration of advanced Li-ion batteries in vehicles, aircraft, ships and weapons applications meeting military needs. System management is performed directly by the military manufacturer or by the battery assembler. Therefore, having battery assemblers in Europe will help respond to specific military needs, especially in times of crisis, and will contribute to the development of European battery power systems able to meet the needs of the defence industry.

— Research on Li-ion batteries with **lithium iron phosphate** as the cathode material and **lithium titanate** replacing the graphite in the anode to improve the specific energy and reduce discharging and costs. These battery types [13] are of interest to the **naval and land defence sectors**, **especially for military vehicle applications in relation to providing 'silent-watch' conditions**.

The current know-how in relation to Li-ion battery production was developed primarily by civil companies serving consumer electronics markets in particular, creating over time geographically located robust supply chains and production experience. In order to position itself independently of the cell manufacturers and battery assemblers, the military industry needs also to build up extensive know-how in the field of electrical energy storage and conversion in electrochemical cells and fuel cells.

[13] Although lithium iron phosphate and lithium titanate batteries are commercially produced, they are normally not used for powering vehicles. They are in any case an attractive solution for use in military vehicles to ensure the silent watch of the vehicles, but further integration work needs to be done.

4. Fuel cell technology

The importance of fuel cells as a power solution providing operational advantages to different mobile, stationary and portable defence applications is investigated in this report. Attention is also given to the supporting hydrogen production and storage technologies. The global fuel cell market for industrial and military applications is expected to grow by a compound annual growth rate (CAGR) of 18 % in the next few years.

Fuel cells are compact, lightweight, highly efficient devices that have the ability to produce clean, reliable electricity from hydrogen (or other fuels) on-site that can be used in a variety of ways. **Fuel cells require less maintenance and zero lubricants, increase endurance and ensure a high specific energy and power density, beyond that which can be achieved using conventional battery power. In addition they have the potential to reduce sound and thermal signatures, which is an essential advantage for defence applications.**

4.1. Applications and demand for fuel cells

Fuel cells can be used in a wide range of products, ranging from very small fuel cells in portable devices such as mobile phones and laptops, through mobile applications like cars, delivery vehicles, buses and ships, to heat and power generators in stationary applications in the domestic and industrial sectors. Fuel cells are rapidly establishing a foothold in the civilian stationary generation market, acting as a source of backup power or allowing consumers to unplug from the grid entirely, and military customers are following suit. Fuel cells are currently used in three main areas: stationary power generation (a 67 % market share), transportation (32 %) and portable power generation (< 1 %) (Technavio, 2017).

The global fuel cell market for industrial and military applications is expected to grow by a CAGR of 18 % in the next few years. In particular, the fuel cell market for the automotive industry is expected to grow by a CAGR of 9 % by 2021, with increasing demand for fuel cells in material-handling vehicles, light-duty vehicles, buses and the aerospace sector. Although fuel cell technology has come a long way in relation to technology maturity, large-scale deployment in the domestic and industrial segments has not yet taken place. Other forms of energy conversion still remain competitive, and ongoing R & D is focused on cost reduction and life-cycle cost management.

The defence sector could gain noticeably from the unique features of fuel cells, which can provide tactical benefits to and increase the efficiency of the army. **There is strong military interest in fuel cells as a means of reducing the logistics burden.** Military forces are acting in areas where local fuels often do not comply with European/US standards and thus are not suitable for use in military vehicles (e.g. due to high sulfur content). Fuel cells (with reformers to generate hydrogen for the cells) allow military forces to generate power in the operational theatre (e.g. for power generation in military bases) using local fuels or other sources (e.g. diesel, petrol, ethanol, propane, JP-8), reducing the need to transport fuel with the associated high logistics costs and levels of risk.

Fuel cells of particular interest for defence application are low-temperature polymer electrolyte membrane fuel cells (LT-PEMFCs), alkaline fuel cells (AFCs), molten carbonate fuel cells (MCFCs), solid oxide fuel cells (SOFCs) and DMFCs. **Fuel cells can save energy and reduce the operating costs** associated with dependence on foreign oil. **Fuel cells can be used in remote locations to ensure electric power for battery charging, auxiliary power for surveillance and regular power for communication equipment.**

The military benefits of using fuel cell-based vehicles capable of using logistics fuels include transporting required equipment and conducting autonomous resupply missions and stealth missions. **Stealth for silent-watch-type operations is one of the most promising benefits of hydrogen fuel cell technologies when it comes to military applications.**

Other advantages for the military that fuel cells can provide are as follows.

— Increased power and energy density for greater range and endurance.
— Efficient power generation, especially at low electrical loads to reduce resupply.
— Exportable power cable.
— Technology enabler for long range intelligence, surveillance and reconnaissance payloads and mission scenarios.
— Reduced thermal signature operations.
— Low refuelling times (less than 5 minutes) similar to current petrol/diesel vehicles.
— Low fuel consumption when idle (unlike battery-powered electric vehicles).
— High wheel torque generation for off-road driving.
— Water generation for field uses.

The benefits of **fuel cells for UMVs** are that they are **compact, lightweight and reliable**, with a **high specific energy and power density** compared to conventional batteries (efficiencies of ~ 50-65 %), allowing bigger payloads and longer runtimes. The on-board fuel cells can support long missions of about 300 to 400 miles without needing to be recharged, and the vehicle can use any kind of power to generate hydrogen, including JP-8 (jet fuel), solar (water), natural gas or other petroleum-based fuels. The possibility of also using fuel cells in UGVs and UAVs is also being seriously explored by the army.

Today the use of primary batteries is mostly obsolete for armies, but even rechargeable batteries are heavy. Against this backdrop, fuel cells offer the potential to significantly reduce the weight of the batteries carried by soldiers. A typical soldier can carry a dozen devices, from standard equipment — such as radios, GPS units, and night-vision goggles — to improvised-explosive-device-jamming and mine-detecting devices, all requiring electrical power. **Portable military equipment is also an application that could benefit from fuel cell technology.** The weight slows down soldiers on foot, tethers them to constant resupply and contributes to muscular and skeletal injuries caused by excessively heavy packs. Relying solely on battery technology for power is problematic in the field. Batteries lose their charge, add significant weight and are insufficient to meet the needs for accessible energy. **With fuel cell systems, all electronic devices, navigation tools, medical equipment and other electronics can be charged and operated in the field.** Fuel cell technology has the potential to reduce the weight carried by soldiers significantly, allowing them to carry more ammunition and operationally important equipment (US DoE, 2017). The need for **mobile auxiliary power units** is widespread in the military, where communications and reconnaissance systems are operational while the vehicle engine is not running. Such units are needed in ground vehicles, ships, aircraft and non-tactical light-duty vehicles. The drawback of current battery systems is that they do not run as long as desired. Diesel generators give off undesirable, detectable emissions such as noise, heat, vibrations and particulate matter, making their operation around personnel problematic. In particular, SOFCs, DMFCs and PEMFCs are relevant for portable military applications. While DMFCs are the leading fuel cell type for niche applications, SOFCs are considered the most promising type for military applications for which fuel availability is the major concern (WATT Imperium, 2019; Fuel Cells Bulletin, 2006; CERDEC, 2009; K. Cowey, 2004; Colpan, 2008).

Other applications are defence power supplies for military encampments in remote areas and **combined heat and power applications**, where waste heat from the power generation process can be used for heating and service water.

4.2. Technological challenges for fuel cells

Various materials and technological challenges need to be overcome in order to ensure the mass deployment of fuel cells in the civil and defence sectors. Some of these challenges are: **high sensitivity to hydrogen purity** (e.g. LT-PEMFCs); **catalyst poisoning** (e.g. phosphoric acid fuel cells (PAFCs), high-temperature polymer electrolyte membrane fuel cells (HT-PEMFCs)); and **corrosion issues due to high temperatures and/or aggressive environments** (e.g. PAFCs, MCFCs, SOFCs). Challenges such as **lightweight storage tanks** and **thermal management** to shed waste heat are also common for civil and military applications. Operational difficulties that must be taken into account are that **storage tanks suffer from hydrogen embrittlement** after several recharges and are an **explosive hazard if not handled properly**. **Challenges in liquid storage** include **high cost, complexity** (need for very low temperatures and cryogenic vessels) and **safety concerns.** There are also **logistics issues** such as limited availability and refuelling that requires special equipment and skills. Therefore, liquid storage is not the optimum option to be used by the military. **The energy required to get hydrogen in and out** is an issue for reversible solid-state materials. Although not a challenge unique to fuel cell technology, **high-performance sealing technology** is a relevant aspect for the safe application of fuel cells.

Some specific challenges related to defence technical requirements are as follows.

— **Operation in more challenging environmental conditions.** Fuel cells that have to be used in military applications need to operate at very low (down to – 40 °C in some cases) temperatures, and also up to 60 °C.

— Maintainability and transport requirements can also differ from civil applications.

— **Hydrogen production on-site.** The military needs to be flexible and independent in relation to infrastructure, and therefore needs to have ability to produce hydrogen locally in the field.

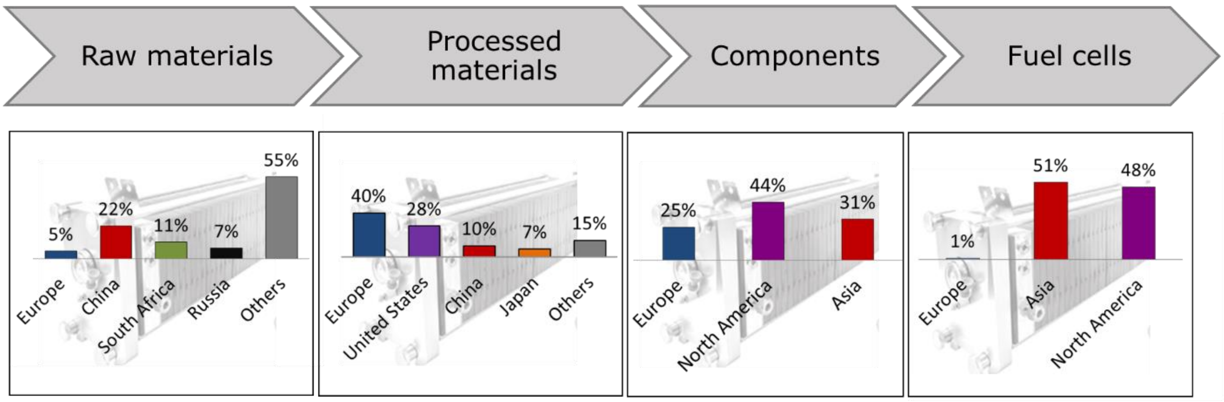
— **Availability of alternative systems that work on logistic fuels.** Fuel cells tolerating sulfur can facilitate military operations.

Nevertheless, the majority of the fundamental research challenges and priorities in the field of fuel cells and hydrogen-storage technologies are common to civil and military applications, which provides a fertile background for synergistic research.

4.3. Key players in the fuel cell supply chain

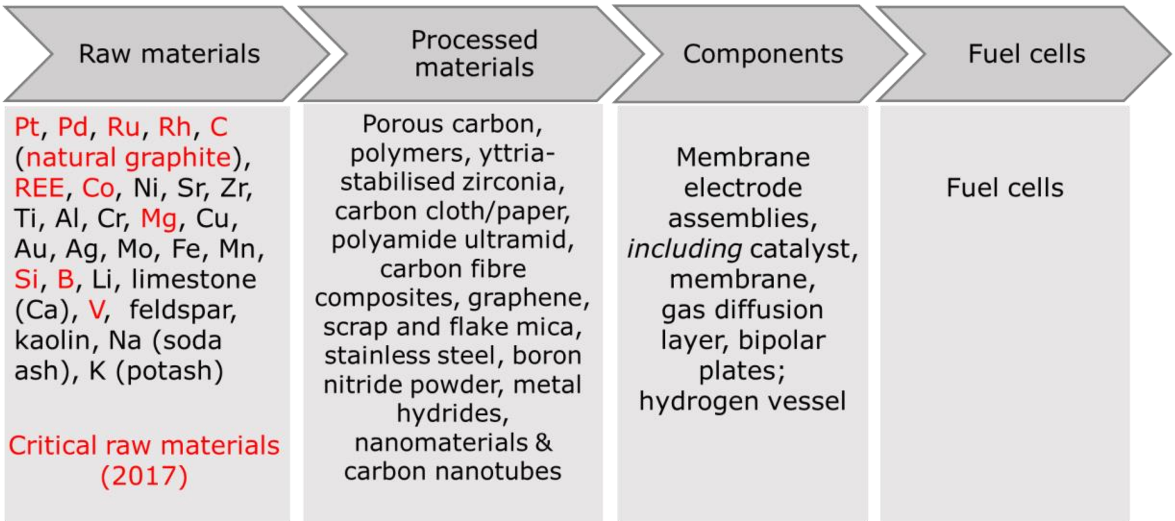
The key players in the supply chain are shown in Figure 10. **China is the major supplier of raw materials for fuel cells** (22 %), followed by South Africa (11 %) and Russia (7 %). **Europe produces only 5 % of the raw materials,** but **it is the largest producer of processed materials** with a production share of about 40 %**. The largest manufacturers and suppliers of fuel cell components** (including hydrogen vessels) and fuel cells **are Asia (mainly Japan)** and **North America (United States and Canada).** There are many European companies involved in fuel cell integration, but this step in the supply chain is not considered in the study. In Figure 11 an overview is given of the raw materials, processed materials and components required in fuel cell technology and considered in the analysis. The country (region) shares shown in Figure 10 are estimated correspondingly.

Figure 10. Fuel cells and hydrogen technologies: key players in the supply chain



Source: JRC

Figure 11. Fuel cells and hydrogen technologies: an overview of raw materials, processed materials and components considered in the analysis

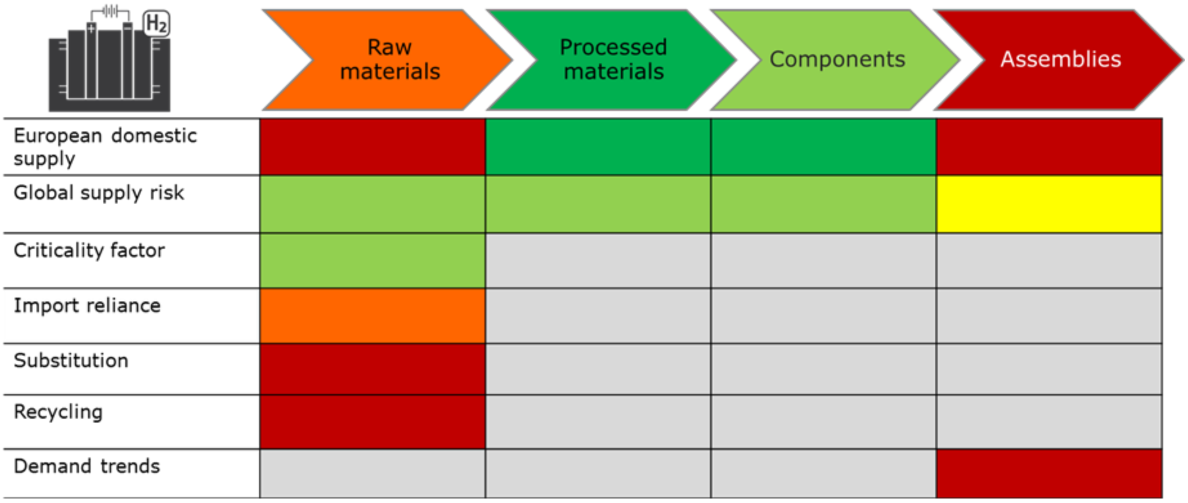


Source: JRC

4.4. Overview of supply risks for the fuel cell supply chain

An overview of the various supply risks and bottlenecks for fuel cells and related hydrogen technologies is shown in Figure 12. The bottleneck assessment performed showed that the **risk to the supply of fuel cells is potentially very high**. **A high risk of supply issues is estimated for the first step in the supply chain — raw materials.** No supply issues should be expected for the other two steps in the supply chain.

Figure 12. Overview of supply risks and bottlenecks in the supply chain of fuel cells and hydrogen technologies

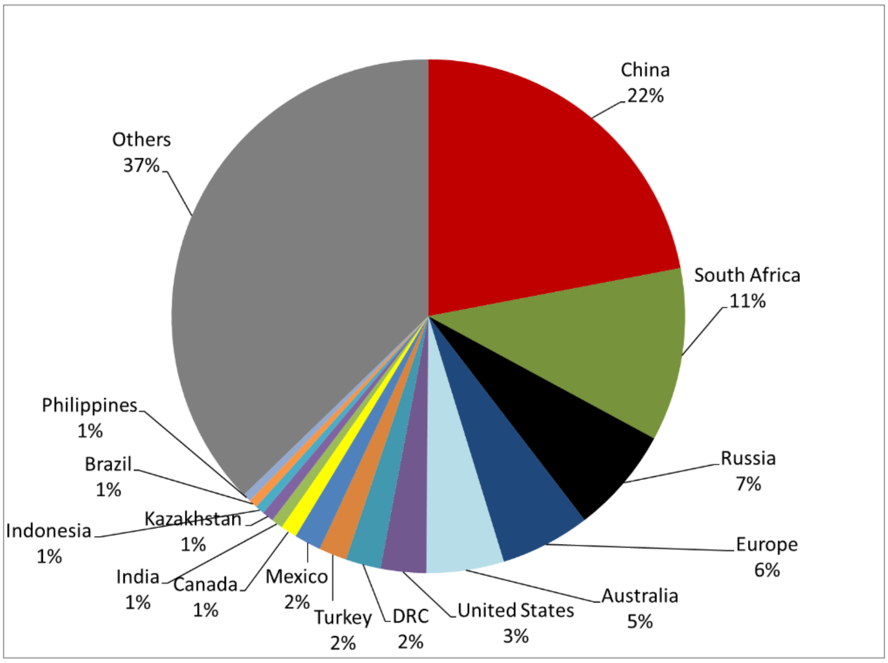


Source: JRC

4.4.1. Supply risks for fuel cell and hydrogen technology raw materials

Europe is fully dependent on the supply of 19 of the 29 raw materials relevant to fuel cell and hydrogen technologies (production and storage). Raw materials that are particularly essential for the production and storage of fuel cells and hydrogen, and that are difficult to substitute, highly priced and have a highly concentrated supply, are the PGMs — Pt in particular, but also Pd, Rh and Ru. The major suppliers of PGMs are South Africa and Russia. China is the main supplier of 10 of the 29 materials required in fuel cells. As for Li-ion batteries, however, more than half of the raw materials for fuel cells are provided by numerous smaller supplier countries, thus providing a good possibility of supply diversification. An overview of the different raw materials suppliers for fuel cells and supporting hydrogen technologies is shown in Figure 13.

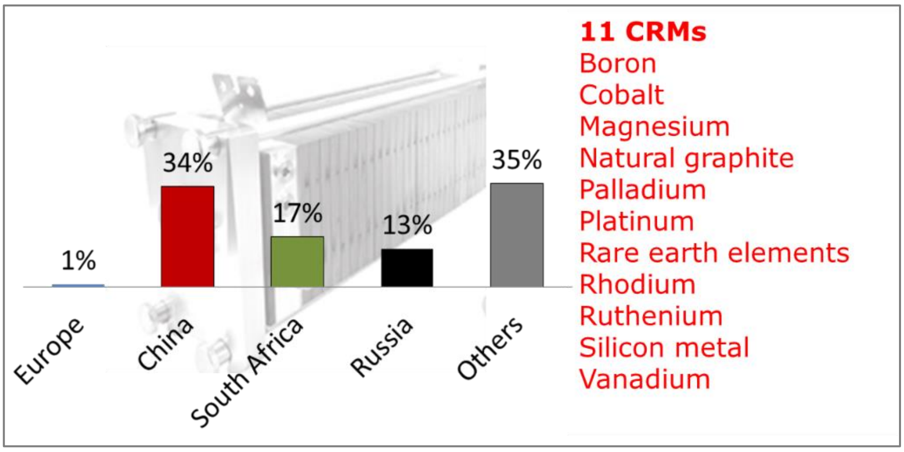
Figure 13. Raw materials suppliers for fuel cells and hydrogen technologies: overview



Source: European Commission, 2017.

Eleven materials, namely Pt, Pd, Co, Rh, REEs, C (natural graphite), Ru, Si, Mg, B and V, are flagged as critical to the EU economy in the 2017 CRMs list. China provides more than one third of the critical materials required in fuel cells and associated H_2 supporting technologies, followed by South Africa (17 %) and Russia (13 %) (Figure 14).

Figure 14. Supply of CRMs for fuel cells and hydrogen technologies: key players

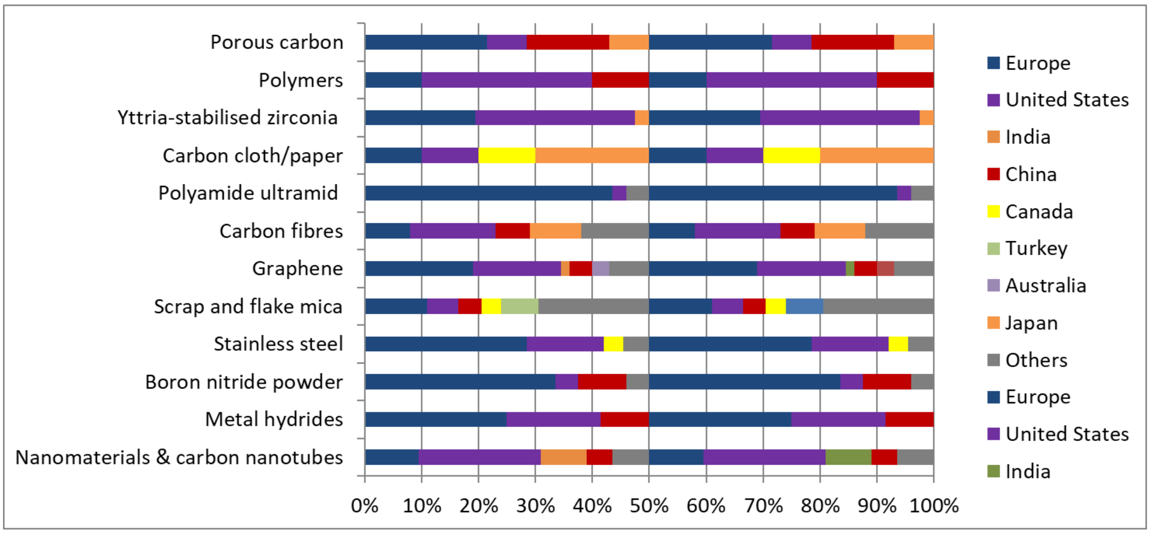


Source: European Commission, 2017.

4.4.2. Supply risks for fuel cell and hydrogen technology processed materials

Europe appears to be the major supplier of processed materials for fuel cells (40 % share), followed by the United States (28 %), China (10 %) and Japan (7 %). Other countries provide only around 15 % of the processed materials. For four particular materials — namely CFCs; polymers (PFSA — perfluorosulfonic acid); carbon cloth/paper; and nanomaterials and carbon nanotubes — Europe produces between 15 % and 20 % of the global supply, which could be expected to be insufficient to satisfy European demand. The countries' production shares of processed materials relevant to fuel cells and hydrogen technologies are displayed in Figure 15.

Figure 15. Country production shares of processed materials relevant to fuel cell and hydrogen technologies



Source: JRC

4.4.3. Supply risks for fuel cell and hydrogen technology components

Europe has relatively strong positions in relation to the supply of components, providing around 25 % of the global supply. The major supplier of components is North America (44 %), followed by Asia (31 %). Europe has the capacity to produce all of the major components used in fuel cells, namely bipolar plates, catalysts, gas diffusion layers, membranes and hydrogen storage vessels.

4.4.4. Supply risks for fuel cells

With regard to manufacturing of fuel cells, **European production is marginal — only 1 % of global production**. The key players are North America and Asia.

4.5. Civil versus military fuel cell supply chains

Fuel cells are a promising power source for military applications as well. There is a large overlap between the civil and military needs, such as high energy density (greater than in currently available Li-ion technology), low parasitic power, simplified balance of plant (BOP), high degree of safety and a wide power range. Nevertheless, the main military interests rely on only a part of the overall technology chain, focusing on distributed, thus local, hydrogen production and on specific fuel cell types, mostly DMFCs, SOFCs and PEMFCs.

Several companies are operating in both the civil sector and the defence sector, including ACAL Energy (United Kingdom), Accumetrics (United States) and Plug Power (United States). There are other interesting examples of fuel cells where companies have used international partnerships to strengthen the fuel cell supply chain, which may suggest an approach that could strengthen this supply chain in the EU. In both cases the companies concerned have a strong presence in the military and civil domains and have entered partnerships to increase the size of the markets they can access. In addition, such a partnership enables companies to offer new technologies to their customers.

For instance, General Motors (United States) and Honda (Japan) have been collaborating on fuel cell technology development since 2013, with the aim of producing next-generation hydrogen fuel cell systems for both companies' future military and civil products starting in 2020 (Forbes, 2017). The goal is to reduce the cost of development and manufacturing.

SFC Energy (Germany) teamed up with ZeroAlpha Solutions (United Kingdom) to trial SFC fuel cell technology with the UK Ministry of Defence in 2017 in the Army Warfighting Experiment and Information Warrior exercises (SFC, 2017). **The fuel cells provided extended 'silent-watch' capabilities and enhanced endurance for both vehicle and dismounted applications.** Fitelnet Oy (Finland) and Elbit Energy (Israel) are other companies providing fuel cells for the military.

Sufficient information on companies providing fuel cells for the military could not be found, which limited the possibility to calculate defence-related supply shares and make a comparison with civil shares.

4.6. Recommendations for policy actions and research to reduce bottlenecks in the fuel cell supply chain

4.6.1. Recommendations at the level of raw materials for fuel cells and hydrogen technologies

Diversifying the supply of raw materials is identified as a possible policy action. More than 50 % of the raw materials used in fuel cells and the supporting hydrogen technologies are supplied by various smaller suppliers (Figure 13), which provides a good opportunity for diversification. Securing trade agreements with such suppliers could be a way out in the event of a crisis or war that leads to potential supply interruptions. **Substitution of PGMs** in this technology is another measure which could reduce the raw materials dependency of Europe.

4.6.2. Recommendations at the assembly level (fuel cells)

Several recommendations at the assembly level could be identified from the analysis performed.

- Promoting **common business cases and collaboration between the military and civil** (dual-use) sectors in the field of fuel cells to increase investment.
- Stimulate the deployment of **highly competitive awards-based programmes** that encourage domestic small businesses to engage in European defence R & D that has the potential for commercialisation, i.e. high technology readiness level.
- Creating **R & D and procurement collaboration with other countries** that are well placed in terms of the technology readiness and manufacturing readiness of fuel cell and hydrogen storage systems, such as Japan, United States and Canada.
- Support an **increase in manufacturing opportunities in Europe** by creating an attractive investment environment.

4.6.3. Other policy and R & D recommendations for fuel cells and hydrogen technologies

While fuel cells are becoming competitive for specialised applications, their cost is still the major challenge to their broad introduction to the market. Cost reductions are mainly expected from increased production and the related learning curves. A beneficial effect on costs will also be provided by the replacement of expensive materials and components with cheaper alternatives, while retaining the same overall performance. Since catalysts are a major cost driver, their substitution in fuel cells is already a topic of ongoing research (e.g. Partial-PGMs, CritCat projects, Horizon 2020 projects).

The long-term performance of hydrogen components, material–hydrogen compatibility for metallic storage systems and components, and innovative hydrogen storage in solid materials (e.g. carbon nanotubes, boron nitride, graphene and other hybrid nanomaterials, glass capillary arrays, glass microspheres, doped polymers, etc.) are all common to both the civil sector and the defence sector, where research is already being carried out.

In general, **future 'dual-use' research** could be done to:

- develop low-cost materials and components for hydrogen storage systems; and
- develop low-cost, high-volume manufacturing methods.

Research is also needed on **fuel cell system integration for different applications**.

For military purposes, operating fuel cell systems independently from a hydrogen infrastructure is an essential point. The hydrogen needs to be produced on-site. This aspect is especially important for mobile fuel cell applications, but also for defence applications in general, with regard to logistical topics. The most feasible way to produce hydrogen for military purposes is to reform diesel fuel or kerosene, as both fuels are readily available in the armed forces and logistics are available for these types of fuels. However, logistic fuels contain some amount of sulfur, which is detrimental to fuel cells as it poisons the noble metal catalysts. Desulfurisation is therefore considered to be a very important step in fuel-processing technologies. Carbon monoxide (CO) must also be removed to prevent the degradation of the fuel cell's platinum catalyst.

- Research on **portable on-site fuel reformers and desulfurisation methods** (innovative materials for on-site H_2 purification) applicable directly on logistic fuels is a possible research area.
- The development of **systems that would operate on logistic fuels** is another specific defence-related topic.

Challenges to be met involve the **miniaturisation of systems and the ability to tolerate fuels containing sulfur.** An example of such fuel cells is the recently announced enzymatic fuel cell, which has the potential to power everything from electronic devices to cars and off-grid power systems (Newatlas, 2014). Still, advances in relation to size and capacity have to be made to ensure the large-scale deployment of this technology for both civilian and military use.

Non-desulfurised hydrogen can however be used safely in certain types of fuel cell, such as HT-PEMFCs, without disturbing the functioning of the cell and while providing higher efficiency. However, water loss and the coincident increase in membrane resistance to proton conduction are significant barriers to the high-performance operation of traditional proton exchange membrane **fuel cells at elevated temperatures** where the relative humidity may be reduced. This could again be a subject for dual-use research, though the military could have the bigger advantage.

The development of **fuel cell systems (and related technologies) able to operate under harsh environmental conditions** could give an advantage to the army, for instance during operations in Arctic or desert environments.

Replacing methanol due to its toxicity with ethanol in DMFC is one more topic in which the military may have a particular interest.

5. Robotics

5.1. Applications and demand for robotics

Robotics is an emerging field of technology offering enormous potential for many civil and defence applications. Robots are currently widely applied in lots of areas, such as industry, agriculture, medicine, transportation, social services, the military, space exploration and undersea operations. The market for robots can commonly be categorised into two major segments based on their function and the market needs they are designed for, namely **industrial robots** (accounting for 80 % of the current market) and **service robots** (20 % of the current market, with almost half being robots for logistics). It is expected however that service robotics will displace industrial robotics in terms of sales and market value over the next two decades (Mordorintelligence, 2018). These two categories are further investigated in this study. Exoskeletons (or wearable robotics) have also been analysed due to their increasing importance and market share for both civil and defence applications. UVs, such as drones, are also sometimes referred to under the general heading of robotics, however they are investigated separately due to their specificities and increasing importance.

It is difficult to predict the actual growth in robotics due to the variety of sectors making use of robots. A growth rate of between 10 % and >20 % is forecast for the different branches of the industrial and service robotics market. The growth projections for exoskeletons, which are also required in various sectors, are even more optimistic, forecasting a CAGR of up to 40-50 % in the next few years (The Business Research Company, 2018). Robotics offers enormous potential for defence. **Robots can perform military operations considered too risky, too complex or even impossible for humans. Military robots are autonomous or remote-controlled mobile robots designed for military applications, from transport, to search and rescue, to attack.** Robots are used in the military on all three fronts — ground, water and sky — for rescue operations, disaster management, surveillance and security. Major tasks performed by robots include bomb disarmament, mine clearance, surveillance and help in search-and-rescue operations. Some other applications include image interpretation for target identification and classification, diagnosis and maintenance of sophisticated weapon systems such as radars and missiles, support and carriage of ammunitions, camera-equipped and shock-resistant platforms to provide firepower remotely, missile target range and trajectory analysis for evaluation of kill zones, launch times and simulations to assist in qualifying missile performance in various environments.

Currently, **exoskeletons** represent only a small share of the global robotics market. However, their **use in both the civil healthcare sector and the military sector is expected to increase steadily in the future**. It is a continuously evolving field. The use of exoskeleton suits for military personnel could vastly improve the safety and strength of soldiers. While the development of military exoskeletons seems to be vital, the development of exoskeletons to be used in the medical world is also making great strides, and seems to have the potential to change the future of medicine. Due to the broad nature of the medical field, exoskeletons could be used to help patients, doctors and nurses alike (Fieldtex, 2017).

5.2. Technological challenges for robotics

The technological challenges relating to robotics can be divided into software- and hardware-related challenges. Software-related challenges include the ability to perform more and more intelligent tasks by using **complex software architectures**. For exoskeletons in particular, software to coordinate the exoskeleton's movements is crucial, and continued improvements are needed.

With regard to hardware challenges, continued developments in design at both the system (robot) and the component level is necessary. Main components such as **gears**, **motors**, **power units**, etc. **need to become lighter and smaller**, especially for exoskeletons, for which weight is a critical point. Smaller, more powerful, high-speed and precision electronics is another challenge for exoskeletons. **Sensors** are a critical and key component of robots. Research on sensors, which is an interdisciplinary field that includes electronics, element mechanics, material science, measurement and control, signal processing, bioengineering, etc., is attracting increasing attention from robot researchers, and its complexity needs to be recognised.

Materials are often a very important ingredient, allowing components to become smaller and lighter. For instance, the development of innovative materials (e.g. vanadium-based materials) could contribute to the creation of miniaturised, multifunctional motors and artificial muscles (RBR, 2013). A large amount of different materials are used in robotics in general. However, light metal alloys, such as **titanium**, **magnesium** and **aluminium alloys**, normally used in partnership with **composites** (CFCs, Kevlar, polymer–metal composites, etc.) are of particular interest for robotics due to their favourable strength-to-weight ratios. Other innovative materials such as **metallic glass**, **printed liquid metals** and **liquid silicone rubber** are seen as potential game changers in the field of **soft robotics**. New materials and advances in making **electronic skin for interactive robots** are under development. **Flexible (stretchable) electronics** are realised via the synthesis of novel materials such as composites of soft materials with conductive fillers or via smart structural engineering and designs such as serpentine-like structures for interconnects or wires. One of the main challenges facing electronic skin development is the ability of the material to withstand mechanical strain and maintain sensing ability or electronic properties, including the fragility of sensors, the recovery time of sensors, repeatability, overcoming mechanical strain and long-term stability. More efficient robot designs will require multifunctional materials, integrating processes such as sensing, movement, energy harvesting and energy storage. Such materials can change over time to adapt or heal (Hammock et al., 2013). Recyclability and self-healing properties are therefore critical in the future design of new electronic skins.

Military exoskeletons. In general, the defence industry needs cheaper and lighter exoskeletons, with longer battery lives, which would clearly give an advantage to the troops. Military exoskeletons face many of the same challenges as their civil counterparts, in relation to being comfortable to wear for many hours and their integration with already established military equipment and standards. Military exoskeletons have to be universal, yet comfortable and fully integrated with the soldier while operating on the battlefield. Furthermore, the exoskeletons have to be reliable and very durable, and have to keep working even under harsh conditions such as impact, humidity, pressure, very low or very high temperatures, etc.

An important requirement for military robots is that they can incorporate **signature-reduction (stealth) technologies including advanced materials to make them harder to detect**. Such materials are magnetic (silicone, urethane, nitrile and neoprene) and dielectric (e.g. foams, plastics, elastomers-type polymers) absorbent materials. Low-emissivity paints are also used for vehicles to reduce emissivity in the infrared spectral band. Multispectral patterned textile netting is used to provide visual camouflage and to mitigate and reduce thermal signatures and near-infrared signatures (providing protection against thermal imagers and other related threats such as heat-seeking missiles).

Another challenge for military robots (e.g. explosive ordnance disposal robots) is that they need to operate under tough conditions. Therefore, **the main differences between civilian and military robot systems are mostly related to water-, dust- and shock-proofing the equipment**.

One more essential requirement for the military is ensuring the non-traceability of the devices; in other words that the enemy cannot make use of the device or the data collected by the device. Therefore, **securing the data link and issues such as tempest shielding** are very important. In addition to these issues, there are also a number of **(quick) deployment aspects** that are very important for military robots (and less so for their civil counterparts). Examples are the choice of the battery pack, which needs to be optimised not only for the **longest possible operation time**, but also for **robust operation under very low and high temperatures**, **resistance to shocks**, **safe air transportability**, **low maintenance**, etc. In addition to the batteries, the fast-deployment requirements also impact the design of the robotic tool itself, as in the military these tools are often transported using standardised pallet sizes, so the robot needs to stick to these design limits.

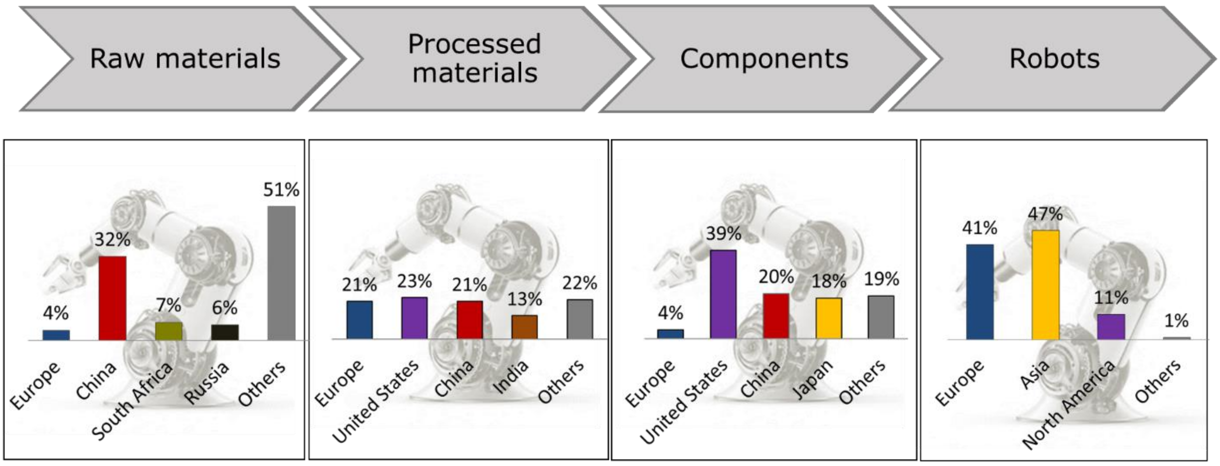
Other issues ranging from cybersecurity to standards and regulations will need to be further addressed as the robotics sector develops. In this respect **materials engineering, design, electronics and software are**

some key areas in which further research is needed. However, such issues are not the main focus of the report.

5.3. Key players in the robotics supply chain

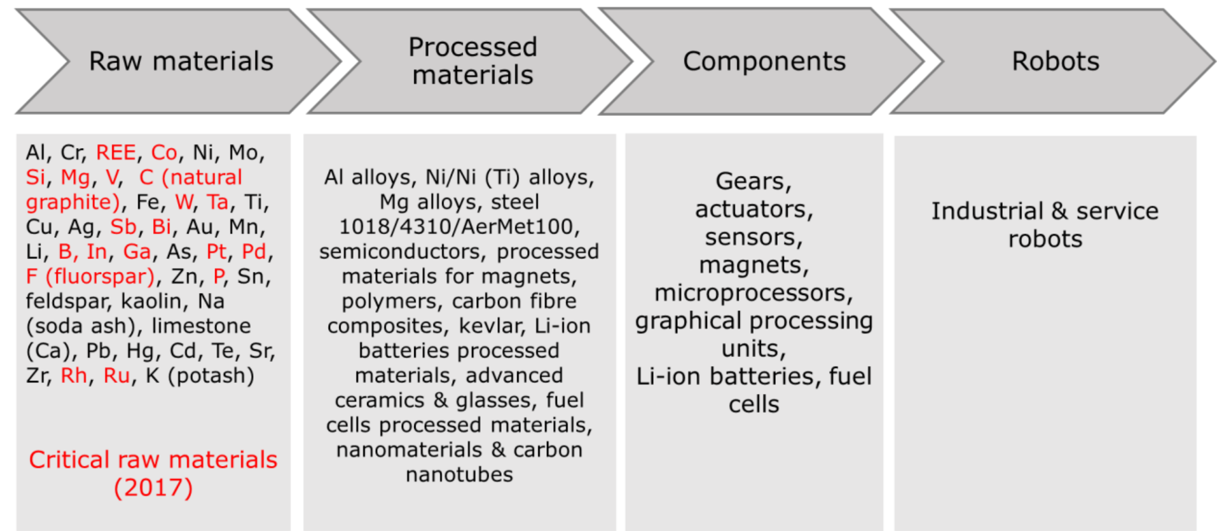
The key players in the robotics supply chain are shown in Figure 16. China is the major supplier of raw materials for robotics, followed by South Africa and Russia. **Europe produces only 4 % of the raw materials, but it is among the largest producers of processed materials (20 % production share)**, along with the United States and China. The largest manufacturer and supplier of robotics components is the United States, followed by China and Japan. **Europe, with a marginal production share of 4 %, is vulnerable in relation to the supply of components**, but it has rather strong position in the last step, i.e. the supply of robots. The integration step of industrial robots has not been considered in the analysis. In Figure 17 an overview is given of the raw materials, processed materials and components required in robotics that have been considered in the analysis. The country (region) shares shown in Figure 16 are estimated correspondingly.

Figure 16. Robotics: key players in the supply chain



Source: JRC

Figure 17. Robotics: an overview of raw materials, processed materials and components considered in the analysis

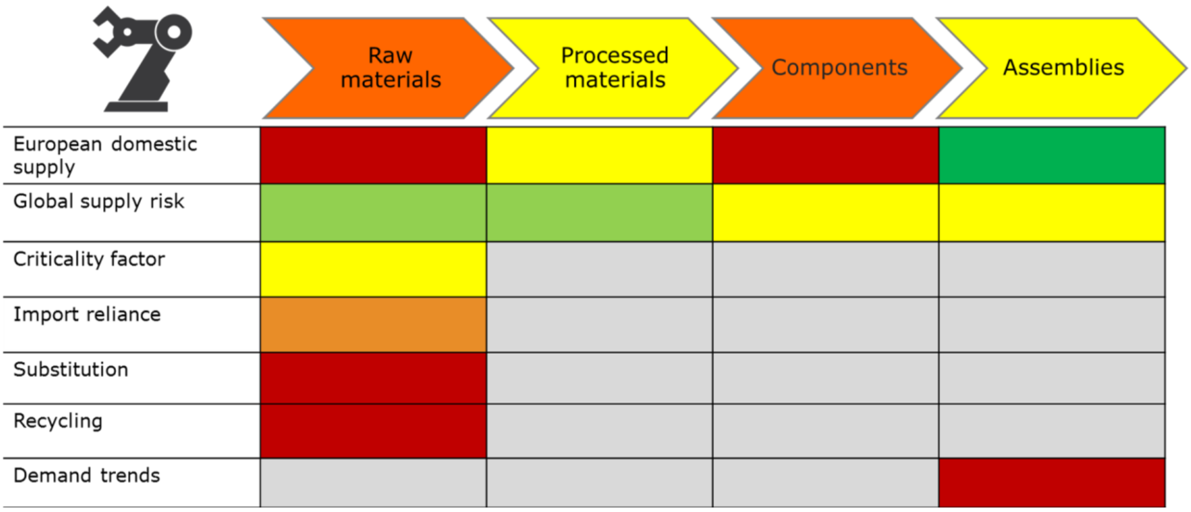


Source: JRC

5.4. Overview of supply risks for the robotics supply chain

An overview of the various supply risks (issues) and bottlenecks for robotics is shown in Figure 18. **The bottleneck assessment that was performed showed that the risk to the supply of raw materials and components is potentially high, and that there is a medium risk in relation to the supply of processed materials and assemblies.** Though Europe is one of the major producers of industrial and service robots, the highly concentrated supply and the expected rapid growth in demand are factors contributing to the medium supply risk assessed for the last step of the supply chain. Moreover, the lack of raw materials and components, the lack of a sufficiently skilled work force in Europe and the increasing competition from China (acquisition of leading European robotics companies by Chinese companies) are additional factors that may challenge the competitive position of Europe on the global market.

Figure 18. Overview of supply risks and bottlenecks in the supply chain of robotics

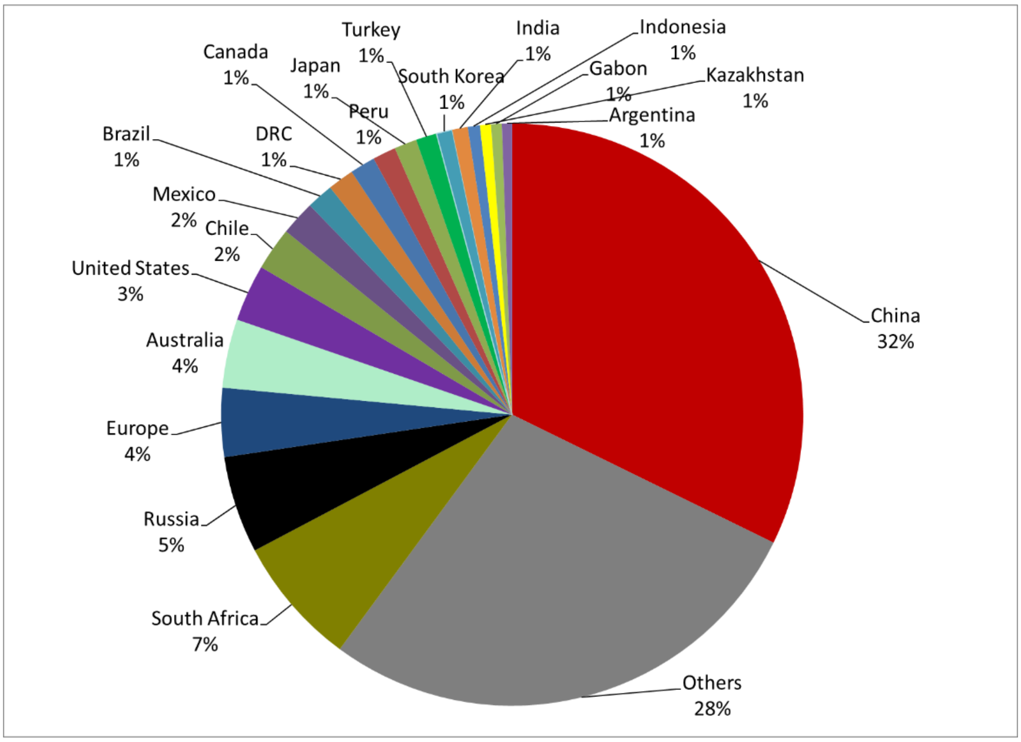


Source: JRC

5.4.1. Supply risks for robotics raw materials

In total, 44 raw materials were identified as being relevant to robotics and analysed in the study. Europe is fully dependent on the supply of 33 materials from outside, mainly from China, which provides more than one third of the raw materials required in robotics. Other key suppliers are South Africa and Russia, and there are many smaller suppliers. Europe provides around 4 % of the raw materials for robots. However, since more than 50 % of the materials for robotics are supplied by numerous smaller countries, there are **significant opportunities for supply diversification**. An overview of the different raw materials suppliers for robotics is shown in Figure 19.

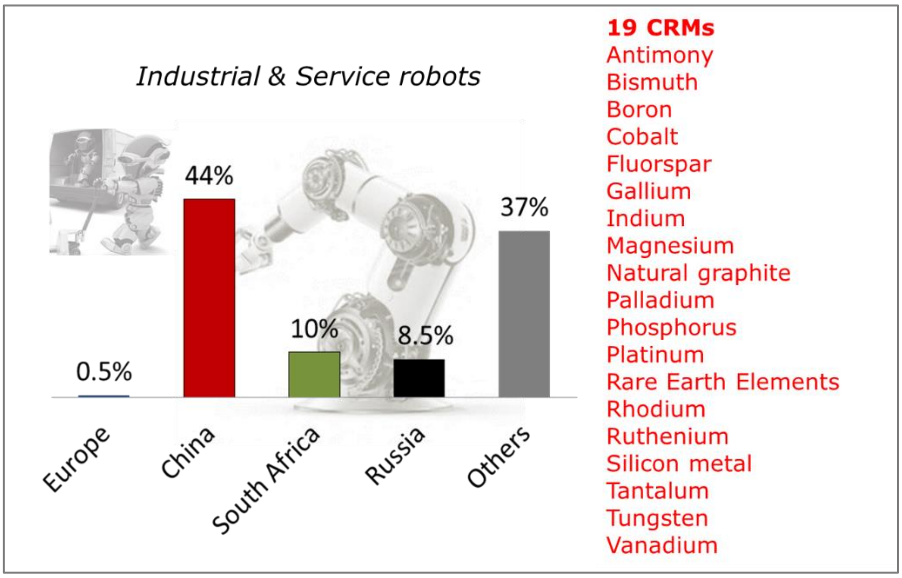
Figure 19. Raw materials suppliers for robotics: overview



Source: European Commission, 2017.

Nineteen of the 44 raw materials are flagged as critical to the EU economy, namely Ta, W, P, F, Ru, Rh, Ga, In, B, Pd, Pt, REEs, Bi, Sb, V, Mg, C, Si and Co. China also appears to be the key supplier of CRMs for robotics, providing more than 40 %, followed by South Africa (10 %) and Russia (around 9 %) (Figure 20).

Figure 20. Supply of CRMs for robotics: key players

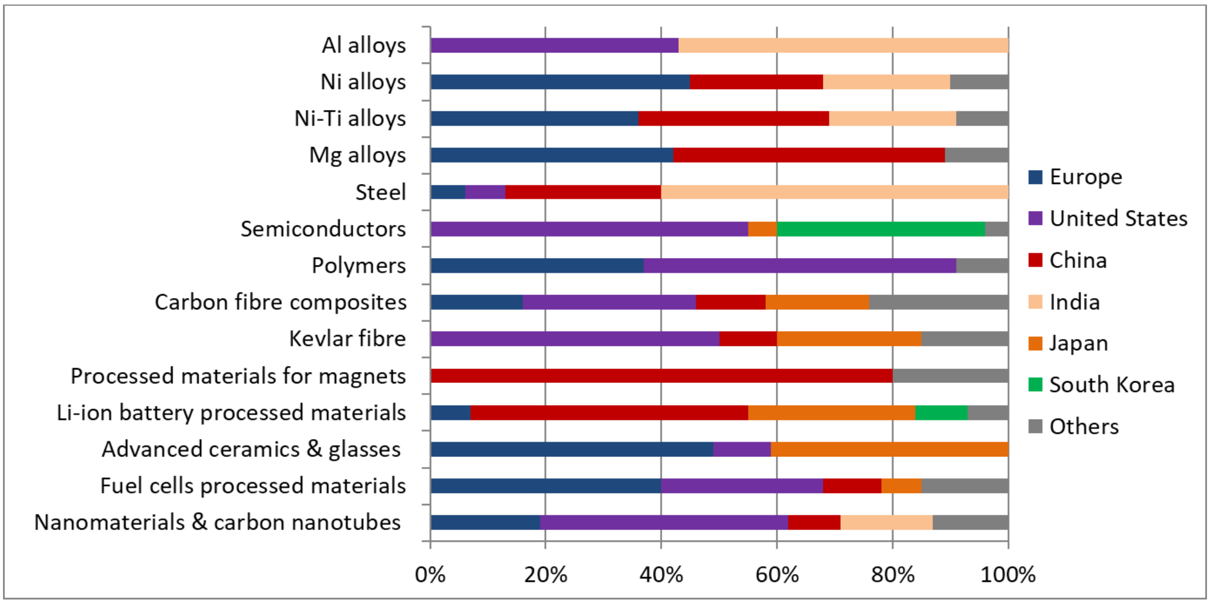


Source: European Commission, 2017.

5.4.2. Supply risks for robotics processed materials

In total 29 processed materials (including processed materials for Li-ion batteries and fuel cells) were identified as being relevant to robotics and analysed in the study. **Europe is well positioned in the second step in the supply chain, supplying more than 20 % of the processed materials required in robotics. The major supplier of processed materials is the United States, with a 23 % share, followed by Europe (21 %), China (21 %) and India (13 %).** There are also possibilities to diversify the supply if needed. It should be noted, however, that Europe is fully dependent on the supply of several processed materials such as specific Al alloys, semiconductors and aramid (Kevlar) fibre, for which the United States and India (for Al alloys) are key suppliers (Figure 21). Potential bottlenecks could also occur in the supply of specific steels required in robotics, along with processed materials for Li-ion batteries. The materials are listed arbitrarily, beginning with materials used in large quantities or essential functional materials for the technology (e.g. semiconductors).

Figure 21. Country production shares of processed materials relevant to robotics

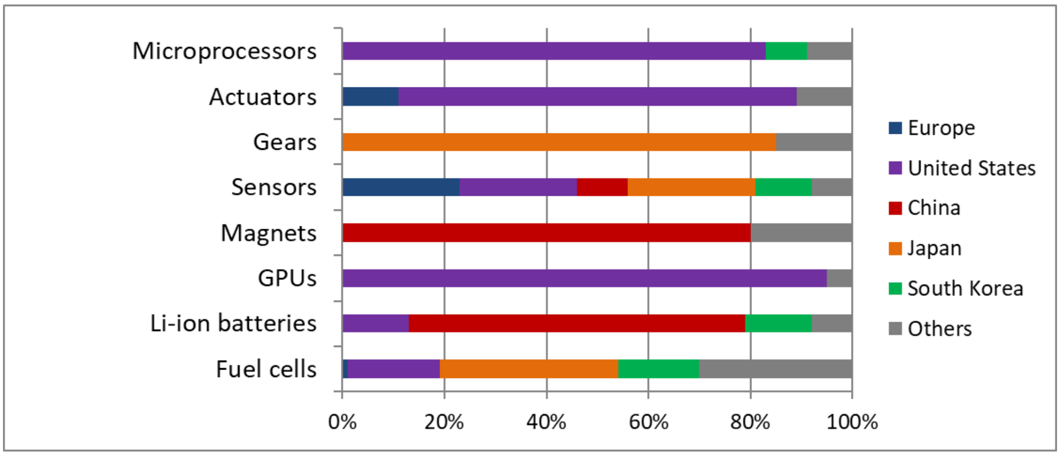


Source: JRC

5.4.3. Supply risks for robotics components

The key supplier for components for robotics is the United States with around a 40 % share, followed by China (20 %) and Japan (18 %). **Europe has marginal share of the supply of components — around 4 %.** Around 20 % of the components are provided by a number of small players. More concretely, the United States is the major supplier of actuators, controllers (microprocessors) and GPUs, and one of the key suppliers of sensors and fuel cells. Japan is the key supplier of gears, sensors and fuel cells. China is the major supplier of Li-ion batteries and magnets. Other key suppliers are Israel (actuators), South Korea (microprocessors and fuel cells) and Canada (fuel cells). Europe is one of the three major suppliers of sensors and actuators. However, **Europe is strongly dependent on the supply of six of the eight analysed components, namely microprocessors, gears, GPUs, magnets, Li-ion batteries and fuel cells.** Although chips and processors are not produced in Europe, robotics companies do not consider this to be a potential bottleneck, believing that there will be enough supply globally. Batteries, on the other hand, are seen as an imminent bottleneck. Future batteries are expected to be solid-state batteries, for instance solid-state lithium and graphene. The EU has introduced a very strong programme in graphene, but the intermediate steps are also important, and this might be semi-critical, according to experts in robotics. The country production shares for components used in robotics are shown in Figure 22. Components are listed arbitrarily.

Figure 22. Country production shares of components relevant to robotics

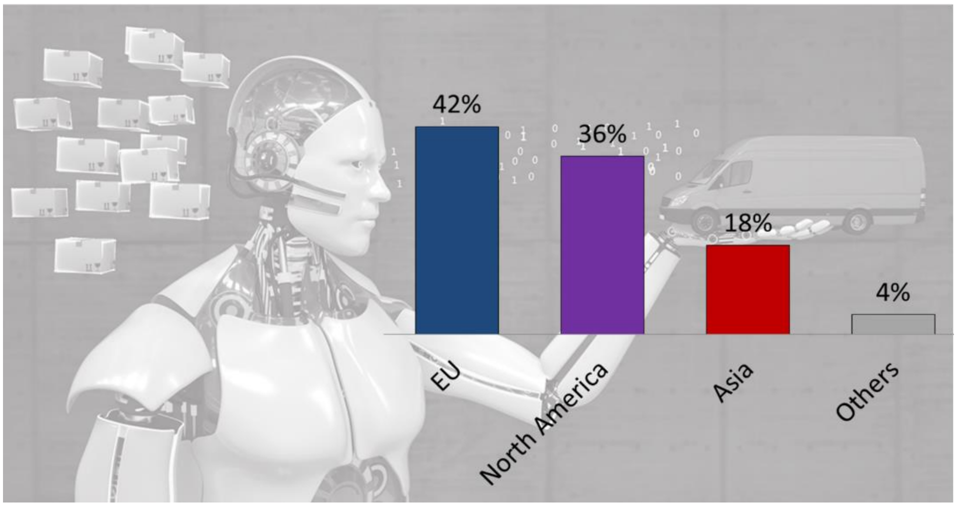


Source: JRC

5.4.4. Supply risks for robots

Asia, mainly represented by Japan with a 47 % production share, is leading the industrial robotics market, followed by Europe (41 %) (Figure 16), while North America (mainly the United States) is better positioned in non-industrial robots. The United States also has the biggest number of highly innovative robotics companies. **The EU is strongly positioned and a major player in the market of service robots** (RockEU2, 2018), followed by North America and Asia (Figure 23).

Figure 23. Country production shares of service robots

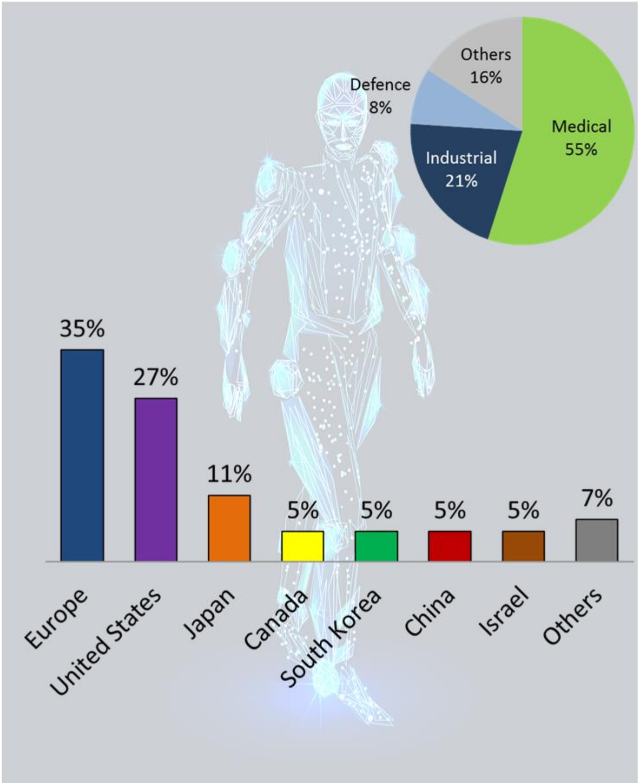


Source: JRC, RockEU2, 2018.

Europe is leading the market for civil exoskeletons, mainly for medical and industrial applications, followed by the United States (27%), Japan (11%) and numerous smaller players (Figure 24) (Exoskeleton Report, 2015) ([14]). The main application for exoskeletons is currently the medical sector. **Defence represents only 8 % of the exoskeleton market. The key players in military exoskeletons are US companies.**

([14]) Supply shares calculated based on number of companies per country.

Figure 24. Country production shares of exoskeletons



Source: JRC, *Exoskeleton Report*, 2015.

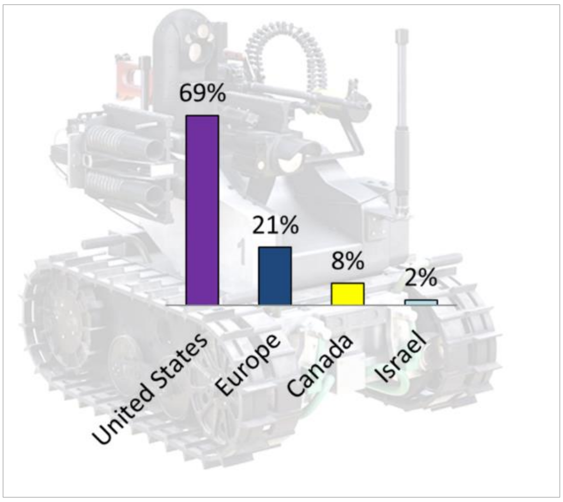
5.5. Civil versus military robotics supply chains

There are various players operating in the civil and defence markets. The main civil industrial robotics companies are ABB Ltd (Europe), Mitsubishi (Japan), Yaskawa Electric Corp (Japan), Kawasaki Robotics Inc. (Japan), Stäubli (Europe), KUKA Robotics (former European and currently owned by a Chinese company (Technode, 2019), B+M Surface Systems GmbH (Europe), FANUC Robotics (Japan) and Rockwell Automation Inc. (United States), among others.

The key players in military robotics believed to disrupt the defence robotics market are Boston Dynamics (United States), Ekso Bionics (United States), Neptec Technologies (Canada), Energid Technologies (United States), Robo-Team (United States), SRI International (United States), MRX Technologies (United States), M-Tecks Robotics (France), Neya Systems (United States), Silent Falcon (United States) and Qinetiq Group (United Kingdom) (Disruptor, 2017). Other European companies include API Technologies (United Kingdom), BAE Systems (United Kingdom), Dassault Aviation (France), European Aeronautics Defense and Space (France), Finmeccanica (Italy), M-Tecks Robotics (France), SKYWATCH (Denmark) and Thales Group (France).

In total around 50 defence robotics companies have been identified and considered in the analysis. The production shares in Figure 25 have been established in terms of the number of companies per country, and a clear prevalence of US companies can be observed (Disruptor, 2017; Venture Radar, 2018).

Figure 25. Country production shares of military robots



Source: JRC, Disruptor 2017, Venture Radar 2018.

With regard to exoskeletons, wearable robotics for the military is the most dynamic subset of the exoskeleton industry. Military exoskeletons are being tested by the Australia, Canada, China, Russia, South Korea, United Kingdom and United States. These are just the projects that the public is aware of. Many other military exoskeleton projects remain secret (Exoskeletonreport, 2016).

5.6. Recommendations for policy actions and research to reduce bottlenecks in the robotics supply chain

5.6.1. Recommendations at the level of raw and processed materials for robotics

Securing access to the raw materials for which Europe has no domestic production, such as Cr, Co, Mo, C, Ni, Mg, V, Cu, Sn, Sb, Bi, etc., and diversifying the supply for the other raw materials are identified as being relevant policy measures at the level of raw materials. More than half of the relevant materials for robotics are supplied by multiple small suppliers, which gives **good opportunities for the diversification of the supply.**

At the level of advanced materials the following **'dual-use' opportunities for R & D actions** have been identified.

— Development of **advanced light and high-strength structural and functional materials** is the main research line for robotics, including exoskeletons (or wearable robotics). Promising materials appear to be magnesium, aluminium, titanium alloys, special steels and composites (fibre reinforced), including combined polymer–metal composites. **Pioneering materials for special applications such as multifunctional motors, artificial muscles** (e.g. vanadium-based materials), etc. are also needed.

— Development of **innovative materials, including paints and textiles**, to mitigate and reduce signatures for specific military applications.

— Development of **new materials and advances in making electronic skin for interactive robots** and associated **flexible or stretchable electronics** such as smart textiles based on flexible carbon nanotube composite coatings [15]; printed liquid metals [16], metallic glass [17] and liquid silicone rubber for soft robotics advancements.

(15) Carbon nanotubes are produced from synthetic graphite, for which the primary feedstock can be calcined petroleum coke and coal tar pitch. Chemical vapour deposition is the most widely used method for the production of carbon nanotubes. Different metallic catalysts (based on Mg, Al, Co or Ni) are however used during this process.

5.6.2. Recommendations at the assembly level (robots)

Several opportunities for R & D actions have been identified at the assembly level, namely the following.

- Development of **smaller, more powerful, high-speed and precision electronics**. This is essential for the development of the future military and civil robotics.
- **Design optimisation of the robotic tools for military robots**. Besides batteries, the design of the military robotic tools should also be suitable for transportation using standardised pallet sizes.
- **Cyber physical security of electronics systems** (such as controllers) **for military robotics applications**. This is a key issue to be addressed as robotics systems develop increasing levels of autonomy, artificial intelligence and software integration. Potential adversaries might tamper with commercial off-the-shelf electronics and with associated software to affect the functionality of military equipment during procurement or in-service updates. Therefore **R & D investment in methods to protect military systems (and critical civil infrastructure) against cyber supply-chain attacks** will be required. Cybersecurity is thus an area from which civil–military synergies could arise.

Military exoskeletons need to have increased strength and endurance in demanding environments, ensuring the high survivability of the soldiers and at the same time being light and comfortable to wear for many hours, as well as enabling integration with already-established equipment and standards. Specific research recommendations to meet similar requirements are both hardware and software related, such as the development of the following.

- **Smaller and more efficient power/energy sources** (batteries, fuel cells or other alternative sources) (Quora, 2017; Xiaoping Ouyang et al., 2016) **and electric motors**. One of the most daunting problems to be solved in the field of exoskeletons is the creation of a compact power supply powerful enough to allow an exoskeleton to operate for extended periods without being plugged into an external power source. The choice of an optimal battery pack, resistant to low and high temperatures and shocks, and ensuring safe air transportability, long operation time and low maintenance, etc. is an important deployment aspect for military robots in general.
- **Armour with high ballistic performance** ([18]) and increased blast and shrapnel protection.

Other recommendations in the field of exoskeletons are software to coordinate exoskeleton movements, vital-sign and stress monitoring technologies, visual augmentation systems/operators, automated remote sensors for increasing situation awareness and reducing the surveillance (and cognitive) burden on soldiers, improved weapons interface, improved thermal management and improved communications connectivity.

5.6.3. Other policy and R & D recommendations for robotics

Besides the field of raw materials, other policy initiatives to support the development of the robotics sector in Europe could be as follows.

- Ensure needs a sufficient **high-skilled work force to attract and maintain robotics technical expertise**. Robotics companies in Europe already perceive this as being a big potential bottleneck for the future development of this sector in Europe. Companies are interested in hiring enough high-level maths software engineers and people with robotics PhDs. The main concurrency in skilled work force is expected to come from China and India. Therefore, both companies and academia should be

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([16]) Intrinsically stretchable liquid metals include eutectic Ga-In alloy (EGaIn) or Ga-In-Sn alloy (Galinstan).

([17]) Metallic glasses are a relatively new class of materials made from complex, multicomponent alloys. Various metals such as Mg, Ti, Al, Fe and Zr can be used as the feedstock.

([18]) Bullet-resistant or anti-ballistic materials are usually rigid, but may be supple. They may be complex, such as Kevlar, Lexan and carbon fibre composite materials, or they may be basic and simple, such as steel or titanium.

encouraged to identify skills gaps and skills shortages for the robotics sectors. **Tailored retraining and skill-raising programmes can be an important follow-up,** which the European Commission can support. It is also up to stakeholders (industry, academia, etc.) to take advantage of relevant EU funding, such as Erasmus and European Structural and Investment Funds.

— **Europe should strengthen its local robotic market** and seek ways to increase and sustain internal market demand through various initiatives, actively involving robotic stakeholders. Support for the industry is needed in many ways, from increasing awareness and incentives to encouraging new and established companies to carry out advanced research and development. Providing funds for robotics research in terms of size, weight, technology, software, materials and applications is expected to significantly influence the European robotics market. Great emphasis should be put on SMEs as a growth strategy of the European civil and defence robotics market. Almost all major companies and factories in the region have been automated. The European Commission could incentivise promote incentivising the automation/robotisation of SMEs at Member State level.

— **Europe is lacking manufacturers of important components for robotics.** The dominance of foreign suppliers, specifically for some higher-level components that are expected to be key components for future technological development (e.g. GPUs), is seen as a threat by the robotics industry. **Therefore, strengthening and investing in the local components manufacturing industry** would be profitable for robotics companies. It would increase production in Europe and prevent companies from setting up manufacturing plants in Asia. In addition, this would establish a new revenue stream for Europe through selling technologically advanced robotic components to robot manufacturers to other countries. The European Commission could invite Member States to define appropriate incentives for existing local robotic-components-related companies to invest in Europe, and support the development of new businesses. In addition, measures to discourage the inflow of components produced outside Europe could be defined again at Member State level.

More potential policy initiatives aiming to strengthen Europe's position in robotics are listed in the relevant JRC technical background report (MatDual, 2019).

6. Unmanned vehicles

6.1. Applications and demand for unmanned vehicles (UVs)

UAVs are used for various civil and commercial applications. These comprise remote sensing for aerial monitoring and investigation for agriculture, infrastructure inspection, border monitoring and surveillance, research and development, and other data-collection processes, along with the transport of goods, for example parcels in the logistics sector. The transport of passengers is still in the initial stage, however promising developments have been reported recently.

The global UAV market is expected to grow by a CAGR of between 18 % and 27 % over the next few years (Research Nester, 2019; MarketWatch, 2019; TechSci Research, 2019). Much higher growth of > 80 % CAGR is anticipated for particular drone sectors, such as smart commercial drones (Reuters, 2018a). Industry analysts have considered UAVs to be a 'market discontinuity' due to their disruptive innovation, which is fundamentally changing the capabilities in the aeronautics sector (Valerdi, 2005). The impact of the shift from manned aircraft to UAVs in both society and the military is tremendous, due not only to the mere expansion of the number of aircraft, but also to the quality of the newly offered services. Manned military aircraft will be gradually replaced by unmanned ones (between 30-50 % by 2020 (DefenceProAc, 2019)), while it seems only a matter of time until this process also affects the civil sector.

The market for UGVs is anticipated to grow by a CAGR of more than 11 % by 2025, and the major applications of the vehicles will serve the defence sector (Markets and markets, 2019). A similar growth rate is also expected for the unmanned maritime vehicles (UMVs — including underwater and surface vehicles) market for the same period (Unmanned Maritime Vehicles, 2013).

Initially, UAVs were predominantly used under environmental and other conditions that prohibited the use of manned aircraft. In this way they extended the operating range of manned aircraft. Accordingly, UAVs were used predominantly in military applications, with breakthroughs from the development of the predator and global hawk drone programmes (Kindervater, 2016). The most important military applications of UAVs are reconnaissance; target and decoy; attack capability to support combat activities; remote sensing, in particular chemical, biological, radiological and nuclear sensing; and the delivery of military cargo to and near combat zones, including lethal and non-lethal payloads. The more the UAVs are integrated with classical weapon systems and/or with each other, so-called multi-UAV systems, the more they will support the vigour needed in combat areas.

Starting from the 1970s, the civil applications of UAVs gained ground, and civil UAVs are clearly dominating the market regarding the number of units, with over a million units sold by 2015 in various fields of application such as agriculture, provision of data for science, logistics and commerce. However, the market size in terms of value is still clearly dominated by military applications, followed by commercial and hobby applications (Statista, 2019a). Also, the environmental requirements are now usually more demanding for military applications than for civil applications. For defence systems, operating temperatures are typically from below 0 °C (in certain cases down to – 40 °C) to up to 60 °C. Furthermore, the requirements regarding maintainability and transport can also differ from civil applications.

The **defence market** for UAVs is today dominated by large UAVs, and it is expected that this will remain the case for the next two decades. The defence industry has in recent years witnessed a growth in the application of other types of UVs and cybersecurity. C4ISR (command, control, communications, computers, intelligence, surveillance and reconnaissance), cyber security, embedded computing and UVs are key applications with potential growing markets. Based on the developments in the UAVs' market for defence applications, it can be predicted that the impact on surveillance by UVs will be significant (EASME, 2017). Autonomous and robotic systems are expected to make a significant change to military operations within the 2021-2040 time frame, at both the global scale and the national scale.

6.2. Technological challenges for unmanned vehicles

The technological progress in aviation, both civil and military, documents meaningful advancements with major improvements in power supply, range and speed (Manzotti, 2016). In addition, the rapid development of the UAV technology benefited from the accelerative robotics advancements in the last decades. Nevertheless, certain technological issues pose a challenge when tapping the full potential of the promising UAV technology.

Fuel cells are already a common source of energy supply in unmanned marine systems. However, they are still a niche product in UAVs. Due to increased energy intensity, the flight capacity (operating range and time) of UAVs can be extended up to threefold when compared to batteries. In addition, (1) refuelling times are much lower when applying a removable-tank design concept, (2) the overall vehicle maintenance is lower and (3) the logistical footprint is smaller. **A technological challenge for fuel cell engines is the lower power density than batteries and internal combustion engines, and the higher investment cost per unit**. **Thus, a marketable portable and portable hydrogen refuelling solution is required** (Ballard, 2019)**.**

Specific challenges related to defence UV technical requirements are as follows.

— As environmental requirements are demanding for military UAV applications, the failure of their components is possible, for example during take-off or landing, or due to collisions with aircraft or projectiles. In order to significantly reduce the 'logistic delay time' in the case of damage, the **possibility to repair the UAV is of key importance to ensure a high level of functionality**. AM enables relevant components to be printed at the location of use ([19]). It is a technological challenge to develop deployable mobile AM units that are able to print UAV components for a specific soldier's needs during their mission at an acceptable speed. Today, the printing time of a whole UAV is still around 20 hours (Busachi et al., 2018).

— **Availability of alternative systems that enhance on fuel logistics.** Fuel cells with an enhanced sulfur-content tolerance level can facilitate military operations in areas where the supply of purified fuels is not ensured (see Chapter 4)

— In the maritime defence sector, **UUVs are required to become more resistant against shaking or shocks due to the explosion of naval mines**. Materials used to support such resistance are (in general, not only for maritime systems) certain composite materials ([20]) and speciality steels (armour steels), for example Armox 370T (Army Technology, 2013) (rolled homogeneous armour plate that combines good resistance to penetration with excellent toughness).

— Beyond the technological challenges at the UV level, progress is also required at the infrastructural level. In fact, the use of UVs, and in particular the combined use of fleets of UAVs, requires reliable communications bandwidth that can be provided by satellites. Therefore, **sufficient bandwidth provided by satellites** is considered an important driver for certain types of UVs (EASME, 2017).

In addition to these technological challenges, there are certain institutional challenges to be overcome. For several years, a major obstacle to the setting-up of a truly European civil drone market has been the **missing legal framework for civil drones**, with consequences for the certification processes of UAV airworthiness. Thus far, for drones weighing less than 150 kg the EU Member States has had the responsibility to establish the requirements for each drone platform, while for drones above 150 kg the European Aviation Safety Agency (EASA) has been responsible for their certification. With the publication of the new regulation in 2019, the European Commission wanted to extend the scope of the EASA rules to all drones, along with putting in place operational requirements and procedures for certain types of drone operations. As a consequence of this harmonisation of the EU drones regulation, all civil drones are sorted into the three main categories — 'Certified', 'Specific' and 'Open' — based on the consideration of the risks involved. The new drone regulation

([19]) As an example, the 'Additive Manufacturing–Rapid Support System' (AM-RS2) includes an AM unit and extended library of pre-loaded pilot geometries of UAV systems, and components.

([20]) For example see: French, M. and Wright A. (2014): Developing mine blast resistance for composite based military vehicles. https://doi.org/10.1533/9781845698034.2.244. Available online 27 March 2014.

has been published in June 2019 to ensure drone operations across Europe are safe and secure. In contrast, for military UAVs specific military certifications with distinctly different legislation and regulation are applicable.

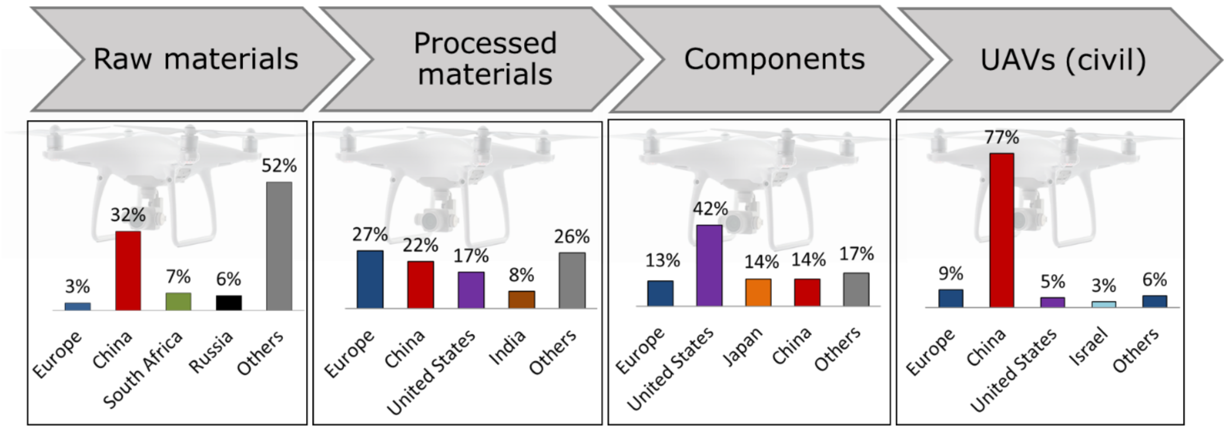
The **research challenges and priorities in the field of UAVs are common to both civil and military applications**, thus providing a fertile background for synergistic opportunities.

6.3. Key players in the unmanned aerial vehicles supply chain

The key players in the UAVs supply chain are shown in Figure 26. **China is the major supplier of more than 30 % of the raw materials required in UAVs**, with a clear lead over South Africa, Russia and Europe. China is the biggest supplier of 24 of the 48 raw materials used in UAVs that have been assessed in this study. **Europe produces only 3 % of the raw materials but is the largest producer of the processed materials** considered relevant to UAVs **with a production share of 27 %,** followed by China, the United States and India. **The United States has a healthy margin as the largest manufacturer and supplier of UAV components,** with a market share of 42 %. The United States is followed by Japan, China and Europe, which together have a market share of similar size. **The production of civil drones is again clearly dominated by Chinese companies,** with an estimate of more than 75 % market share.

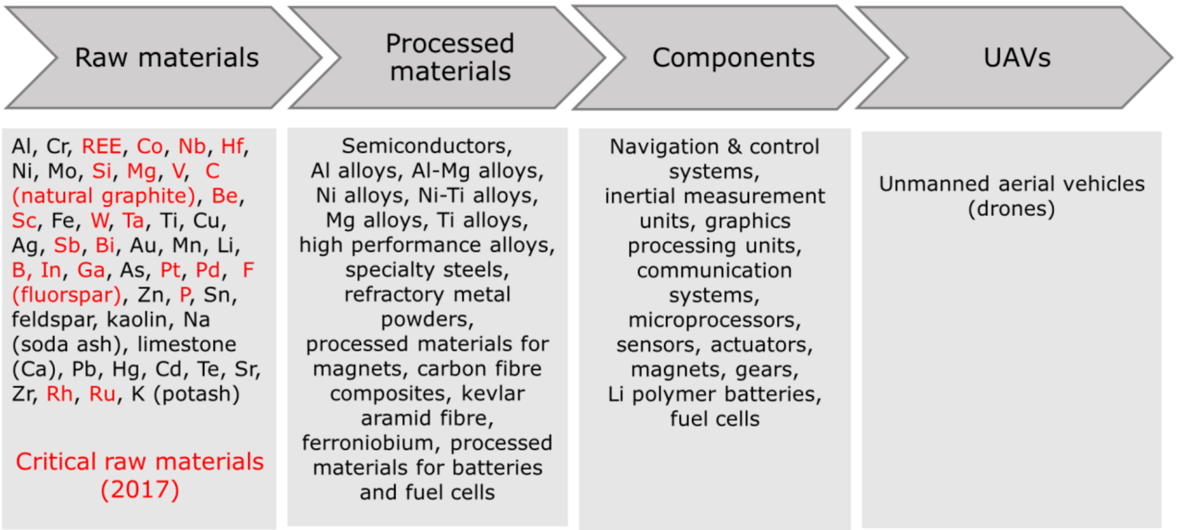
Figure 27 gives an overview of the raw materials, processed materials and components required in UAVs that have been considered in the analysis. The country (region) shares shown in Figure 26 are estimated correspondingly.

Figure 26. Unmanned aerial vehicles: key players in the supply chain of UAVs (civil applications only)



Source: JRC

Figure 27. Unmanned aerial vehicles: an overview of raw materials, processed materials and components considered in the analysis

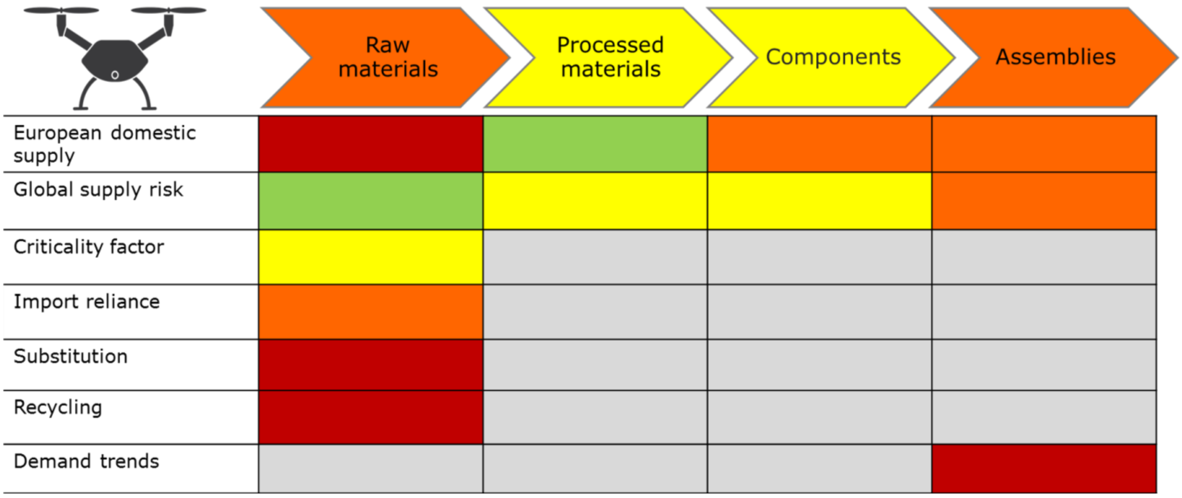


Source: JRC

6.4. Overview of supply risks for the unmanned aerial vehicles supply chain

The estimated supply risks and bottlenecks in the supply chain for unmanned vehicles are shown in Figure 28. The bottleneck assessment performed has shown that the **risk at the 'raw materials' and 'assemblies' (UAVs) supply-chain steps is potentially high**. The other two steps in the supply chain, **'processed materials' and 'components' are at moderate risk**.

Figure 28. Overview of supply risks and bottlenecks in the supply chain for unmanned aerial vehicles

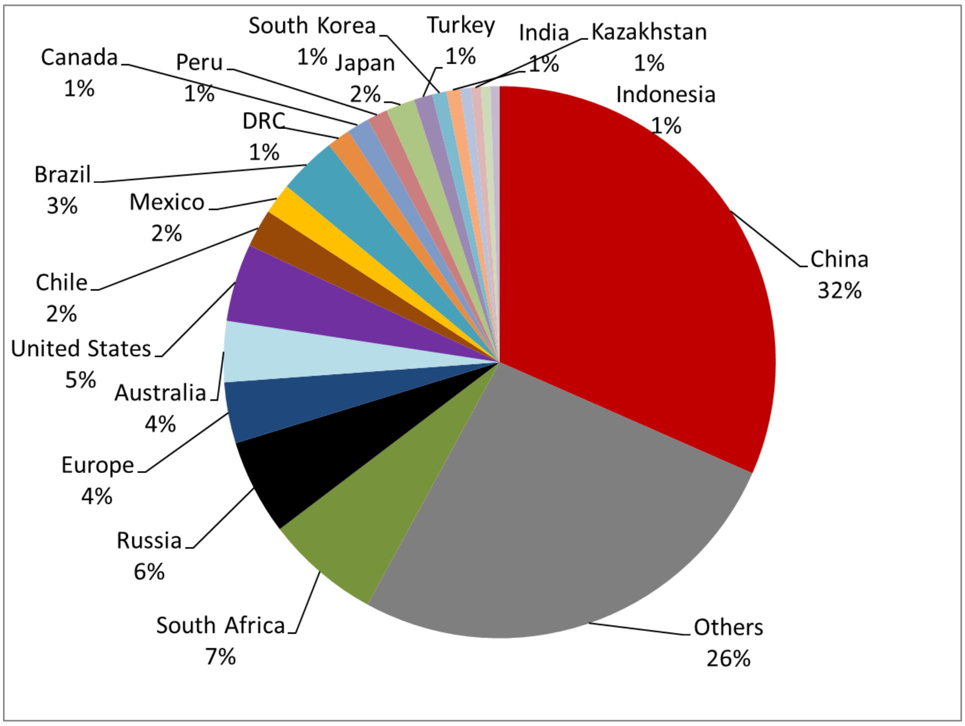


Source: JRC

6.4.1. Supply risks for unmanned aerial vehicles raw materials

In total, 48 raw materials were identified as being relevant to UVs and analysed in the study. **Europe is fully dependent on the supply of 40 of the 48 raw materials relevant to UV technologies.** The materials of particular importance (with a primary production concentration of > 80 % in a single country) are REEs, Mg, Bi, and W, for which the dominant supplier is China, and Nb, for which the dominant supplier is Brazil. Overall, China provides around 32 % of the raw materials, followed by South Africa (7 %) and Russia (6 %). Similarly to robotics, more than 50 % of the materials for UAVs are supplied by numerous smaller countries, which provides significant opportunities for supply diversification. An overview of raw materials suppliers for UAVs is shown in Figure 29.

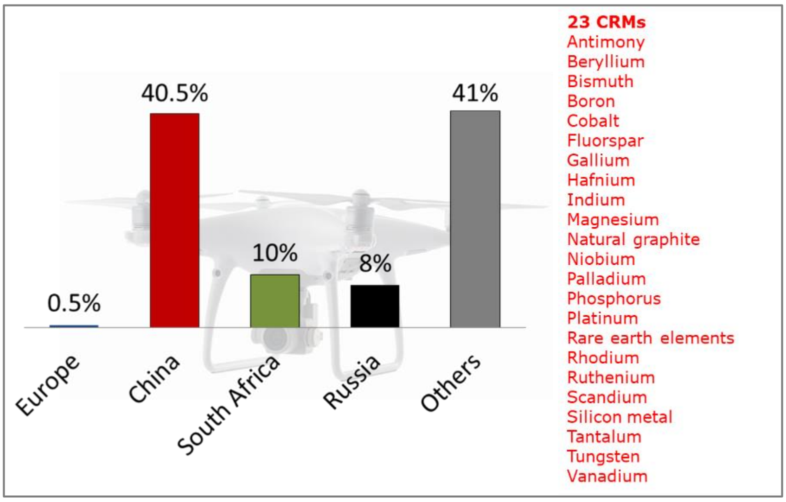
Figure 29. Raw materials suppliers for unmanned aerial vehicles: overview



Source: European Commission, 2017.

Twenty-three materials, namely Co, Si, C (graphite), Mg, V, Sb, Bi, REEs, Pt, Pd, B, In, Ga, Rh, Ru, Fluorspar, P, W, Ta, Nb, Be, Sc and Hf, are flagged as critical to the EU economy (European Commission, 2017). China is the predominant supplier of most of the CRMs for UVs, providing more than 40 %. South Africa and Russia are the next major suppliers of CRMs, with a 10 % and an 8 % share of global production respectively. The supply of CRMs from European countries is negligible (< 1 %) (Figure 30).

Figure 30. Supply of CRMs for unmanned aerial vehicles: key players



Source: European Commission, 2017

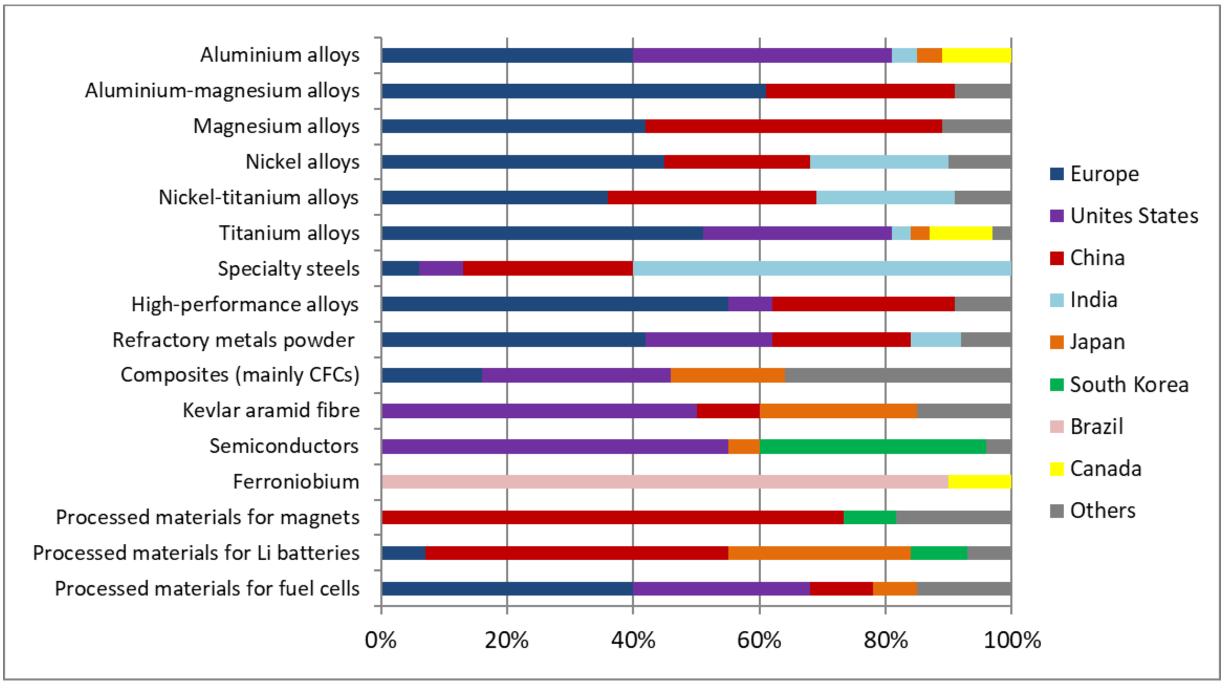
6.4.2. Supply risks for unmanned aerial vehicles processed materials

Within the scope of this study, 14 processed materials have been selected and analysed as relevant for drones, namely: Al alloys, Al/Mg alloys, Mg alloys, Ni alloys, Ni/Ti alloys, Ti alloys, speciality steels, high-performance alloys, refractory metals, composites (CFCs), aramid (Kevlar) fibres, semiconductors, ferroniobium and magnetic alloys. Similarly to robotics, processed materials for lithium batteries and fuel cells were considered in addition in the 'processed materials' supply-chain step ([21]).

Compared to the other parts of the UAV supply chain, **Europe is well positioned with regard to the supply of processed materials, with a share of 27 %.** Other major suppliers of processed materials for UVs are the United States (19 %), China (17 %) and India (9 %). Other countries provide the remaining quarter of the processed materials. For seven of the relevant processed materials, the European share in global production is above 30 %, and for certain alloys Europe even dominates the global supply (Al-Mg alloys, Ti alloys, high-performance alloys). However, for the remaining materials, Europe's share of global production is below 20 %, implying a potential need to diversify the supply sources: Europe's share of the supply of CFCs and speciality steels is 16 % and 6 % respectively. For certain processed materials, Europe shows a strong dependency on imports due to insignificant shares of global production, namely for semiconductors, aramid fibres (Kevlar) and ferroniobium. For these latter processed materials, potential supply bottlenecks could occur.

The country production shares of UAVs relevant processed materials are displayed in Figure 31.

Figure 31. Country production shares of processed materials relevant to unmanned aerial vehicles



Source: JRC

6.4.3. Supply risks for unmanned aerial vehicles components

The most important supplier by far for components for UAVs is the United States (42 %). Other major suppliers are Japan and China (each 14 %), and Europe (13 %). The country production shares for each of the components used in UAVs are shown in Figure 32.

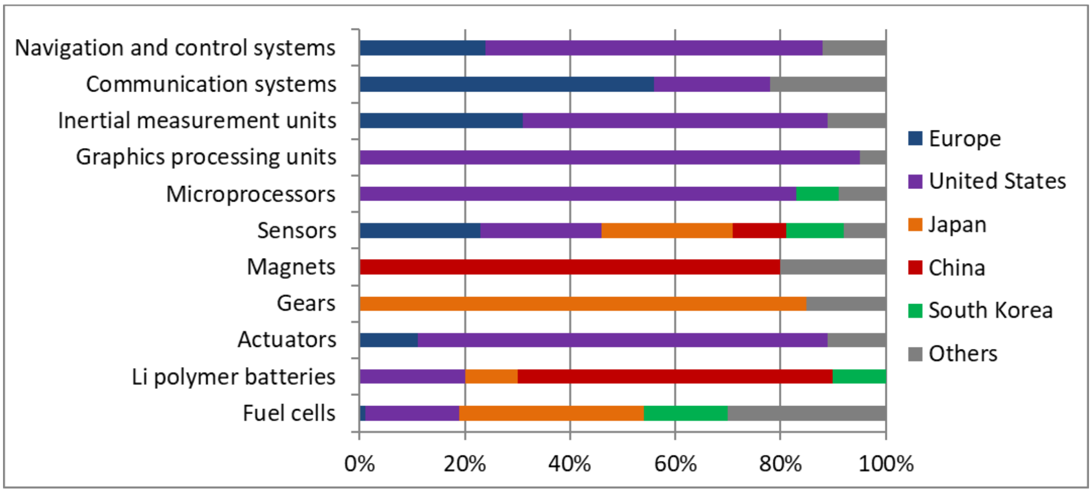
([21]) Batteries are the current power sources of UAVs and fuel cells are considered to be potential future power sources.

Minor important suppliers are South Korea, Canada and Israel. The picture for the EU is very heterogeneous, depending on the specific types of components. The EU holds a solid share of global IMU production, navigation and control systems, and sensors (all > 20 %), and even dominates the global production of communications systems. For actuators, Europe has a market share of at least 11 %.

However, for the other five components, the EU depends to a very high degree on foreign production. Japan is the key supplier of gears, sensors and fuel cells. China is the main supplier of lithium polymer (LiPo) batteries and a key supplier of sensors. Other key suppliers are Israel (actuators), South Korea (microprocessors and fuel cells) and Canada (fuel cells, IMUs, navigation and control systems). **Potential supply bottlenecks are of concern in particular for those components the global production of which is concentrated in only a few countries, namely GPUs, gears, microprocessors and actuators.** In particular, GPU production shows an extraordinary high concentration in a single country – United States (95 %).

The country production shares of UAVs relevant components are displayed in Figure 32.

Figure 32. Country production shares of components relevant to unmanned aerial vehicles



Source: JRC

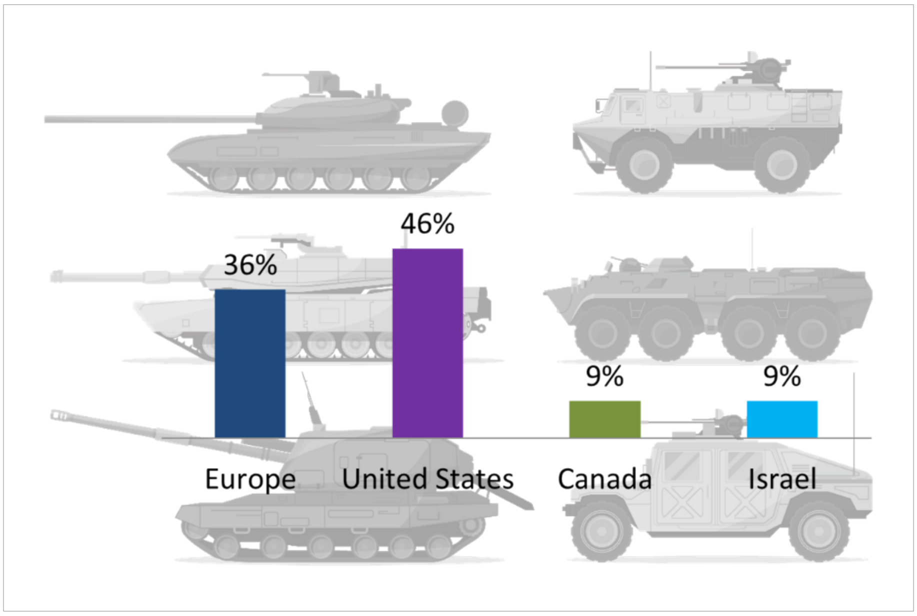
6.4.4. Supply risks for unmanned vehicles (aerial, ground and maritime)

As for the manufacturing of civil UAVs, **China is the market leader by far, with a global market share above 75 %**. Far behind, Europe is the second-largest supplier of civil drones (9 %), followed by the United States (5 %) and Israel (3 %).

The main supplier of UGVs is the United States (46 %), followed closely by Europe (36 %). Canada and Israel together supply around 18 % of UGVs globally (Figure 33) (BIS Research, 2017). Similarly, the United States is the key supplier of UMVs ([22]) (35 %). **United States is also the major supplier of UMVs (35 %). Europe is the second-largest supplier of UMVs with a share of 31 %.** Canada and Japan have small production shares of 7 % and 5 % respectively (Unmanned Maritime Vehicles, 2013) (Figure 34).

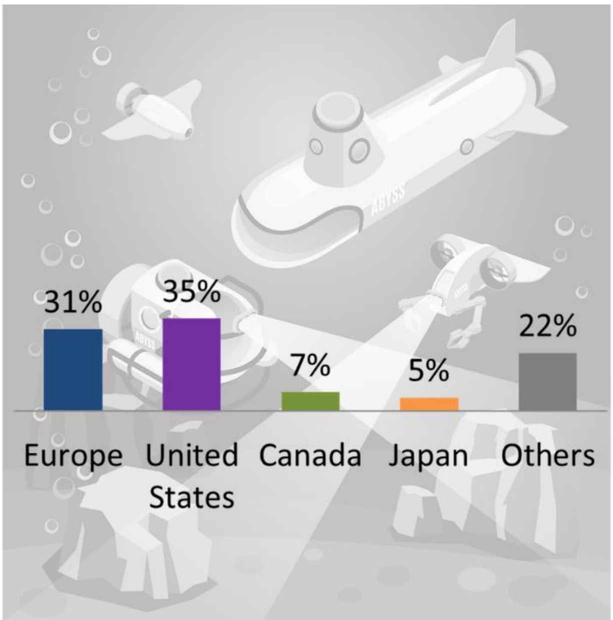
([22]) UMVs include underwater and surface vehicles.

Figure 33. Country production shares of unmanned ground vehicles



Source: JRC, BIS Research, 2017.

Figure 34. Country production shares of unmanned maritime vehicles



Source: JRC, *Unmanned Maritime Vehicles*, 2013.

6.5. Civil versus military unmanned vehicle supply chains

The comparison between civil and military UVs differs for each type of UV (aerial vehicle, ground vehicle, marine vehicle, etc.). There is a large area of overlap between civil and military needs, such as lightweight structures and high energy intensity. For UAVs, we distinguish the case of smaller UAVs from that of larger UAVs. For smaller UAVs, the differences between military and civil needs are often moderate. Key differences are the need for enhanced performance (payload, range of operation, etc.), performance under difficult environmental conditions and reduced vulnerability. Efforts to reduce vulnerability are focused on signature control using a stealthy shape, coatings to absorb radar, heat-masking technology and decreasing the detectability of electronic emissions.

Different procurement models exist for the small UAVs used by the defence sector. The easiest and cheapest way is often the acquisition of ordinary civil drones, which are upgraded to increase performance and/or signature control. Due to the rapid growth of the civil small-UAV sector, only a minority of models is developed for specialised military applications. For large UAVs, the civil and military supply chains are more separated, hindered also by the relative high unit costs.

The key players in the production of military drones are similar to those for civil drones, but the production shares differ significantly. **Major military drone producers are the United States** (Aerovironment, Boeing, Lockheed Martin, Dragonfly, General Atomic Aeronautical Systems) and **Israel** (Bluebird Aero Systems, Elbit Systems, Israel Aerospace Industries). **European companies such as Airbus Defense and Space, Dassault Aviation and BAE Systems** are also mentioned among the important producers of military drones. European companies have acted collectively to develop the next generation of armed drones, most notably the nEUROn UCAV technology demonstrator (in 2012) and the MALE unmanned aircraft. The nEUROn UCAV is the first stealth combat drone developed in Europe, and is a joint effort involving France, Greece, Italy, Spain, Switzerland and Sweden (New America, 2019). **China** (China Aerospace Science and Technology Corporation) and **South Korea** (Korea Aerospace Industries) also have the capacity to manufacture military drones (Reuters, 2018b).

Other countries such as **India, Iran**, **Pakistan**, **Russia**, **Taiwan and Turkey** have also taken steps toward independent armed drone production. Seeking protection against neighbouring China and Pakistan, India developed Rustom-I UAVs in 2009 and armed Rustom-II MALE UAVs in 2015. While Russia and Taiwan remain in the research and development stage, Iran, Pakistan and Turkey have succeeded in developing armed drones (New America, 2019).

There is a **significant overlap between the supply chains of UAVs for civil and military applications.** For small UAVs, the first and second stages of the supply chain of these applications are almost identical, whereas they split for the third and fourth stages, i.e. components and assemblies. For large UAVs, this split might partly start earlier in the supply chain (second or even first stage). The study showed that of the 39 UAV integrators more than 50 % produce civilian drones, only 30 % produce both civilian and military drones and around 20 % produce military drones only. This indicates that the integrators of both supply chains partly overlap, but they are mainly split between the two sectors.

An increase in the demand for undersea warfare systems (including UUVs) is expected in the Asia–Pacific region (represented by China, India, Japan and South Korea) due to the rising tensions between the neighbouring countries and increases in defence spending. This, according to experts, will provide a fertile ground for a significant increase in manufacturing capacity in the Asia–Pacific region (Undersea Warfare Systems, 2019).

6.6. Recommendations for policy actions and research to reduce bottlenecks in the unmanned aerial vehicles supply chain

6.6.1. Recommendations at the level of raw and processed materials for unmanned aerial vehicles

More than half of the relevant raw materials for UVs are supplied by multiple small suppliers, which provides **good opportunities for supply diversification**. Securing access to raw materials for which the EU has no significant domestic production, such as Cr, Co, Mo, C, Ni, Ti, Mg, V, Cu, Sn, Sb, Bi and Nb is essential for the development of this technology at EU level. An overview of raw materials suppliers for drones is shown in Figure 29.

The **development of advanced manufacturing technologies for innovative lightweight and high-strength structural and functional materials** (processed materials) is a relevant research line for UVs due to its potential to provide significant energy-efficiency gains and environmental benefits. Candidate materials are advanced versions of the related lightweight alloys (magnesium alloys, aluminium alloys with scandium or beryllium, speciality steels) and composites (fibre reinforced), including combined polymer–metal composites. In addition, innovative materials for special applications are demanded, for example vanadium dioxide is used for miniaturised multifunctional motors (such as rotary motors) due to its suitability for artificial muscles (Robotics Business Review, 2019). Another striking example consists in the advancements due to the use of alternative alloying metals, including lithium, scandium and beryllium (IDTechEx, 2019).

6.6.2. Recommendations at the assembly level (unmanned aerial vehicles)

Several recommendations have been identified at the assembly level.

— **The development of smaller electronics with better performance (computation speed)** is essential for the development of future UVs. Promotion of private–public partnerships aiming at maximising R & D investments. Due to the significant competitive advantage especially of the United States, it is recommended that a strong focus be put on key areas such as:

- integration of alternative fuel types, also for smaller UAVs;
- establishing a specialised semiconductor industry to support UV development;
- establishing development communities for UAV artificial intelligence, context awareness and obstacle avoidance.

— **Setting up strategic alliances with non-EU countries to establish joint ventures** for specific components identified as being critical, i.e. components that are essential for manufacturing up-to-date UAVs and that have a highly concentrated supply.

— **Promoting common business cases and collaboration between military and civil (dual-use) sectors** in the field of UVs to boost investment volumes. As this is promising for a distinct set of components only, these should first be determined.

— **Mapping and analysis of supply-chain issues for military applications,** for example where specific corporate policies hinder the supply of components produced in the EU to the EU defence sector. As an example, IMU production could be investigated (Bosch, TTTech.), for example via a sectoral stakeholder consultation and stakeholder analysis.

— **Stimulating the deployment of a highly competitive awards-based programme** that encourages and supports EU SME using distinct market measures such as combining SME support measures for scale-up and manufacturing through targeted funds, for example the European Defence Fund. Such programmes can lead to procurement and the development of new industrial capabilities, especially in speciality markets with low numbers of production units (such as research and defence). The European Defence Fund could provide money such a dedicated research programme.

— **Developing innovative software in combination with unmanned aerial systems (hardware)** to enable the effective integration of these systems into European military forces and operations.

6.6.3. Other policy and R & D recommendations for unmanned vehicles

The **military sector requires smaller, more economic and more efficient military drones and robots**, which is only possible with significant technological advancements. Most often, these aims overlap with the R & D undertaken by the civil sector, therefore it is of great importance to make use of potential synergies between the civil and military sector. It is recommended that a platform be established to **stimulate dual-**

use research by all European UV developers (civil and military applications), in order to strengthen the European UV industry.

7. Additive manufacturing (3D printing)

7.1. Applications and demand for 3D printing

The main aerospace components (potentially) manufactured using 3DP (ASTM, 2018) are grouped as follows.

- **Non-structural components.** These components are predominantly made using plastic 3DP and include, for example, parts for the interior of aircraft.
- **Structural parts for jet engine components.** This subsector is already rather mature, and notable examples include complex shaped components such as fuel nozzles, stator rings, turbine blades, fuel injectors and air ducts.
- **Other structural parts.** This subsector is still under development, mainly because of strict homologation and fundamental technical problems for 3DP of large parts. This includes components such as brackets, large components including fuselage components, large metallic structures such as aircraft wings and empennage (EASME, 2016; AM-motion, 2018).

In total, 17 individual raw materials in five processed material families are identified as being those most relevant to 3DP and analysed in the study for both civil and military aerospace. The most common alloy families are **powders of aluminium-magnesium, titanium, nickel, stainless steel and special alloys** (EPMA, 2018). Various titanium alloys, such as those with aluminium and vanadium (grade 5) elements, are used for high-strength and lightweight applications. They are corrosion resistant, can be heat treated and are relatively expensive. A more pure variant (grade 23) is used for brackets, sandwich structures with carbon fibre reinforced plastics, in vanes and in support structures. Relatively pure alloys (grade 2) are also used in space applications, such as for antennas, and are very stiff and light. Compressor disks and blades used in both military and civil applications are made with aluminium-molybdenum-zirconium-containing titanium alloys. Various titanium-aluminium-niobium-containing alloys are used for additional high-rigidity-at-high-temperatures properties for jet engines, blades, valves and rotors, including for example in Genx and LEAP engines for civil aircraft. According to Safran (Viguier, 2018), titanium-based alloys have a great future as lighter parts, and higher-temperature resistance reduces fuel consumption and emissions. Titanium alloys are also galvanically compatible with more use of carbon fibre reinforced plastics, and **titanium powders for 3DP could be extensively used, if they reach 'affordable' market prices**.

3DP potentially allows for a very wide variety of both civil and military applications. The new technology offers specific advantages for aerospace in general and for defence (Objectify, 2019; BCG, 2018), in particular for the following.

- **Prototyping and design freedom.** 3DP can significantly improve product development and allows substantially more design freedom compared to traditional manufacturing. Examples in aerospace include components with complex geometries and performance requirements, such as fuel nozzles (General Electrics (United States), Rolls-Royce (United Kingdom) and Pratt & Whitney (United States)), stator rings, fuel injectors (Morris Technologies), air ducts (Boeing fighters) and parts in helicopter engines (Safran Helicopters), including key parts inside the combustion chamber. These 3D-printed-component-containing engines are almost 30 % more powerful than those previously manufactured. Another example is a Pratt & Whitney engine containing 12 3DP parts mounted on Bombardier aircraft. The components are mainly fasteners and injection nozzles, 3D-printed in titanium and nickel alloys.
- **Lightweight parts.** 3DP allows for substantial weight reduction through the optimised design of a wide range of parts and the combination of multiple parts into single ones. Examples include fuel tanks, engine nacelles, hinges and brackets. The use of 3DP in the previous example of Pratt & Whitney engines has saved a total of almost 15 months over the entire design process, and the final weight of the part has come out at 50 % less than a conventional equivalent. For structural parts, key players are Airbus, Rolls-Royce, Snecma and AvioAereo. STELIA Aerospace has produced a

demonstration 3D-printed reinforced fuselage panel using wire and arc additive manufacturing technology (Bikas et al., 2016) of 1 square meter.

- **Customisation.** 3DP enables the serialised production of unique parts with fewer design restrictions and high customisation potential. Other instances include customised protection gear, connectors for missiles and a variety of parts for satellites. Various examples exist that are produced by Stratasys and Airbus. For non-structural parts such as civil aircraft interiors, 3DP offers customisation potential for small production numbers when different airlines have specific demands. 3DP has the possibility to create small production numbers without expensive tooling needs for each individual airline. The same potential is there for defence purposes, with equally low production numbers for a wide variety of parts and expensive tooling as well.
- **Field operations support/maintenance and repair.** 3DP can also be used to repair existing parts. Hybrid technologies combining conventional machining, and especially DED-type technologies, are intensively studied for aerospace and military applications. 3DP is an enabler of more flexible production capacity in the field. It provides immediate production, reducing complex and costly logistics relevant to defence. It also allows for direct repair and alterations where needed, supporting strategic, tactical planning and troop field support. For defence, examples include documented repairs of components of F35B and F22A fighter jets that would otherwise have been grounded much longer. In one case the parts produced are even manufactured for permanent replacement. In combat situations, being able to quickly restore a fighter aircraft is a valuable asset.
- **For isolated operations** in particular, 3DP allows the production of highly tailored products or simplified short-term replacement and repair parts that were originally based on other materials. Examples include 3D printers on navy vessels that are able to print a variety of parts after 3D scanning of the original objects and, as an ultimate example, the installation of a 3D printer on the International Space Station in 2014.

7.2. Technological challenges for 3D printing

3DP is maturing rapidly (Statista, 2019b). However, **key challenges identified for 3DP are achieving sufficient quality, lower production cost and consistency in production**, in particular to meet aerospace certification, as well as military performance demands (AM-motion, 2018; DefenceIQ, 2016).

- **Quality constraints.** Aerospace restrictions for certification and quality control reduce the 'continuous improvement' potential of 3DP in particular. Lowering safety-related legislative barriers is clearly not an option for aerospace. Hence, 3DP as a technology needs to become more mature regarding quality and reproducibility.
- **Just-in-time and fast manufacturing** is another challenge. The high cost of equipment, raw materials, slow printing times and the limited sizes of powder beds are concerns relating to the production of larger parts. With the significant need for more maturity, rapid improvements are being observed in this area.
- Another area for improvement is the **quality and finishing of parts**. Specific needs are indicated for non-destructive testing (NDT) and other certifications dedicated to metal 3DP-produced parts for aerospace applications.

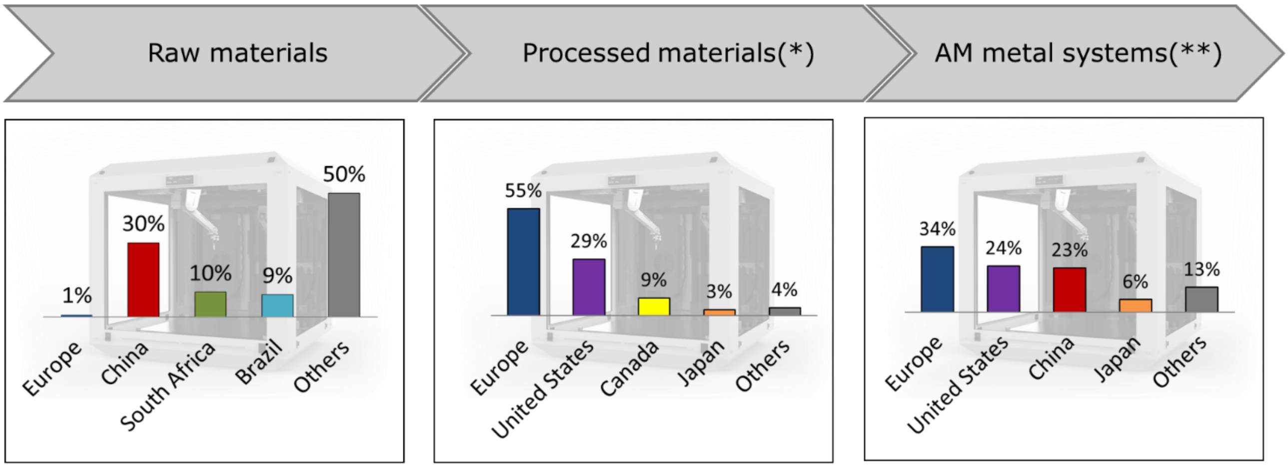
7.3. Key players in the 3D-printing supply chain

This analysis focuses on the same steps in the value chain as considered for the other technologies. However, 3DP is a specific case in the context of this report compared to the other four technologies analysed. 3DP as a technology is both consuming materials to manufacture the 3D printers themselves, as well as for the production of parts by using the technology. The latter has by far the largest impact on the demand for materials. At the same time, **3DP allows for reduction, substitution, recycling and mitigation** in the use of CRMs and traditionally manufactured components. This mitigation strategy is **particularly relevant to defence applications in resource-constraint situations and/or remote locations** in order to **keep aerospace platforms operational**.

The key players in the 3DP supply chain are shown in Figure 35. **China is the major supplier of around 30 % of the raw materials required in 3DP and the largest supplier of seven of the 17 raw materials relevant to 3DP**. South Africa and Brazil are other key suppliers of raw materials. For the other two stages, however, **Europe has strong metallurgical capabilities relating to the supply of processed materials** (55 % production share), in particular for nickel alloys, stainless steels and special alloys. **Europe also has a relatively strong position in the development and supply of 3DP systems** (production share of 34 %).

In Figure 36, an overview is given of the raw materials, processed materials and different AM metal systems that have been considered in the analysis. The country (region) shares shown in Figure 35 are estimated correspondingly.

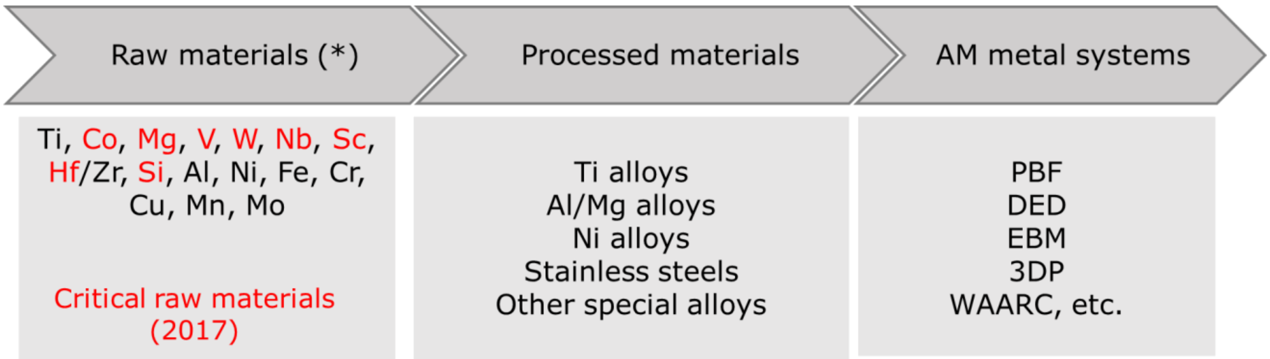
Figure 35. Additive manufacturing (3DP): key players in the supply chain



(*) Based on number of suppliers; market shares based on tonnage or value not available.
(**) Based on the number of industrial metal AM suppliers per country.

Source: JRC

Figure 36. Additive manufacturing (3DP): an overview of raw materials, processed materials and AM systems considered in the analysis



(*) The focus here is on 3DP materials.
Materials required in 3DP systems are similar to the basic materials used in robotics.

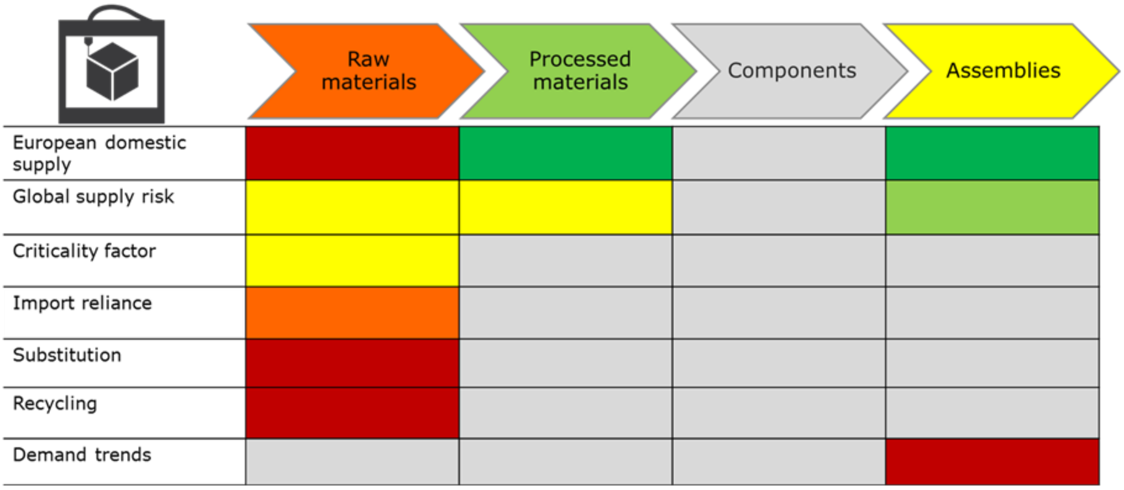
Source: JRC

7.4. Overview of supply risks for the 3D-printing supply chain

Due to the nature of 3DP, the number of supply-chain stages between (non-conventional) materials and finished components will be significantly reduced in the future. Many materials used for conventional manufacturing are traded in established commodity markets. For 3DP in comparison, there is a lack of (standardisation of) established powder recipes. This aspect is highly relevant for guaranteeing part quality and reproducibility, and thus the certification of aerospace components. The cooperation of the 3D-printer suppliers and powder providers **creates a more direct relation between processed materials for 3DP and the actual technology used**. This affects both the supply risk and the competitiveness of manufacturing. Both will increasingly rely on these **specific materials–technology interfaces**.

Similarly to the other technologies, Figure 37 shows the main bottlenecks in the supply chain based on the above analysis. **The bottleneck assessment performed has shown that there is a potential high risk of supply issues for the raw materials step only, and a medium supply risk for the last step of the supply chain (supply of AM metal systems) mainly due to expected rapid growth in demand** (Figure 37)**.**

Figure 37. Overview of supply risks and bottlenecks in the supply chain of 3DP



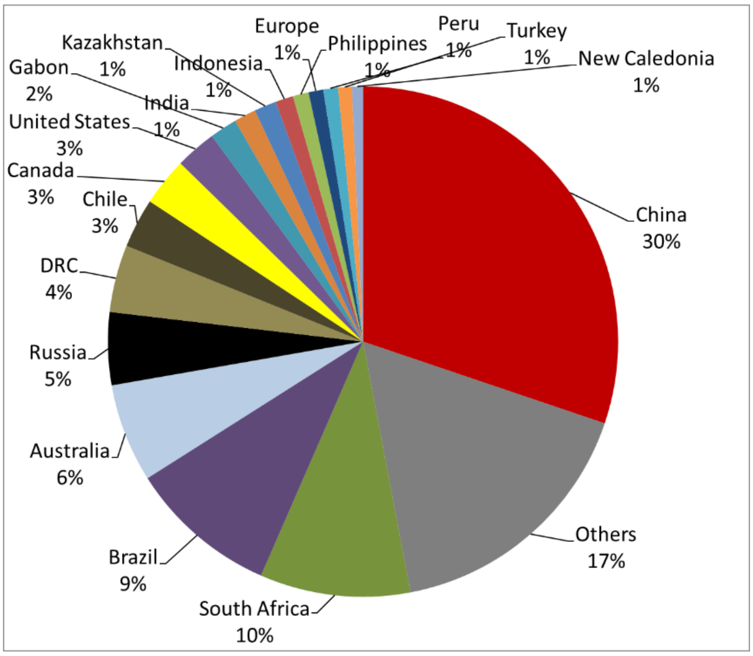
Source: JRC

7.4.1. Supply risks for 3D-printing raw materials

When elaborating on the supply risks and the expected increase in demand for materials for 3DP, the specific demands for dual-use applications relate to the materials present in aluminium-magnesium, titanium, nickel, stainless steel and special alloys. These five main alloy families contain eight CRMs, namely **cobalt, magnesium, vanadium, hafnium, tungsten, scandium, silicon metal and niobium**. The demand for **titanium-** and **nickel**-based AM powders is expected to rise sharply. Recently however, trade sanctions and tariffs for **titanium** are recognised as being a particular threat both to the supply and to the cost levels for the aerospace industry.

An overview of raw materials suppliers for 3DP is presented in Figure 38.

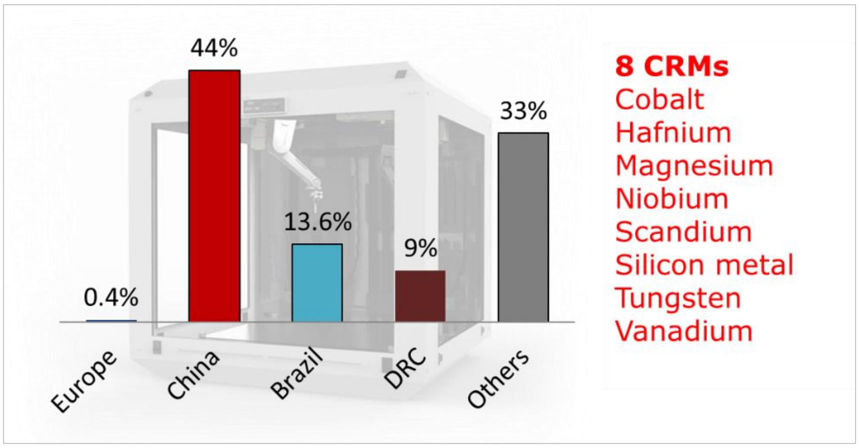
Figure 38. Raw materials suppliers for 3DP: overview



Source: European Commission, 2017.

The key suppliers of CRMs for 3DP are shown in Figure 39. Five of the eight CRMs (European Commission, 2017) identified for 3DP, namely magnesium, vanadium, tungsten, scandium and silicon metal, are supplied from China. Other key suppliers of CRMs are Brazil and the Democratic Republic of the Congo. **The supply of 3DP-relevant CRMs from European countries is negligible (< 1 %).**

Figure 39. Supply of CRMs for 3DP technology: key players



Source: European Commission, 2017.

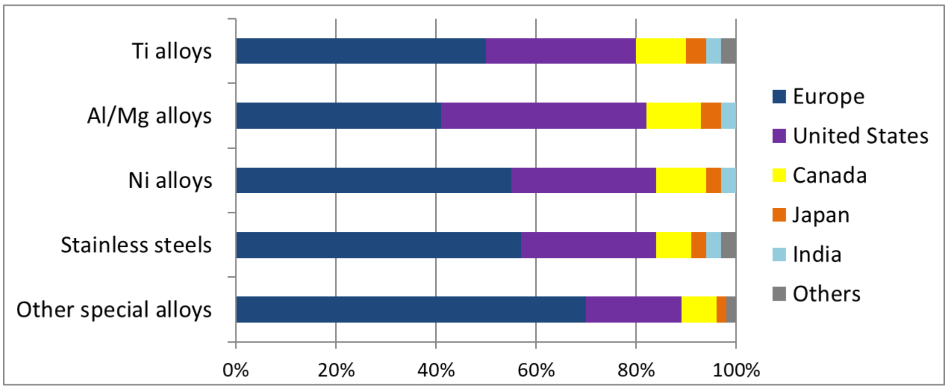
Other materials relevant to dual-use 3DP applications in aerospace are **chromium, copper and manganese**, which are used as **alloying elements to enhance various alloy properties**. **Scandium, niobium and hafnium** (a by-product of **zirconium)** are materials used in special alloys for lightweight and high-temperature applications, and therefore are more specifically related **to defence and space applications**. **Scandium** is used in expensive aluminium-scandium alloys providing impressively lightweight and strong structures. **Scandium** has a very low total global production volume compared to almost all other metals, and **primarily originates from China (66 %)**. **Hafnium** is used in expensive (3D metal powder) nickel-based super alloys in turbine blades, vanes and industrial gas turbines. The supply-and-demand balance of Hafnium is known to be very volatile. Another non-3D-printed military application of **hafnium** is in nuclear control rods in reactors and submarines. **Niobium** is used in the production of high-strength low-alloy steels and in stainless steels for increased resistance to corrosion and high temperatures. This also includes the more common stainless steel 718, with significant quantities of **niobium** typically used where corrosion resistance and high strength at high operating temperatures are sought. These alloys are used in the nuclear industry in nuclear reactor components, and in the space industry in rocket thruster nozzles. A number of different niobium-containing alloy types (C-129, C-3009 and some titanium-niobium) are identified as being relevant to specialised 3DP applications for both civil and military aerospace. **Niobium primarily originates from Brazil (95 %).**

7.4.2. Supply risks for 3D-printing processed materials

Contrary to the results of a previous study (EASME, 2016), **Europe seems well positioned to provide metallurgical and transformative capacities for the production of 3DP powders**. The analysis is based on the data from 63 suppliers of powders and wire that have been identified and scrutinised here. This applies in particular to steel- and nickel-based alloys. However, **Europe is less represented in aluminium and titanium powders (more dominated by the United States and Canada) and appears to have a gap in the supply chain in the case of metal-wire products**. The latter proved to be difficult to document, but it is suspected that these metal wires primarily originate from China as well. This may affect future abilities for the 3DP of large structural parts.

The country production shares for processed materials relevant to 3DP that were considered in the supply chain analysis are shown in Figure 40. Shares are based on the number of suppliers per material.

Figure 40. Country production shares of processed materials relevant to 3DP



Source: JRC

The main concern about the supply chain is the fact that most of the commercially used 3DP technologies are rigid in terms of input-processing variables. Hence, **it is difficult to customise powder compositions according to the end user's needs**. As with the business model of traditional printing, many commercially available metal powders are supplied by the 3D machine providers, and their costs are relatively high. **The lack of flexibility in the recipes available for different machines has an impact on costs, as well as the quality and consistency of the produced parts.**

Despite Europe having a large share of the supply, there are supply concerns. The reason is that **there are only a small number of metal-powder suppliers identified** in total. **Any supply disruptions in one of these early material-production stages are likely to have immediate and severe impacts on the availability of a wide range of components.** It should be noted that the number of players, market shares and ownerships of powder producers and 3DP systems is changing quickly in this rapidly maturing sector.

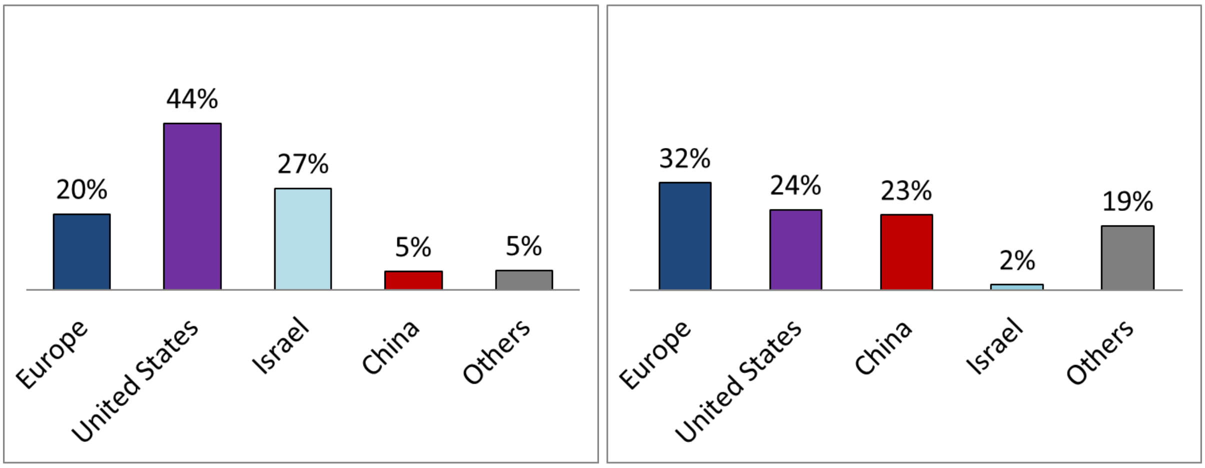
7.4.3. Supply risks for 3D-printing components

In the later stages of the supply chain, Europe is relatively well represented. The civil plus military aerospace sector is marked by a very high level of concentration around key original equipment manufacturers. 3DP suppliers and integrators such as Boeing and GE (United States) are known for vertical steering, taking the lead on key developments. In Europe, Airbus is steering its supply chain more horizontally in this direction. Nearly all major aerospace original equipment manufacturers, including Bell Helicopter, GKN Aerospace, Honeywell, Lockheed Martin, MTU Aero Engines, Northrop Grumman, Pratt & Whitney, Raytheon, and Rolls-Royce, have built infrastructures within their corporations to evaluate and implement 3DP technologies.

7.4.4. Supply risks for 3D-printing systems

For 3DP systems, information is identified on the total unit shipments for each country from 2007 to 2017, along with a detailed list of all identified suppliers (Wohlers, 2018). Rapid growth is observed in the number of manufacturers providing polymer and/or metal 3DP **industrial** machines. **On the basis of total units sold, Europe has a market share of about 20 %**, and the United States and Israel represent over 71 % of the supply. This US share is predominantly in polymer-based systems, which have the largest share in units produced. When analysing the **number of manufacturers of metal 3DP machines** the EU is slightly better represented, as illustrated in Figure 41.

Figure 41. Shares based on the number of units sold between 2007 and 2017 for polymer systems (left); and the number of metal-based 3D printer systems (right)



Source: JRC, Wohlers, 2018.

When analysing in more detail per technology, the Europe's share in the number of suppliers is 25 % and 21 % respectively for the two key sub-technologies, PBF and DED, compared to the total of 32 % for all metal 3DP technologies combined. China has a high and quickly growing number of individual suppliers, though so far with relatively low unit shipments.

Regarding software enabling 3DP (Busachi et al., 2018), we need to distinguish product-design software such as ProE and Solidworks (US-based) and CATIA (EU-based), from software converting drawings for the actual manufacturing process and post-processing software. In general the United States is more advanced here, but European companies are also well represented (AM-motion, 2018).

7.5. Civil versus military 3D-printing supply chains

The metal-based 3DP manufacturing sector clearly has both a military and civil aerospace aspect, characterised by both a very high level of innovation and **complex safety, security and endurance requirements** for the parts produced. Due to rapid developments, it is not possible to provide quantitative numbers on the precise market shares and volumes at stake. Therefore, the quantitative approach of this study identified the geographical locations and development of the supply chain stages, rather than the tonnages produced or economic market shares.

The similarities between 3DP for civil applications and that for military applications originate from the same difficult operating environments and high levels of investment required. They involve common players and share similar technical concerns. Most of the integrators, such as Airbus and Boeing, have both civil and military applications. Hence, **their supply chains have many overlaps**. However, due to more recent investments, the centre of gravity in innovation lies more on the civil side than on the more conservative and secured military side of the supply chains. For civil applications, a large share of EU research and development occurs at small suppliers and SMEs, rather than at large system integrators and aircraft manufacturers. One reason is that, over the last several years, commercial aerospace has been doing rather well macroeconomically, whereas defence budgets and subsequently R & D investment in new technologies like 3DP have been more constrained. As a consequence, the use of 3DP in the defence sector is more anecdotal. **The sector is not yet thoroughly incorporating the technology in its manufacturing processes, and thus is not yet exploiting the full potential offered by 3DP** (EDA, 2018)**.**

Vertical integration versus collaboration in the value chain. One of the particularities of the aerospace 3DP value chain is that integrators and assembly producers seem to be moving along the value chain. As a tentative conclusion, in Europe **integration appears to take place more horizontally in the form of partnerships, with Airbus stimulating innovation in its suppliers and SMEs**. Inside and outside the United States, GE in particular is arranging for a fair amount of vertical integration in acquiring powder suppliers, equipment manufacturers, software enterprises and production companies, leading to the largest installed machine base worldwide and covering the entire value chain. It is not possible to state which strategy is better: The EU approach is not necessarily better or worse than the United States one. It is a matter of **balance between more control and more flexibility**. It is nevertheless a point for **further research to characterise the effect of possible supply disruptions for both strategies**.

7.6. Recommendations for policy actions and research to reduce bottlenecks in the 3D-printing supply chain

7.6.1. Recommendations at the level of raw and processed materials for 3D printing

A key policy action resulting from the analysis is steering towards the **diversification of current raw material extraction** to reduce the current dependency on a few countries for certain materials. For 3DP, this applies specifically to **titanium, cobalt, magnesium, vanadium, tungsten and niobium**. Improving relations and mining conditions under the scope of new trade agreements with, for instance, Australia and Canada is of particular relevance here.

An improved **strategic understanding of the resilience of the military supply chains** is needed. The (future) role of 3DP in the critical sectors of aerospace and defence **warrants careful reconsideration of specific strategies to mitigate supply risks**. **Creating strategic stockpiles for manufacturing** of the main 3DP powders **can be reconsidered** (RPA, 2012). Here, 3DP powders identified in the background report include titanium grade 2, grade 5 and grade 23, Al-10Si-Mg, Al07Si-0.6Mg, nickel alloys 316L and 625, stainless steel alloy 718; CoCr and possibly specific zirconium and niobium alloys.

Here, specific R & D actions are recommended that can, for example, be embedded in research on advanced materials for the future. For 3DP this includes specific investigations into the balance between the **technical**

advantages of the use of scandium, niobium, hafnium and zirconium in special alloys as advanced materials, along with their raw material supply risks and very specific mining and refining conditions, which are not as yet well documented.

Another strategy to consider is to **strengthen the protection** of specialised SMEs producing 3DP powders in Europe **against hostile foreign takeover**. Further analyses of the costs and benefits of both these mitigation strategies should be related **to the risk for the defence sector of not being able to keep aerospace platforms operational**, and the risk for the civil sector of not being able to keep aircraft production uninterrupted and competitive.

7.6.2. Recommendations at the assembly level (3D-printing systems)

For wire products for the production of larger parts, Europe is ahead in the related DED technology development. At the same time, Europe seems to suffer from a poor supply chain for metal wires. From an R & D perspective, it is recommended that the **lack of customisation capabilities** between the processed materials used and the specific 3DP technology developed should be further investigated. Specific attention must be paid to the availability of **high-quality, environmentally friendly and cost-effective materials**, depending on the individual application. Europe's AM **community relies on a limited selection of conventional feedstock materials, and the range of available high-quality materials needs to be expanded**.

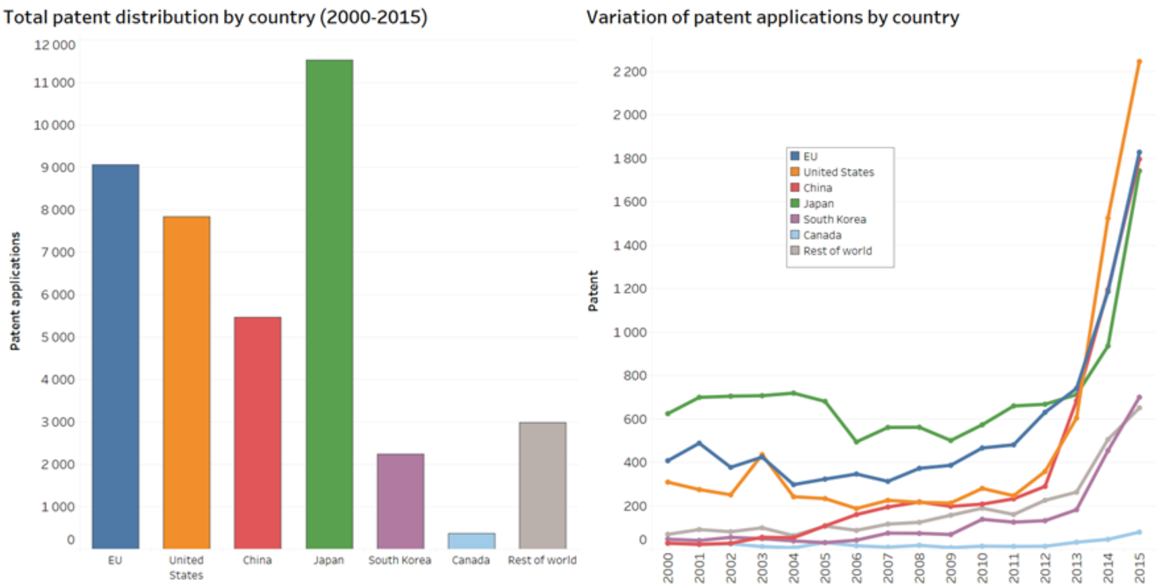
7.6.3. Other policy and R & D recommendations for 3D printing

Three other main areas for possible action are identified, related to **technology development**, **standardisation, safety** and the **protection/valorisation of IPRs** for 3DP (AM-motion, 2018).

— Technology development

The aforementioned technological limitations are not expected to remain for long: **the high speed of development will provide** more capable machines and quality materials **for each part of the market, including the military section** with its high performance demands. The patent analysis confirms this development pace. In the past around half of the patents were related to processed materials. In recent years patents related to technology alone prevail. The analysis shows that globally there is **a great deal of research being done on overcoming the current disadvantages** of metal 3DP. The highest growth rates in patents in over the past several years is observed for the United States, China, the EU and Japan, as shown in Figure 42. More information can be found in the related background report (MatDual, 2019).

Figure 42. Variation in patent applications related to 3DP



Source: JRC, European Patent Office

The domain of 3DP for the **repair and maintenance** of equipment seems of particular relevance **for the defence sector**, for example for operations in remote locations. Currently, this domain is poorly documented and **requires further analysis and R & D effort**.

— Standardisation and certification; safety

In this respect there is a clear need for **standardisation of metal powders and wire recipes for AM**. With EU companies and SMEs being well positioned to produce high-quality components, the standardisation of 3DP material recipes would assist EU companies in particular. The preference of the aerospace industry itself is to have a stable and international standardisation process involving European and international bodies (AM-motion, 2018; DefenceIQ, 2016). With regard to the pace of Chinese research and development seemingly being much faster than that of the EU, it is recommended that targeted research and innovation actions be funded in this technical domain.

For the 3DP-relevant materials under REACH, **nickel** is restricted for certain uses related to skin contact. **Cobalt, magnesium, niobium and tungsten** are registered under REACH, but their specific properties may trigger more demand rather than more substitution in the future. For 3DP, the powders of these metals in particular need to be further investigated regarding **safe handling and proper removal and recycling from powder beds**. This can lead to higher handling costs for additive manufacturing in Europe.

— Digital security and IPR protection

Protection of intellectual property (IP) is a key piece in the broader framework of competition policy. This applies in particular to 3DP as an emerging technology. In military and dual-use sectors, **protection against foreign hostile takeover of SMEs should be improved** to prevent security-related technologies and IP from being captured by others. Europe is particularly strong in innovation in metal-based AM. This further requires, on the one hand, special **attention to be paid to the functioning of IP regimes to protect developed copyright**. On the other hand, strategies need to be developed that foster the **valorisation of new 3DP capabilities in a fair manner**.

A particular area of **IP concern** is the protection **of information provided with or within CAD files**. Here the creation of a suitable IP framework that clarifies the implications of 3DP in relation to original designs is recommended, in particular for components with a military purpose (AM-motion, 2018).

A variety of actions are proposed in relation to **materials research, manufacturing capabilities and coordination and support needs**. These include the following.

— Improving standardisation to promote high quality and consistency, and lowering the costs of AM powders. The same goes for the development of standards and quality-assurance systems, in particular for finishing, testing and certification steps after parts manufacturing.

— The role and necessities for AM to recycle parts and unused powders, including guidelines for maintaining or restoring material properties.

— Developing a knowledge repository of materials and process parameters.

— Identifying powder properties for the quality and consistency of powder production.

— Developing new sustainable materials and processes and related characterisation in the field of multifunctional materials, multi-materials and materials with highly improved functionality for aerospace applications, in particular for special alloys used in defence and space such as niobium, hafnium/zirconium and scandium.

— Increasing the size of the production envelope for larger airframe structures using AM technologies.

— Improving safety assessment, safety management and guidelines and education on environmental health and safety challenges with AM, in particular for the handling of metal powders and their unique properties.

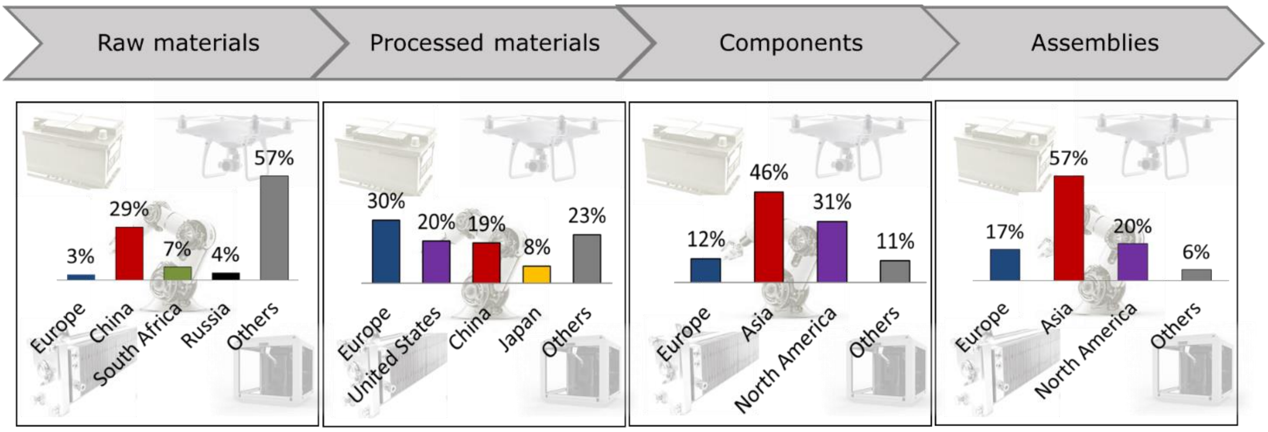
8. Conclusions

Study findings

Rapid growth in demand of between 10 % and more than 30 % is expected over the short and medium term for the five technologies examined here. Securing adequate and continuous access to raw and processed materials, and components, is of the utmost importance for the competitiveness of European industry.

The dependence of Europe on the supply of raw materials for the five analysed technologies is extremely high. Europe produces on average around 3 % of the overall raw materials required in Li-ion batteries, fuel cells, robotics, UAVs and 3DP technologies (Figure 43). China dominates global production, supplying around one third of the raw materials. Other key suppliers are South Africa (7 %) and Russia (4 %). Brazil, Australia and Chile are also shown to be key suppliers for 3DP and Li-ion batteries. More than half of the raw materials are produced by numerous small suppliers with minor shares of global production (<4 %).

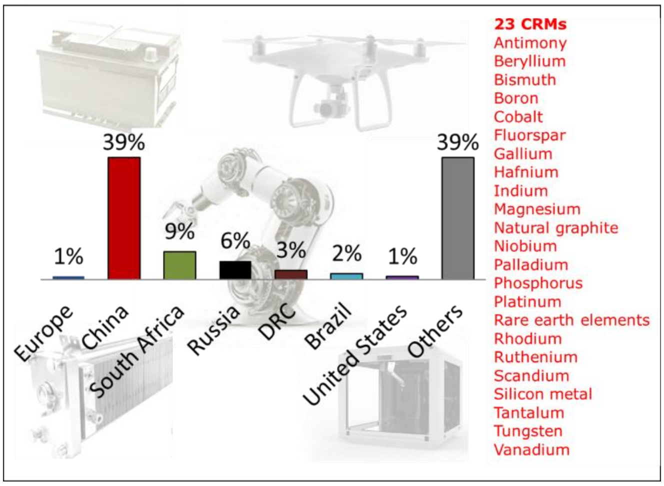
Figure 43. Key suppliers of raw materials, processed materials, components and assemblies for Li-ion batteries, fuel cells, robotics, UAVs and additive manufacturing (3DP) technologies



Source: JRC

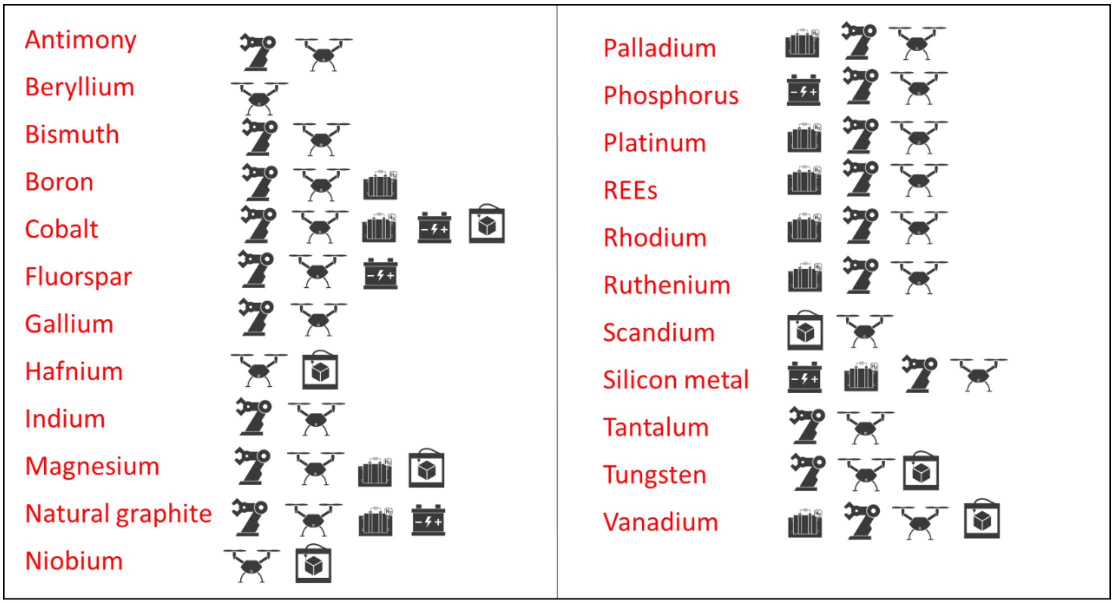
Europe supplies only 1 % of the CRMs required in the five technologies in question. The major supplier is China, with a share of almost 40 %, followed by South Africa (9 %), Russia (6 %) and many smaller suppliers (Figure 44).

Figure 44. Key suppliers of CRMs for Li-ion batteries, fuel cells, robotics, UAVs and additive manufacturing (3DP)



Source: JRC, European Commission, 2017.

Figure 45. Critical materials required in Li-ion batteries, fuel cells, robotics, UAVs and additive manufacturing (3DP)



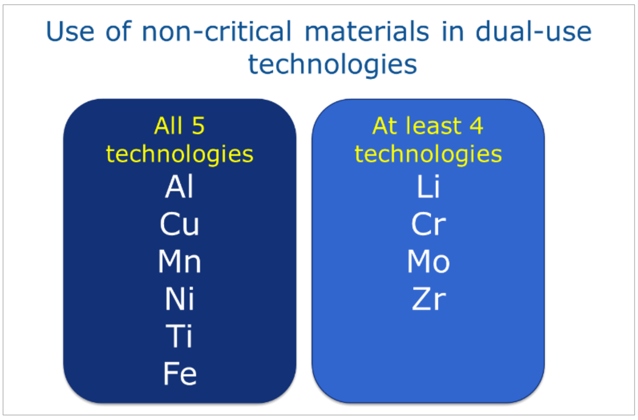
Source: JRC

In total, 23 CRMs have been identified as necessary for Li-ion batteries, fuel cells/hydrogen technologies, robotics, drones and 3DP technologies. The main CRMs at risk are cobalt, used in all five technologies, and natural graphite, magnesium, silicon metal and vanadium, used in four of the five technologies. Most of the critical materials are used in three of the technologies (Figure 45).

Critical materials and REACH. Nine of the CRMs are registered in REACH, namely antimony (Sb), beryllium (Be), cobalt (Co), graphite, magnesium (Mg), niobium (Nb), cerium (Ce), neodymium (Nd) and tungsten (W) (ECHA, 2013). These substances of concern need to be progressively replaced by suitable alternatives in future. The enforcement of REACH is a Member State obligation, and therefore they are taking care of this. Member States may allow for exemptions from REACH in specific cases for certain substances, on their own, in a mixture or in an article, where necessary in the interest of defence (Article 2.3 of REACH). The European Defence Agency is also working on this issue, and information can be found in EDA (2019). The line between defence and civil protection (e.g. police, firefighters) is sometimes difficult to draw, and goods used for defence are used for civil purposes. But civil protection material may also be used for defence purposes. Another piece of chemical legislation (classification, labelling and packaging) is following the same route as REACH in the defence sector.

With regard to the use of non-critical materials that might merit further attention in future, the study has found that 6 materials are extensively used in all five technologies, namely Al, Cu, Mn, Ni, Ti and Fe; while four materials, namely Li, Cr, Mo and Zr are required in at least 4 of the examined technologies (Figure 46).

Figure 46 Non-critical materials required in at least four of the five technologies: Li-ion batteries, fuel cells, robotics, UAVs and additive manufacturing (3DP)



Source: JRC

With the exception of Li-ion batteries, Europe is generally an important supplier of processed materials for the five technologies, providing, on average, about one third (Figure 43). Other key suppliers are the United States (20 %), China (19 %) and Japan (8 %). Canada, India and South Korea are shown to be key suppliers for 3DP, robotics and Li-ion batteries.

Though a strong player in the production of processed materials, Europe is highly dependent on the supply of certain materials, such as aramid fibre, semiconductors, ferroniobium and processed materials for Li-ion batteries (main supplier China). Such dependencies apply to both the civil and the defence sectors. Europe also relies, to a lesser degree, on the supply of nanomaterials, specific Al alloys and speciality steels.

In terms of component supply, **with the exception of fuel cell technology, Europe's domestic production of components is relatively low**. **Europe produces, on average, around 12 % of the components required in Li-ion batteries, fuel cells, robotics and drones** (Figure 43). A key issue for batteries is the lack of EU capacity in Li-ion cell component manufacturing (cathodes, anodes, electrolytes and separators) and in cell manufacturing itself. There is high dependence on China for both. Although the European share in Li-ion cell production is expected to increase, thanks to the European strategic action plan for batteries adopted in 2018, Li-ion batteries for common military applications are still assembled from commercial cells manufactured in Asia. China is also a major supplier (80 %) of the REE magnets used in robots and drones for both civil and defence applications. The main concern of EU industry for robotics and UAVs is the lack of EU component manufacturers, with the United States leading the supply of actuators, controllers (processors), GPUs and IMUs, while Japan dominates the supply of high-precision gears. Overall, the key suppliers of components resulting from the analysis are the United States (fuel cells, robotics, drones), China (Li-ion batteries, robotics, drones), Japan (Li-ion batteries, fuel cells, robotics, drones), Canada (fuel cells) and South Korea (Li-ion batteries).

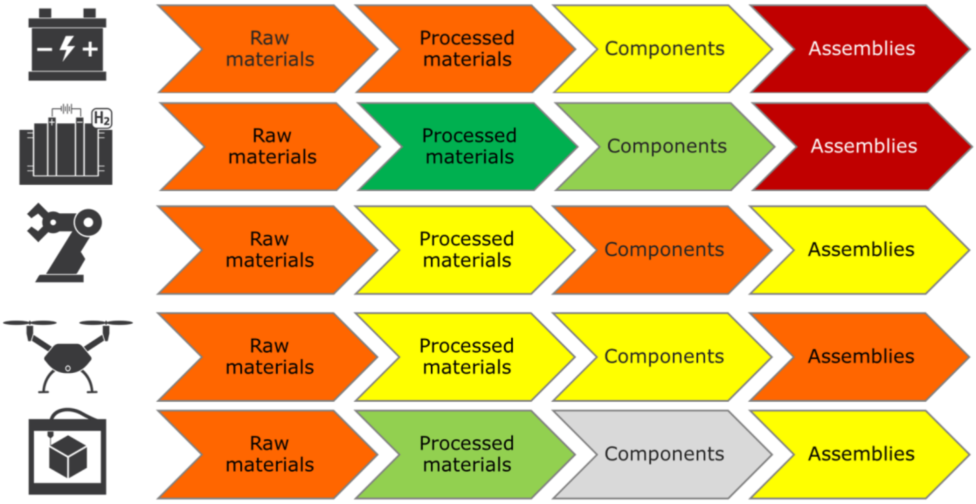
Europe produces, on average, around 17 % of Li-ion batteries, fuel cells, robotics, drones and 3D metal systems globally (Figure 43). **Europe is a strong player in the production of robots and 3D metal systems.** It has some production of drones, though not enough to satisfy its needs (assuming European demand is around 20-25 % of global demand, as observed for other established technologies). **Europe is very weak as regards the supply of Li-ion and LiPo batteries and fuel cells, which are predominantly provided by Asia (China, Japan and South Korea) and North America (United States and Canada).** Japanese manufacturers dominate industrial robotics, while United States manufacturers dominate non-industrial robotics, UVs and artificial intelligence. Manufacturers in the United States are also the key players for military exoskeletons. The United States and China dominate UAV assembly and UAV manufacturing. Regarding 3D printers for industrial use, the United States leads in polymer-based technologies, with Europe strongly present in metal AM. For aerospace applications, the United States and the

EU are equally present in the top 15 system integrators, exploring and driving the development of 3DP on a large scale.

The role of China as a key supplier in the supply chains is worthy of note. It has acquired, and continues to expand its dominant position in the Li-ion battery and drone supply chains, and has ambitious plans in the fields of robotics, fuel cells and 3DP.

The analysis shows that the weakest step in the supply chain for the five technologies under investigation is the supply of raw materials. Furthermore, the supply of assemblies appears to be very critical for three of the technologies, namely Li-ion batteries, fuel cells and drones. The supply of processed materials is shown to be critical for Li-ion batteries, though some supply risks are also detected for robotics and drones. At components level, though some supply risks are detected for Li-ion batteries and drones, robotics seems to be the most vulnerable technology (Figure 47).

Figure 47. Supply risks identified for Europe in the supply chains of Li-ion batteries, fuel cells, robotics, UAVs and 3DP



Source: JRC

Some general cross-cutting issues identified in the analysis are related to **sensors** and **software development skills**. Sensors will become ever more important, and their development and the processing of their data should receive close attention. Software development skills will be a key enabler for the development of robotic and autonomous systems for both European military forces and civil applications.

General policy recommendations

It is important that European industry is preserved, organised and supported in order to reduce Europe's strategic dependency and increase **security of supply via diversification**, especially with regard to the supply of raw materials and components, both of which are shown as weak links in the supply chains. **Besides increasing domestic production, other suggested strategies include the substitution of critical materials, recycling and finding alternative suppliers.** In addition to reducing the demand for primary materials of limited supply, recycling can also reduce production costs, save energy, lessen resource consumption and diminish our environmental impact. However, it remains a challenge to develop a cost-effective, environmentally friendly recycling process with high recycling efficiency ([23]), which produces cleaner, higher-quality recycled materials. This needs attention, in terms of both research and policymaking.

([23]) The Chromic EU project will develop new processes to recover chromium, vanadium, molybdenum and niobium from industrial waste.

Another important aspect is that the **security of supply with regard to material dependence should be always examined in a value-chain approach**, taking into account the linkages between various value-chain steps. The study advances this point by investigating the raw materials, processed and advanced materials, components and assemblies required for five strategic emerging technologies. The collection of reliable data for processed materials, and often for components, has been identified as an issue that merits further attention.

The EU's dependency on raw materials goes beyond physical access to the individual minerals, and is affected by other economic conditions related to mining conditions, ownership, trade restrictions, environmental permitting and other uneven conditions. Industries outside the EU are typically less concerned with responsible sourcing, potentially causing an uneven playing field. This is undermining social and environmental conditions in developing countries. **Securing sustainable access to the right quantity and quality of raw materials** will be key to future responsible EU industry developments.

The study also highlights the **need for more effective action on (critical) raw materials in Europe**. Such actions can tackle supply risks at any step in the supply chain, such as **joint procurement, promoting recycling and substitution**, among others. **Supply diversification**, via trade agreements or tailor-made trade contracts with different supplier countries, could decrease the threat of supply shortages. Such a contract would secure the supply from a certain country, giving the supplying country planning reliability (a win-win situation). **Stockpiling** could be one of the options to mitigate short- to medium-term supply disruptions in the event of a crisis. Different stockpiling options could be examined at EU or Member State level, supporting corporate strategies to mitigate risks. A dedicated study could be commissioned to evaluate and analyse in more depth the potential of stockpiling materials essential to the development of certain technologies, along with the environmental, social and economic impacts, taking into account the expected technological developments of the future.

In order to tackle the extremely high **dependence of Europe on the supply of raw materials** this study identified the need for more cooperative and effective action on securing the supply of (critical) raw materials. In order to do so, distinct measures are identified by this report, which require as a basis the **permanent monitoring of raw materials markets and (strategic) value chains.** It also puts in evidence the need for industry and policymakers to work together and to **ensure access to up-to-date reliable information for the Member States and stakeholders** (e.g. as done in the Raw Materials Information System) in relation to the most critical CRMs. **The exchange of data and information, and international cooperation, should be supported in an integrated manner at the EU, Member State and corporate levels.** The above could be of great support to strategic sectors, including the dual-use and defence sectors, thus supporting the development of a coherent EU CRM policy.

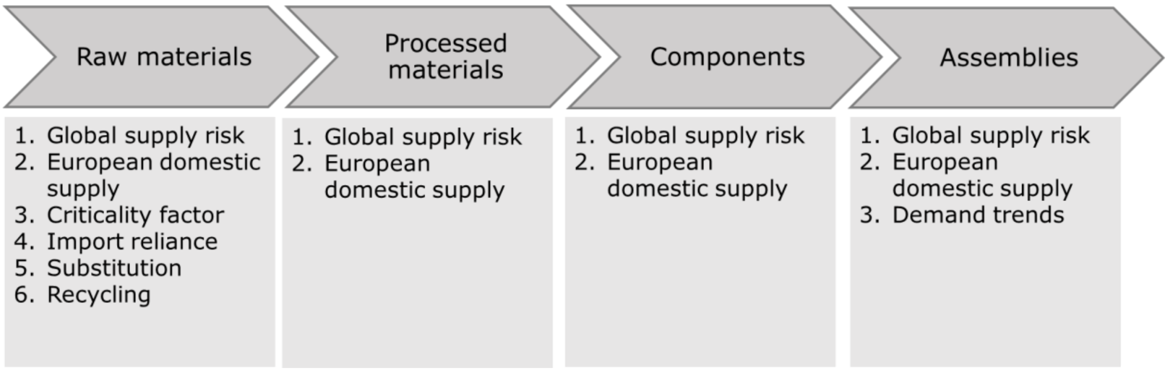
Lastly, inclusive, **strategic and comprehensive discussions are needed on the role and future competitiveness of these emerging technologies** — particularly on material availability, sustainability, IPR protection, software development and digital security for key military and civil supply chains.

Annexes

Annex 1. Methodology and data

In order to identify forthcoming bottlenecks in the supply chains of the five technologies selected for this study, a tailored methodology was developed and applied. In this dedicated methodology, the materials supply issues and potential bottlenecks in the supply chain for the five dual-use technologies (battery cells, fuel cells, robots, drones and AM systems) are assessed using several parameters for each step of the supply chain: raw materials, processed materials, components and assemblies. For each step, several parameters were taken into account that might weaken or jeopardise sustainable supply in Europe (Figure 48).

Figure 48. Parameters used in assessing the potential bottlenecks in the supply chain



Source: JRC

Six parameters are used to evaluate the potential supply risks at the level of raw materials, namely: (1) global supply risk; (2) European production (domestic supply); (3) criticality factor (whether a material is flagged as critical in the 2017 CRM list); (4) import reliance of Europe for a particular raw material; (5) substitution; and (6) recycling. The import reliance, substitution and recycling parameters are assessed using data from the 2017 CRM study. For steps 2, 3 and 4 in the supply chain, two parameters are used: (1) global supply risk; and (2) European production (domestic supply). The global supply risk for all steps has been determined using the Herfindahl-Hirschman Index (HHI), based on concentration of supply. The European domestic supply corresponds to the European shares determined during the supply-chain analysis. An additional parameter — demand trends — is considered at the last step in the supply chain, indicating demand increases forecast for the future.

The indicators are normalised in the range of 0 to 1; lower values indicate a relatively higher degree of supply risk. The results are presented visually in the form of a traffic-light matrix. The following two marginal cases are distinguished.

— **Red area** (corresponding to value 0), indicating a **very high supply risk** and the presence of substantial supply issues combined with a limited ability to adapt or tackle them due to the nature of the impact/risk.

— **Green area** (corresponding to value 1), indicating the **best case scenario**, or no detectable supply issues.

Intermediate values, represented by yellow, orange or various intensities of green, indicate that a potential supply issue/risk is detectable with medium to low confidence. The relationship between colour, score scale, risk scale and bottlenecks is shown in Table 1.

Table 1. Relationship between given scores, colours and bottlenecks

Colour	Score	Risk scale	Bottlenecks
(red)	0-0.2	Very high (VH)	Existence of severe bottlenecks in the supply chain and the presence of other significant factors, negatively influencing the supply combined with limited ability to adapt due to the nature of the supply risk
(orange)	0.2-0.4	High (H)	Presence of severe and widespread bottlenecks in the materials supply chain
(yellow)	0.4-0.6	Medium (M)	Bottlenecks are detectable which can affect the supply at medium confidence
(light green)	0.6-0.8	Low (L)	Bottlenecks are hardly perceptible and if they exist, they have low impact on the supply risk
(dark green)	0.8-1	Undetectable (U)	No bottlenecks are detectable which would weaken the security of supply

The materials identified for each technology contribute to each parameter with an equal weight through an arithmetic mean before being combined and scaled from 0 to 1.

More details about the parameters used for evaluation of the potential bottlenecks and materials/ components/ assemblies supply risks are given in Table 2.

Table 2. Definition of the parameters used in the bottlenecks assessment

Indicator	Description	Supply chain step
Global supply risk	Calculated using a metric of market concentration (known as the Herfindahl-Hirschman Index)	All four steps in the supply chain
European domestic supply	Estimated European supply as a share of the global supply, scaled from 0 to 1 (*).	All four steps in the supply chain
Criticality factor	Whether or not a raw material is flagged as a critical material in the 2017 CRM list. The score given is 0 if critical and 1 if non-critical.	Step 1: raw materials
Import reliance	The European import reliance as estimated in the 2017 CRM study, scaled from 0 to 1.	Step 1: raw materials
Substitution	Represents substitution index in relation to the supply risk (SI_{SR}) as defined in the 2017 CRM study.	Step 1: raw materials
Recycling	Refers to the end-of-life recycling input rate (EOL-RIR) as provided by the 2017 CRM study, scaled from 0 to 1.	Step 1: raw materials
Demand trends	Takes into account the technology uptake forecast in the short and medium term (by 2030); lower values correspond to high expected uptake rates.	Step 4: assemblies

(*) It is assumed that 30 % domestic production could satisfy European needs, considering that European demand is around 20-25 % of global demand (assumption based on data from different energy sectors). Therefore, European production of 30 % or higher is considered safe (= 1); production shares of less than 30 % are scaled down accordingly.

This methodology is meant to give an indication of whether or not the selected dual-use technologies are susceptible to supply issues and where in the supply chain these shortages might be expected. Thus, it allows us to identify where in the supply chain intervention is needed.

Methodology robustness check regarding using companies' headquarter location

The calculation of the supply shares for the raw materials step is rather straightforward using data from the criticality assessment (European Commission, 2017). This is not however the case for the other steps of the supply chain. Often, big companies own production facilities and sales offices in multiple countries for which the supply shares are not normally known. This makes it very challenging and often impossible to collect pertinent data specifically for processed materials and components and sometimes for the final product (assembly). Therefore, a simplified approach of using headquarters location to assess country supply shares was adopted. Such an approach, however, could introduce some form of discrepancy into the calculation of the final supply chain shares, since they can differ from the supply shares calculated using the geographical location where actual production takes place. The possible discrepancy introduced due to this approach was assessed for battery technology where data are available for the last two steps — components and Li-ion cell production. Figure 49 shows country supply shares calculated using the headquarters approach and the geographical location of the production facility. Figure 50 illustrates the comparison between final supply-chain shares for Li-ion components and Li-ion cells using both approaches. With the exception of Europe regarding Li-ion cell production, where a large discrepancy is observed, the deviation for the other countries is estimated to be between – 50 % and + 44 %.

Conclusion

In spite of this deviation, the fact that China is the major supplier in the supply chain in both cases is evident. The shares of other suppliers also show relatively small differences. It is assumed that similar conclusions can be also drawn for the other technologies in the study.

Figure 49. Comparison between country supply shares based on headquarters and on the geographical location of production facilities for Li-ion components (cathodes, anodes, electrolytes and separators) and Li-ion cells

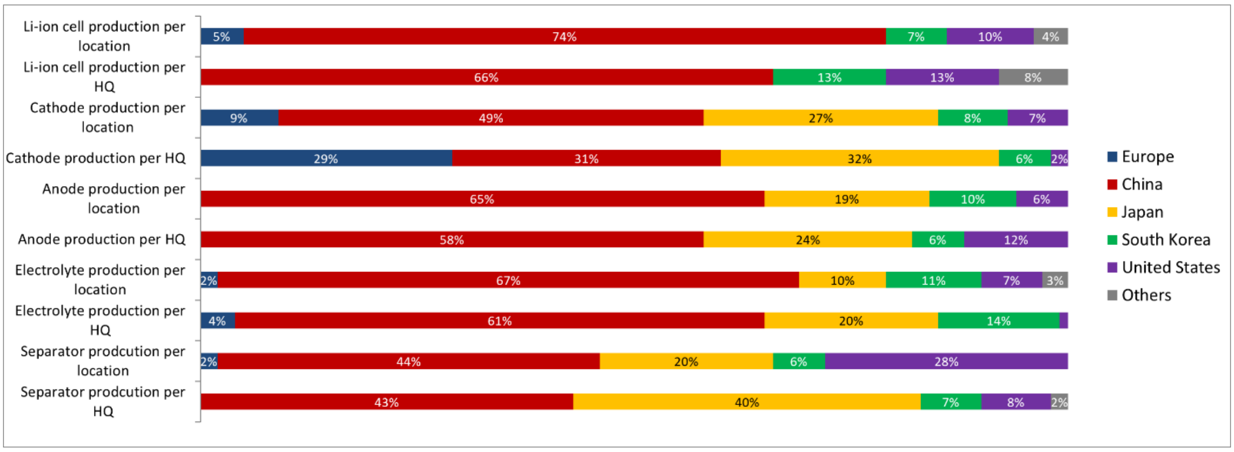
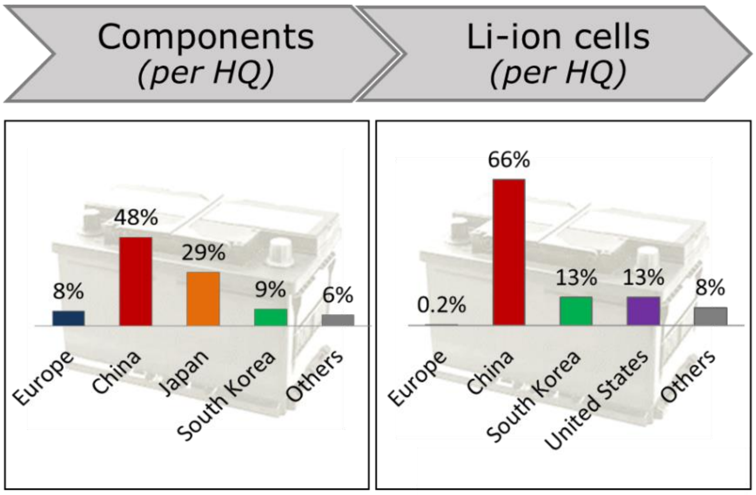
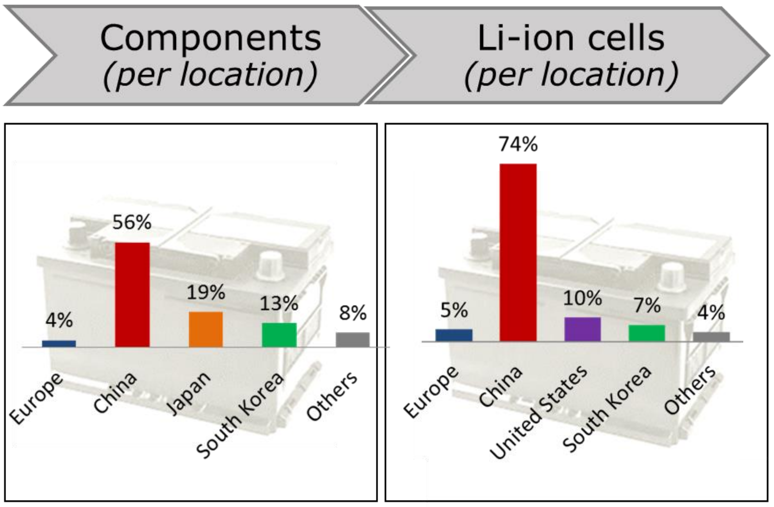


Figure 50. Overall country supply chain shares for Li-ion components and Li-ion cells: comparison between (a) headquarters location and (b) geographical location of production facilities



(a)



(b)

Data used in the analysis

Public open sources such as Statista, USGS, Europages, European Commission reports, etc. were used for the analysis to the greatest possible extent. Market/consultancy reports, commercial (companies') websites, associations' reports and websites were also used.

Data on raw materials were taken from the 2017 CRM (European Commission, 2017) study on critical raw materials.

Data on processed materials, components and assemblies (e.g. batteries, fuel cells, robots) were taken from various sources. Shares were calculated preferably using production data/capacity or market/sales data whenever possible. Otherwise, data on revenues were used. If no other data were available, the number of companies per country was used to estimate country shares.

As a rule, the location of a company's headquarters was taken into account in order to allocate a company to a specific country. If a company with its headquarters in Europe has production facilities in other non-European countries, for instance, it still counts as a European company in the analysis and vice versa.

The following countries are considered to be 'Europe' in the report: the EU-28, Belarus, Norway, Switzerland and Ukraine. Cross-continental countries such as Russia and Turkey are not considered to be 'Europe' in this study.

The data used for supply chain analysis for all investigated technologies are summarised in the related JRC technical background report EUR 29889 EN (MatDual, 2019).

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List of acronyms and initialisms

3DP	3D printing
AFC	alkaline fuel cell
AM	additive manufacturing
BOP	balance of plant
CAGR	compound annual growth rate
CFC	carbon fibre composites
CRM	critical raw material
DED	directed energy deposition
DMFC	direct-methanol fuel cell
EASA	European Aviation Safety Agency
EDA	European Defence Agency
EU	European Union
GPU	graphics processing unit
HT-PEMFC	high-temperature polymer electrolyte membrane fuel cell
IMU	inertial measurement unit
IP	intellectual property
IPR	intellectual property rights
LCO	lithium cobalt oxide
Li-air	lithium-air
Li-CFx	lithium carbon monofluoride
Li-ion	lithium-ion
LiPo	lithium polymer
Li-S	lithium-sulfur
LT-PEMFC	low-temperature polymer electrolyte membrane fuel cell
MALE UAV	medium-altitude long-endurance UAV
MCFC	molten carbonate fuel cell
NCA	nickel cobalt aluminium

NMC	nickel manganese cobalt oxide
PAFC	phosphoric acid fuel cell
PEMFC	polymer electrolyte membrane fuel cell
PGM	platinum group metal
PBF	powder bed fusion
R & D	research and development
REE	rare earth element
SMEs	small and medium-sized enterprises
SOFC	solid oxide fuel cell
UAV	unmanned aerial vehicle
UCAV	unmanned combat aerial vehicle
UGV	unmanned ground vehicle
UMV	unmanned maritime vehicle
UUV	unmanned undersea/underwater vehicle

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