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List of Abbreviations:

ADCPs	Acoustic Dopple Current Profilers
CTD	Conductirvity, Temperature, Depth
GNSS	Global Navigation Satellite System
IMUs	Inertial measurement units
LIBS	Laser-induced Breakdown Spectroscopy
LiDAR	Light Detection and Ranging
LI-FI	Light Fidelity
MV	Mining Vehicle
RMI	Raw Materials Initiative
SLAM	Simultaneous localization and mapping
TSS	Total Suspended Solids
UCS	Uniaxial Compressive Strength
VIPS	Voltammetric In Situ Profiling System

1 Executive Summary

The research roadmap aligns the future vision of ¡VAMOS! with the evolution of three different temporal domains: relevant sectoral drivers, the product evolution – its features, functions, capabilities and performance – and the underlying research & development aspects that are required to support a successful trajectory of the ¡VAMOS! concept to its full implementation.

The development of the research is therefore structured over three areas – Navigation & Spatial Awareness, Automated Extraction Solutions and Environmental Impact Tools – and investigated through three layers of assessment: definition of related capability targets, technological alternatives and underlying research (See Figure 1).
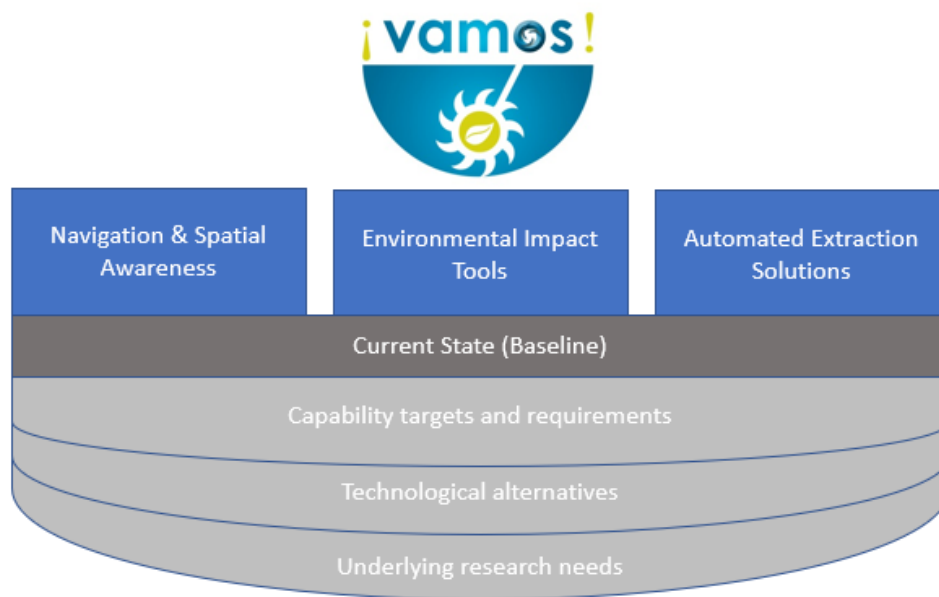
Figure 1 - ¡VAMOS! Research Roadmap structure

The Future Research Roadmap sub-task comprised three main activities:

- **(Joint) Roadmapping workshop:** Collection of inputs in the areas of interest (Figure 1) under the proposed time horizon (2030). Jointly organised with UNEXMIN Project (GA: 690008), it was held in Bled, Slovenia, in January 2018.
- **Roadmap development:** Processing workshop results against the backdrop of the Innovation Agenda (Deliverable 1.2) with the contribution of consortium partners via email.
- **Environmental Considerations:** Considerations toward near-zero impact mining.

Highly innovative solutions as well as components of the proposed systems require a strategic, forward-looking assessment for leveraging its main functionalities and potential. In this context, Technology Roadmap and Scenarios Exploration are proposed methods for assessing future challenges, emerging technologies & underlying research, market, environmental and political factors. Both methods were implemented in short exercises on the future research roadmapping workshop in Bled, Slovenia on the 30th of January 2018.

A depiction of the roadmap main components is illustrated in Figure 2.

Figure 2 - ¡VAMOS! Research Roadmap Illustration

	Current state to short-term (2025)	2030+	Extended Targets	¡VAMOS!
Capability targets and requirements	Dual Means; Miniaturized fibre optic lasers, automated calibration and database building; Improved accuracy and coverage; Improve density measurements; Improved operating bandwitdths; Increase concentration; size and noise reductions	Through-the-rock communication; Rapid resource model updating; Bio-friendly acoustic signal, w. negligible noise; Hybrid locomotion; Integration of sensor-based material characterization; Fast production control/optimisation; Mobile U/W navigation structures For global; Resolution and distance levels - 3x	in-situ sampling; Drilling & Coring; Inter-robot communication; Renewable power; Sub-mm accuracy; Molecular structure analysis (AI); Dynamic LIBS analysis/ libraries; Integrated Processing/ Waste Management; > 250 Mpa cutting; 3D materials tomography; Underground application; Multiple Means	Automated Extraction; Low Energy Consumption; Fossil-free mine production
Technological Alternatives	GNSS; LI-FI; LiDAR; LIBS; Fuel Cells; Acoustic sensors	AR Glasses; High pressure water jets; Point attack cutting tool; 3D printing; Floating Photovoltaic; Swarm Robotics; Semantic SLAM	Biomimetic locomotion; Sonar fracturing; Energy Harvesting; Real time autonomous logging	Real-time integration; Reduced emissions and; Improved rock cutting; Environmental risks identified and minimized; Increase in EU's mineral reserve
Underlying Research Areas	Submerged rock cutting; Analyutics & Optimisation; Artificial Intelligence; Data processing; Visualisation; Materials Science; Automation & Robotics; Sensors & IoT; Rheology and Slurry flow; Environmental Impact			

This report describes the development of the research roadmap (Section 3) including the i) review of relevant research roadmaps, ii) description of the workshop results and iii) development and consolidation of the ¡VAMOS! Future research roadmap. Section 4 concludes this deliverable with recommendations (see Table 5) developed considering the main technological components and alternatives identified against the set of criteria developed by the Innovation Agenda (Deliverable 1.2).

2 Introduction

2.1 The ¡VAMOS! Project

Estimates indicate that the value of unexploited European mineral resources at a depth of 500-1,000 meters is ca €100 billion, however, a number of physical, economic, social, environmental and human constraints have as yet limited their exploitation. ¡VAMOS! will provide a new Safe, Clean and Low Visibility Mining Technique and will prove its Economic Viability for extracting currently unreachable mineral deposits, thus encouraging investment and helping to put the EU back on a level playing field in terms of access to strategically important minerals. Deriving from successful deep-sea mining techniques, the ¡VAMOS! mining solution aspires to lead to: Re-opening abandoned mines; Extensions of opencut mines which are limited by stripping ratio, hydrological or geotechnical problems; and opening of new mines in the EU. ¡VAMOS! will design and manufacture innovative automated excavation equipment and environmental impact monitoring tools that will be used to perform field tests in four mine sites across Europe with a range of rock hardness and pit morphology. ¡¡VAMOS!! will:

1. Develop a prototype underwater, remotely controlled, mining machine with associated launch and recovery equipment
2. Enhance currently available underwater sensing, spatial awareness, navigational and positioning technology
3. Provide an integrated solution for efficient Real-time Monitoring of Environmental Impact
4. Conduct field trials with the prototype equipment in abandoned and inactive mine sites with a range of rock types and at a range of submerged depths
5. Evaluate the productivity and cost of operation to enable mine-ability and economic reassessment of the EU's mineral resources.
6. Maximize impact and enable the Market Up-Take of the proposed solutions by defining and overcoming the practicalities of the concept, proving the operational feasibility and the economic viability.
7. Contribute to the social acceptance of the new extraction technique via public demonstrations in EU regions.

2.2 Deliverable D6.6

2.2.1 Objectives

The concept of using seafloor mining methods for the extraction of mineral resources inland is so radical that this development is not foreseen in European policies and the various research roadmaps created in support of Europe's extractive industry (e.g. SRA of ETPSMR, ERA-MIN roadmap, etc). In order to exploit the full potential of ¡VAMOS! in creating a paradigm change in mining, a revision of current policies and roadmaps is necessary for the definition of new research topics supporting further technology development in the short, medium and long-term. This activity is also meant to mobilise the European raw materials research community, directly involving them in the project activities.

2.2.2 Approach

The Future Research Roadmap sub-task comprised three main activities:

a. Roadmapping workshop: a joint workshop with the UNEXMIN Project (GA: 690008) was organized in Bled, Slovenia (January 2018), bringing together experts from the minerals and robotics communities. Three key areas – i.e. technological clusters - were identified akin to the projects and conference scope – automated extraction solutions, navigation & situational awareness and exploration technologies. Interactive sessions were carried out for each area providing input for the roadmap and for exploring future scenarios.

b. Roadmap development: the roadmapping workshop provided a background for starting up discussions on the further development of the various elements of the proposed technology. Challenges were identified and research areas supporting the further evolution of related technology are described in incremental steps within the investigated timeframe (2030 and beyond) in a continuum since the production of Deliverable1.2 "Innovation Agenda".

c. Environmental considerations: submerged mining will eliminate several environmental concerns and reduce others. In line with Europe's strategic goal to make near-zero impact mining a reality, the research roadmap will also address these issues together with any further identified topics that require R&D support in the future.

This report summarises these activities and is structured as follows:

Three technological areas concerning ¡VAMOS! were identified: geological data collection & navigation and spatial awareness, automated extraction solutions and environmental impact tools. The former two were defined as per the Bled workshop, whilst the third component was added to integrate the environmental aspects covered by ¡VAMOS! project. For this report, it was decided to integrate geological data collection into the navigation and spatial awareness system, given how intertwined these areas are in ¡VAMOS! and since mineral exploration is not the primary focus of the project, but rather mining (extraction). Section 3 will therefore address these three areas. They are here described in terms of their current state (baseline) with three layers of assessment consisted of i) capability targets and requirements, ii) technological alternatives and iii) underlying research needs.

As a backdrop, considerations brought through a scenario exploration during the Bled workshop are also outlined.

3   Future Research Roadmap

The research roadmap aligns the future vision of ¡VAMOS! with the evolution of three different temporal domains: relevant sectoral drivers, the product evolution – its features, functions, capabilities and performance – and the underlying research & development aspects that are required to support a successful trajectory of the ¡VAMOS! concept to its full implementation.

Deliverable D1.2 - Innovation Agenda identified key innovation targets based on market and policy requirements. This served as baseline preparation for the research roadmap approach definition. As part of its innovation process together with other tasks, the ¡VAMOS! Project sought to capture an integrated plan to boost the output from innovative products, components and services. In relation to the work carried out in Work Package 1, the scope of Deliverable 6.6 includes:

- Features and product differentiation strategies based on the assessment of market needs and competitors' offers or solutions;
- Synergies with other products services and initiatives that are currently on the market or that are being developed by other research groups;
- Identification of innovation players, innovation networks and financiers in Europe through continued dissemination and joint EU-Project collaboration and conferences;
- Identification of potential links with non-raw materials related themes, such as ICT, robotics, space, environmental research and more;
- Link to project communications and dissemination for maximum visibility of the ¡VAMOS! concept.

3.1 Review of published technology/research roadmaps

Relevant research roadmaps related to the raw materials sector were published in a European context during the past decade; namely, the VERAM Research & Innovation Roadmap (2018), ERA-MIN Research Agenda (2013) and the ETP-SMR Strategic Research Agenda (2009). These documents point to important directions in terms of research priorities at European level in order to enhance EU capacities to respond to mounting challenges on raw materials supply as described by reference documents such as the Raw Materials Initiative (2008) and the Strategic Implementation Plan (2013). Table 2 provides an overview of the themes covered by these publications.

Table 1 - Past research agendas/roadmaps on raw materials at EU level - Key topics covered

Publication	RMI (2008)	ETP-SMR (2009)	ERA-MIN (2013)	VERAM (2018)
Short Description	3 pillars were defined for sustainable supply of raw materials in the EU	Guiding document for mobilizing stakeholders, stimulate investments in research and generate policy options	Identification of challenges and innovation needs, and definition of research goals in key areas	4 key priorities were outlined, with 9 Research & Innovation areas
Key areas covered	Fair access to raw materials on world markets. The right framework to foster sustainable supply of raw materials from EU sources Increased resource efficiency and promoting recycling in the EU	Critical Raw Materials (CRM) for Europe Promotion of skills and focused research on innovative exploration, extraction technologies, recycling and materials substitution. Increase resource efficiency and foster substitution of raw materials, Promote recycling and facilitate the use of secondary raw materials in the EU.	Primary resources supply Secondary resources supply (Recycling) Substitution of critical raw materials Public policy support and mineral intelligence Education and international cooperation Interdependencies and transversal issues	Fostering a sustainable supply of raw materials to feed new and existing value chains Resource efficient processing of raw materials Raw materials in new products and applications Closing material loops by maximizing the recycling of products, buildings and infrastructure

Other roadmaps pose relevant and transferrable developments in terms of research and innovation pathways that could be adapted and integrated as part of the evolution of the ¡VAMOS! mining system. For instance, Daim et al. (2017) identified robotic technologies for the power industry outlining alternatives in terms of functionality, working environment, motion pattern, propulsion type and related requirements (See example in Table 3). Other interesting example is the METS Roadmap[1], where five areas with opportunities for Australian companies to improve competitiveness were identified. For each area, the enabling Science & Technology factors as well as research priorities were outlined (a detailed description can be found in Annex 6.1):

- **Data driven mining decisions:** sensors and IoT, analytics and optimisation, visualisation;
- **Social and environmental sustainability**: monitoring and sensing, site and equipment selection;
- **Exploration under cover:** next generation drilling technologies;

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[1] Mining Equipment, Technology and Services Roadmap (CSIRO, 2017)

- **Advanced Extraction:** advanced cutting and drilling technologies, sensors and ore sorting;
- **Mining Automation & Robotics:** machine vision, materials and robotics, control systems and algorithms, virtual and augmented reality.

Table 2 - Example of robotic technology alternatives for the power industry identified by Daim et al (2017)

Application	Main Function	Working Environment	Motion Pattern	Propulsion
Submersible mini-robot	Visual inspection of submerged components	Underwater	Underwater navigating	Water Jet
Concrete crawler for robotic inspection	Inspection of concrete structure	Concrete surface	Climbing & Crawling	Caterpillar track

3.1.1 ¡VAMOS! alignment with EU-level roadmaps

The ETP-SMR[2] called for research initiatives to help Europe to secure supply of critical raw materials, reducing dependence on imports and to develop innovative and sustainable production technologies to extract such resources. With regards to extraction technologies, the document underlines the need for moving towards zero impact and fully automated operations, reducing footprint, optimising land use and energy use. In the mining/quarrying section of ERA-MIN Research Agenda the need for eco-efficient onshore and offshore mining technologies is also emphasised. Most recently, the VERAM roadmap outlined the required raw materials related research and innovation topics towards 2030 and 2050. In particularly the sections "Primary supply" and "Improved utilization of raw materials from EU sources" (Table 4) are relevant to the ¡VAMOS! Research Roadmap proposition

Table 3 - VERAM Research Roadmap - filtered for ¡VAMOS!

Priority Area 1 – Fostering a sustainable supply of raw materials to feed new and existing value chains	
Primary supply of EU raw materials for sustainable value chains	Improved utilization of raw materials from EU sources
Required research and innovation activities towards 2030-2050	
- Develop new and adapt conventional technologies and operations to increase automation in quarries and mines to reduce energy consumption on rock mass transportation and haulage and to advance fossil-free mine production. - Develop systems, technology and processes for integrated real-time process control, digitisation and automation in mines. - Develop new technologies for environmental protection and for the reduction of emissions and waste from mining and quarrying activities - Improve hard rock-cutting techniques and deploy continuous cutting machines for automated and efficient operations within small and large deposits, deep-sea mining and special conditions mining (2050).	- Develop novel deep-sea processing without environmental impacts and integrated waste management (2050). - Develop in-situ bioleaching at large scale without environmental risks (2050) - Develop knowledge on societal influence and social acceptance of different forest management systems, mining and exploration activities, e.g. research on areas of conflict regarding forestry and mining with regard to human health, ethics, gender, rural development and urban life, social and economic aspects, policy and governance, and new ways for planning and managing green infrastructure.

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[2] http://www.etpsmr.org/

3.2 Future Research Roadmapping Workshop

The challenges currently faced by the mining sector, and by extent the European supply of raw materials, are pressing for more innovative, step-change technologies to be developed. It is well acknowledged that robotics and automation are key factors for enabling a response and ¡VAMOS! can become an important alternative in this respect. Highly innovative solutions as well as components of the proposed systems require a strategic, forward-looking assessment for leveraging its main functionalities and potential. In this context, Technology Roadmap and Scenarios Exploration are proposed methods for assessing future challenges, emerging technologies, market, environmental and political factors. Both methods were implemented in short exercises on the future research roadmapping workshop in Bled, Slovenia on the 30th of January 2018.

3.2.1 Scenarios exploration process

The first session of the workshop introduced participants to Global Mining Megatrends (CSIRO, 2017) and to the INTRAW World of Raw Materials Scenarios for 2050 (Annex 6.2 and 6.3, respectively). Participants were divided into two groups (¡VAMOS! and UNEXMIN) and were engaged in exploring key factors stemming from each of the three INTRAW scenarios (Schimpf et al, 2017) with regards to each project.

Table 4 - ¡VAMOS! Scenario exploration overview (Bled workshop, 2018)

INTRAW Scenario	Opportunity	Challenge
National Walls	National production will have to increase, opening additional opportunities for ¡VAMOS!	IP exchange and further development of the technology could be problematic.
Unlimited Trade	- Cross-fertilization of the technology developed under ¡VAMOS! with other technology domains (e.g. space, civil engineering, robotics, environment, civil construction, demolition, and conventional dredging) - Mining of small rich deposits	Potential limited application for ¡VAMOS! mining method due to cost and productivity limitations
Sustainability Alliance	¡VAMOS! offers an environmentally superior solution to conventional or seabed mining increasing market demand.	Still existing risks and impacts need to be minimized further

3.2.2 Key research clusters

The second session of the workshop focused on the main components and functionalities of three pre-identified technological clusters:

·   Geological data collection and exploration;
·   Navigation and Spatial Awareness;
·   Automated extraction solutions

Participants were divided into three groups according to their background and engaged in a technological gap analysis discussion of each component and functionality with the time horizon of 2030. This process was divided into three main elements: a future vision (where do we want to go?), the current status (where are we now?), and the short to long-term developments.

Considering both the UNEXMIN and ¡VAMOS! projects concepts, the participants identified possible future research/technology pathways that should be pursued. The pathways to the identified research/technology opportunities were defined together with their benefits and how to achieve them.

3.3 Research Roadmap

During the past decade, the mining industry put automation and remote control at centre-stage and this is likely to continue into the future. Currently, the so-called digital transformation encompasses several of these aspects together with ICT solutions e.g.(wireless) communication and sensor systems. The autonomous mining working group from the GMSG (Global Mining Standards Group) published an industry response to expected growth in application of automation on mine sites (Figure 3). By 2030 it is expected that around 40% of operations will be fully autonomous. According to the World Economic Forum (2017) it can be assumed that the adoption rate of autonomous machines in mining will rise from 0.1% (2017) to 25% in 2025. Regardless of precise numbers, it is well agreed that automation of operations is a process that is still far from being fully applied and deployed across the industry with a clear trend for growth over the next decade and beyond. This in turn can boost the performance of the operations in terms of productivity and unit costs against a variable mine geology and ever-changing topographical conditions.
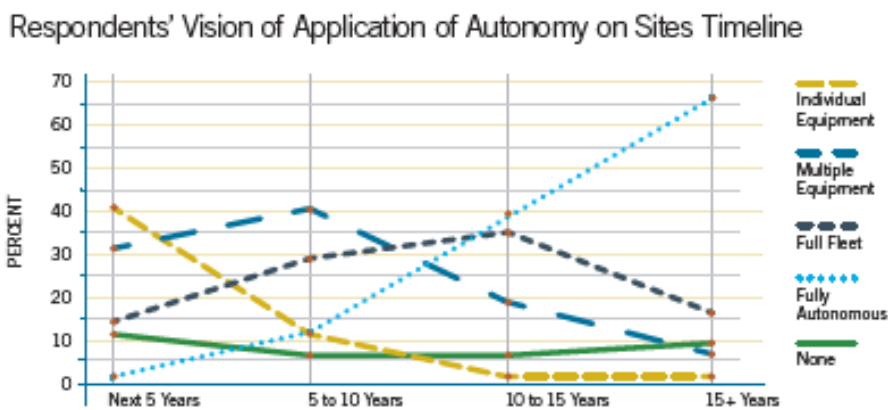
Figure 3 - Expected application of autonomy on mine sites (GMSG, 2017)

The ¡VAMOS! project has many technological components that are highly affected and/or dependent on the above-mentioned developments and therefore the proposed roadmap seeks to further analyse specific components evolution. The following sub-sections explore a set of technological systems covered in ¡VAMOS! – here defined as: Navigation & Spatial Awareness, Automated Extraction Solutions and Environmental Considerations. Additionally, the last sub-section investigates some emerging technologies that are not currently included in the ¡VAMOS! project, but when considering longer time frames could provide enhancements to ¡VAMOS! functionalities and performance. Those

illustrate the importance of monitoring technological alternatives to increase the portfolio of options and chances for a successful implementation.

3.3.1   Navigation & Spatial Awareness Systems

Bled Workshop

Four primary areas of geological data collection were identified in the process: 1 - (better) geological modelling; 2 - integrated geophysical methods; 3 - sampling; 4 - upscaling spectroscopy (resolution and processing). All the identified areas of research are interconnected and have the same priority in research/technology improvement and application, as they all aim for better and more precise geological data collection. The conjugation of these opportunities would be translated into improvements in the exploration and exploitation phases of mining, where UNEXMIN and ¡¡VAMOS!! are envisaged to be used.

Data

Naturally, the ability to increase data granularity relies on successful application of a variety of sensors and related interpretation. Their integration into the operating procedures is enabling miners to increase their operational effectiveness. For space and time information it enables a real time treatment of operations and optimal decision-making, better responding to geological (geometallurgical) properties and also fluctuations in market needs. A key capability to ¡VAMOS! is the ability to fuse data from a variety of sources, that is, different tools that generate complementary information that can be integrated, interpreted and automated altogether. ¡VAMOS! leverages this condition for its Navigation & Spatial Awareness system with sophisticated algorithms.

Under the scope of **Navigation & Spatial Awareness systems**, two dimensions were considered: hardware and software.

Hardware

- Laser 3D/LiDAR optical solutions are currently being employed in different industries including mining to generate high resolution laser scans. Structured light systems are already available for underwater applications and are still to be integrated with LiDAR in the same system with capacity for in-depth measures. For 2030 resolution and distance levels are to be improved to 3x current levels. Incremental improvements on coverage range and blind-spot avoidance are expected. Real time capabilities with data analysis can further improve the utilisation of such technology in the context of mining/¡VAMOS! system.

- GNSS use is currently restricted in some environments including underwater. In the short-term improved accuracy and coverage are expected as well as more flexibility and extended underwater applications. More research needs to be dedicated to covering smaller areas in an ocean environment. By 2030 it is expected that costs will be reduced and adaptations will appear such as mobile underwater navigation structures for global positioning.

- Acoustic sensors. Multi Reflection sonars are already available in relatively good resolution and ranges. In the short term, it can be expected a size and noise reduction of devices. For 2030, biological friendly acoustic signal, with negligible noise, should be aimed at.

- Overall Communications. A variety of options is currently available to be applied individually or combined in an operational setting, such as acoustic, LI-FI, Wi-Fi and cables. In the short term the most interesting evolution could be with regards to the size of the devices (reduction) and improved operating bandwidths, immune to conductivity changes. By 2030 effective through-the-rock communications should be possible, though such functionality would be of greater value to underground, flooded environments. Beyond this time-horizon, underwater inter-robot communication should have been developed and C2-to-robot capability.

- Locomotion can be improved in the short term with hybrid, dual means capacity (legs + wheels). Depending on research efforts, it could be feasible by 2030 to evolve towards multiple means of locomotion, such as biomimetic, metamorphic etc. This in turn can improve the flexibility of ¡VAMOS! to operate in a wider variety of terrains more effectively with less risks. Applications, functions and the working environment (underwater, floor-grounded) define the motion pattern alternatives, propulsions and any additional requirements.

- IMUs are currently challenged by drift-related restrictions – VR/AR north seeking. However, eradicating this restriction is believed to pertain to longer time-horizons of development, beyond 2030 and research should start now to guarantee success.

- LIBS (Hardware component) has already high-resolution spectrometers, with processing and AI prototypes. In the upcoming years research will need to investigate the development of miniaturized fibre optic lasers, automated calibration and database construction. Moreover, self-learning AI algorithms should be further developed and implemented for classification, identification and quantification. Targets for 2030 may include systems for molecular structure analysis and 3D materials tomography.

Software

- SLAM/Sensor fusion. Given the unconventional properties of operating underwater with visibility issues (turbidity, obstacles etc.) an important aspect is the capability to fuse data from different sources. However, currently this means a CPU intensive task, given the huge amount of data generated. Also, ¡VAMOS! already tested signed distance functions for effectiveness checking and VR integration. In the short-term uncertainties are still present with regards to underwater applications considering its niche nature. By 2030 more integration should be achieved, together with the hardware for capturing data, semantic SLAM and topological mapping. Beyond this time horizon a sub-mm accuracy can increase the granularity of the data sets generated form these technologies.

- Artificial Intelligence. Although broad in terms of application, in this case AI should be developed to focus on the fault tolerances. On the shorter to longer-term, opportunistic science emergence is therefore expected with potential applications stemming from self-awareness capabilities

- Real time mine models. Modelling the mine operation in real time requires the congregation of a variety of data sources and appropriate models and software for interpretation. More broadly, recent advances are being made for changing the mining process from a discontinuous to a continuous one, where comparisons between model-based predictions and actual performance are done in real time instead of at the end of production processes. The ability to incorporate this data in resource/reserve models in real time while also optimising the mine planning and control decisions represents a large potential for improvement in efficiency of any type of mining operation (Benndorf & Buxton, 2017). Important exchanges were made between ¡VAMOS! and the Real Time Mining Project[3]. On the concrete case of ¡VAMOS!, simple mesh models are readily available. Further research is then required on the integration of sensor-based material characterization, rapid resource model updating, and fast production control optimisation applied to the ¡VAMOS! context. That is, modelling of chemical and physical parameters gathered and delivered to C2 stations in real time.

In terms of LIBS technology, proof-of-concept is already deployed for restricted geological databases, signal pre-processing, AI for identification, classification and quantification of elements. Further development in the upcoming years are expected for more advanced LIBS pre-processing (artifacts removal), self-learning AI, dynamic LIBS analysis and LIBS 2D/3D imaging. The target for 2030 and beyond is to reach for dynamic LIBS libraries and AI for advanced chemical structure analysis capacity.

3.3.2 Automated Extraction Solutions

It still needs to be defined how the ¡VAMOS! project could benefit from the technological advances made in cutting technology. The use of alternative methods like in-situ leaching or rock weakening methods is also expected to increase, which could aid and widen the range of rock types that could

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[3] Real-time Optimisation of the Extraction and the Logistics process in Highly Complex Geological and Selective Mining Setting (H2020 GA: 641989) https://www.realtime-mining.eu/

be accessible with the ¡VAMOS! technology. In this sense, research should be considered on the environmental barriers to the extension of these alternative methods.

To date, fragmentation in hard rock mines is almost entirely done via explosives and blasting techniques. Cutting power of existing mechanical excavation technologies does not allow for hard rock (ca. 250 MPa) operations. Some (disc) cutting techniques for tunnelling and development purposes have shown capacity to deal with this level of rock strength, however they have not been employed for ore production due to high costs of wear and tear. Most of the research on this topic is already taking place in the EU, however, most of the development to be expected in this field will be industry driven. Nevertheless, it is important to mention the potential partnerships between industry and academia and initiatives such as the EUREG[4] and RCC[5] are worthy of mention in the European context. Research on materials and cutting technology is therefore still needed for reaching commercial levels of application in hard rock environments. The currently acknowledged trend favours equipment manufacturers to consider disc undercutting and point attack tool cutting. However, roller disk cutting typically requires the equipment to be gripped into more than one free face (e.g. tunnel walls), something hard to replicate in a submerged environment. One alternative could be to put the cutter underneath the weight of the machine. Therefore, the point attack tool cutting technology is the most efficient one requiring minimum forces by achieving a maximum result.

Assistance for the submerged cutting process can be enabled by high pressure water jets in removing the cut material out of the cutting groove in a fast way and in also developing cracks made by the cutter picks further into depth of rock material.
Another important aspect for the specific operating conditions is what the material properties can deliver in terms of performance. For instance, the development of diamond composite material for cutting tools can provide a very sharp interaction geometry with the rock, with lower rates of wear over time.
Additionally, the development of a rock cutting test rig where rock cutting in submerged conditions could be scaled 1:1, tested under different water pressure conditions, simulating the application in different water depths (on-shore and off-shore applications).

As ¡VAMOS! applies a less traditional fashion of material movement system – pumping/dredging – improving the knowledge on rheological flow properties of the materials being excavated can be an enabling factor on improved performance of slurry circuitry in relation to particle size and density. This can also underline the development pumping and riser systems with greater concentration capabilities – this may reduce slurry pumping and dewatering energy requirements. Furthermore, blockage potential can be reduced by developing solutions for optimising density measurements and control valve systems for slurry concentration.

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[4] European Rock Extraction Research Group (https://eureg.blog/)
[5] RockCutting Center (Advanced Mining Technologies, RWTH Aachen: http://www.imr.rwth-aachen.de/index.php/rockcutting-center-rcc-378.html)

With the aim of improving the transportation of dredging material from the flooded pit, an adapted version of the MV with an on-board crusher can facilitate the operation in environments where large pieces of rock can be displaced – or where there is a strong variation in rock properties, such as with hard xenoliths or other intrusions. This can in turn increase the range of ¡VAMOS! application. Also, material buffering solutions may enable a steady and consistent riser feed to maximise average material volumetric flowrates.

The FAME[6] project seeks to develop flexible and mobile combinations of technology to exploit European deposits – particularly Greisen, Skarn and Pegmatite formations. It emphasises the need for environmentally friendly processing technology solutions that can be complementary to the extraction solutions offered by ¡VAMOS!.

3.3.3 Environmental Considerations

The ¡VAMOS! project seeks to offer a low-impact mining alternative system by design, but such new approach can also impose new environmental considerations. Therefore, extensive evaluation has to be undertaken so as to map the state of environment in the ¡VAMOS! operational context. Deliverable 1.3 assessed relevant parameters which offer a baseline for environmental modelling of possible operational impacts, such as:

- Vibrations;
- Underground water contamination;
- Spreading of particles in suspension to adjacent aquifers;
- Spreading of metals and other pollutants in the form of solution in to the adjacent aquifers; and
- Minor risks of oil spills.

The next 10-years research developments should actively engage in developing active measurement of inputs, throughputs and impacts, namely:

- Sensor networks and technologies to provide smart monitoring alerts on emissions, leakages, vibrations etc.;
- Integrated dashboards displaying real time monitors on energy usage, emissions, contaminants and general environmental impact assessments;
- Hybrid and renewable energy technologies, such as solar farms, geothermal etc.

In that sense, research is to focus on the successful connectivity integration and functionality of the Voltammetric In Situ Profiling System (VIPS)/multi parameter sensors to provide CTD (Conductivity, Temperature, Depth) and trace metal concentrations in real time. Potential alternatives can be considered such as on-line CTD with optical sensors to be combined with VIPS operating from the vessel. The aim is to increase the applicability at increased depths.

With regards to sediment loads, processing and calibration for TSS (Total Suspended Solids) can be very difficult in scenarios of significant thermocline and extremely fine sediments. ADCPs (Acoustic Doppler Current Profilers) can be integrated on the MV to generate real-time TSS to the MV model.

3.3.4 Emerging technologies

Whenever looking into longer time-frames it is important to keep watch of possible emerging technologies that might not be readily available at present and not covered in the present system conceptualization but can show initial promising results and theoretical application. Those may become important options to be integrated in the system under research. This means that 'technological watchlists' can be formed and monitored for increasing the optionality and thereby the chances of a successful achievement of targets. This in turn improves the 'moving-up-the-ladder' chances of technology readiness levels and feasibility of the system. Some emerging technologies are currently being reported in the so called 'digital transformation' with expected integration over the next 10-15 years in conventional mining operations (Figure 4).
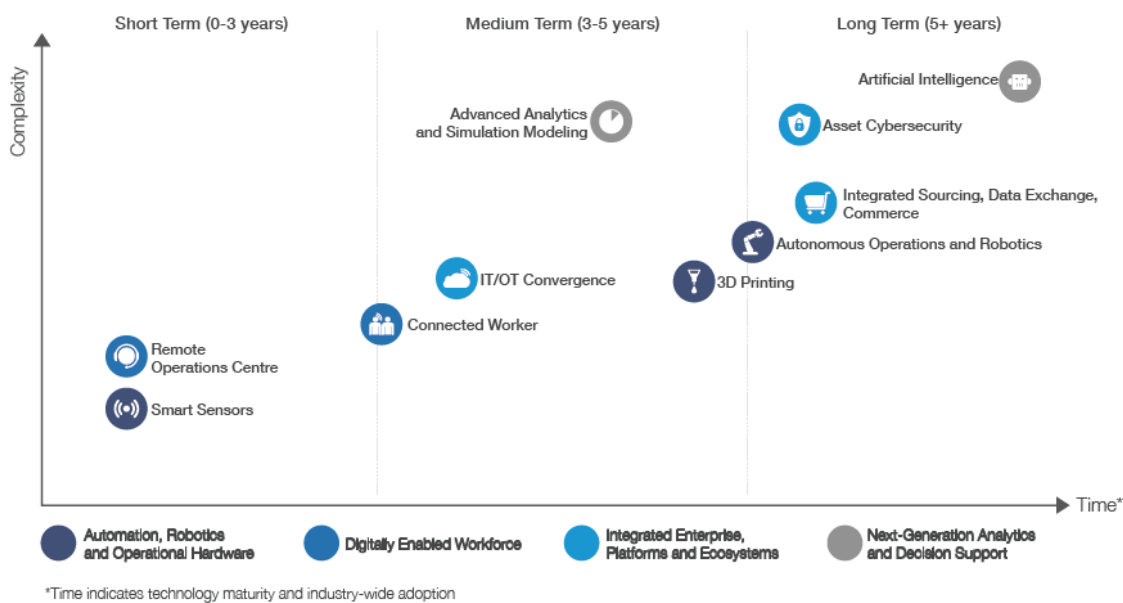

Figure 4 - Time and complexity for digital initiatives to reach scale (WEF, 2017)

In that sense, this section summarises a few examples of emerging technologies external to ¡VAMOS! that could be potentially employed in an array of application and functionalities of the system and therefore are to be further monitored and evaluated (Figure 5).

For instance, graphene supercapacitors and fuel cells could improve the energy storage capacity and for the latter power generation is an alternative to conventional diesel generators. Also, improved batteries can be used in the AUV for better (longer) utilisation. Smartdust sensors and swarm robotics could help for improving the understanding of the region under inspection. Additionally, it may enable multi-tasking and interoperability of the system (fleet of different vehicles working together). Energy harvesting alternatives could reduce power consumption even further and improve energy management and optimisation. Current trending technologies such as 3D printing could assist the supply of spare and wear parts for ¡VAMOS!, especially in very remote operations, whilst Augmented Reality glasses could assist in the maintenance of the mining system, especially on harsh missions in remote areas.
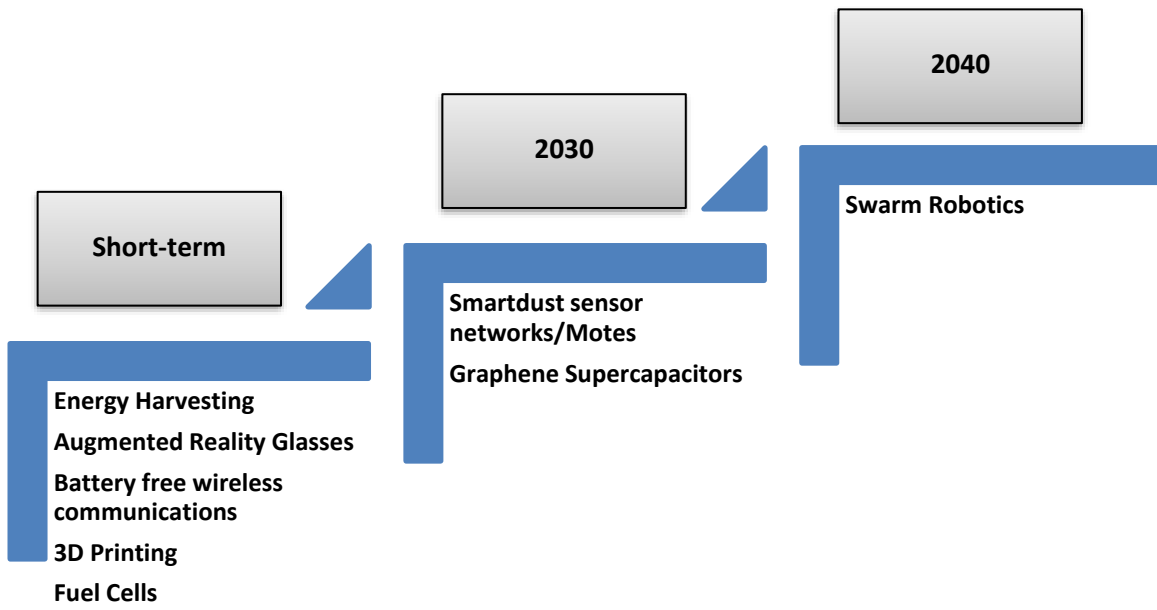
Short-term

2030

2040

Swarm Robotics

Smartdust sensor networks/Motes

Graphene Supercapacitors

Energy Harvesting
Augmented Reality Glasses
Battery free wireless communications
3D Printing
Fuel Cells

Figure 5 - Emerging (external) technologies and respective time horizons for reaching scale

4   Recommendations & Conclusion

Much of future research for ¡VAMOS! is related to advancing incremental development of technological components for guaranteeing efficient functionalities and to reach performance targets. This, however, does not preclude the identification and uptake of technological alternatives not covered during the project development. These can be technologies that are currently incipient and technologies that will surface in the upcoming years. Digital solutions for instance can help ¡VAMOS! in generating many functionalities, such as:

- Improved analytics and visualisation tools;
- Real time modelling and simulations;
- Performance optimisation;
- Energy consumption optimisation;
- Predictive maintenance;
- Environmental impact monitoring;

Furthermore, ¡VAMOS! operational design and capacities will determine the types of deposit where it can be used. The conjugation of operational alternatives and customisation, and respective suitability to a variety of deposit is an important matter of research for successful implementation of ¡VAMOS!. By 2030 this can be achieved by researching the parameters/frameworks for such assessment, re-assessing EU reserves with ¡VAMOS! technology as the main lever.

Table 5 - Future research recommendations summary

Recommended Future Research	Description
Design a range of renewable energy power solutions and schemes for off-the grid deployment of ¡VAMOS!	Renewable energy power solutions will be to a great extent site-specific. One robust alternative is the FPV (Floating Photovoltaic)[7] that could be adapted to be concurrently deployed on the flooded pit.
Develop auxiliary drilling and coring capabilities.	Integrate drilling and develop a real time 'reading' capacity, conducting sample analysis during the drilling process. Extend on-board environmental sampling capability of AUV, with real-time autonomous logging (transparency of operations and rapid identification of any anomalies)
Develop in situ mineral sampling apparatus for the MV	
Create a system where multiple machines operate together	Improved machine-to-machine communication, interoperability, positioning and signal processing for robots – swarm robotics.
Design innovative mineral processing facilities onshore tailored to the deposits likely to be targeted by ¡¡VAMOS!!	Novel and small-scale processing technologies and management tools that minimise waste, while reducing inputs such as energy and water. Cross-fertilisation with other initiatives such as FAME Project.
Further enhance system automation for deployment in regions where human supervision is difficult to accommodate	Further develop and finalise an "auto-tuning" or "plug and play" facility for the PNA systems, eliminating site reliance on technical experts.

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[7] https://en.m.wikipedia.org/wiki/Floating_solar

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6 Annex

6.1 METS Roadmap – Filtered for ¡VAMOS!

Key areas	Enabling Science & Technology	Research Priorities
Data driven mining decisions	Sensor and the internet of things	- Low cost, combined and integrated sensors to collect multiple information types and reduce the overall number of sensors needed. - Improved sensor durability and sensitivity to function in high temperature, harsh or remote environments with reduced maintenance, while producing reliably calibrated data. - Self-powering sensors through battery developments such as miniaturisation, increased capacity and density, and renewable energy sources. - Wireless connectivity of in-situ remote sensors through on-board electronics. - Advanced materials that embed sensors directly into the materials of parts and equipment.
	Analytics and optimisation	- Improved mathematical models and algorithms to identify association and correlation across constantly growing and highly diverse datasets. - Algorithms and / or sampling methods to improve analytics performance and minimise / avoid false positives. - Improved systems for data storage and management that can handle the rapidly increasing amount of data captured. - Improvements in quality of data captured and development of decision-making algorithms to improve autonomy. - Develop common mine models / representations and define interface / interoperability standards.
	Visualisation	- Tools and user interfaces that improve the interrogation of data and facilitate remote collaboration and support to resolve issues and identify new opportunities. - Advanced visualisation and virtual / augmented reality to provide real-time operational context, situational awareness and remote analysis.
Social and environmental sustainability	Monitoring and sensing	- Ubiquitous real-time sensing for environmental, health and safety monitoring to improve TBL outcomes, including the development of sensors that are biodegradable and / or bio-compatible. - Advanced materials with pervasive sensing that can be applied to industry parts, equipment and infrastructure, and can monitor a range of environmental indicators. - Improved sensing and characterisation technologies that embed social and environmental considerations in extraction and processing decision making. - Technologies for waste and discharge water monitoring and management.
	Site and equipment design	- Improved tailings dam design factoring social and environmental risks, rising operational cost pressures and lower grades (which could increase waste). - Advanced extraction technologies that improve the footprint of mining activities and increase recovery rates, such as in-situ recovery technologies. - Technologies and processes for remediation of contaminated sites, including bioremediation processes, 'green chemistry', phytoremediation, ultrasound, etc - Low emissions energy technology feasibility studies / integration. - Advanced material developments focusing on light weighting and energy harvesting to reduce fuel and energy inputs.

		- High performance, modular, low energy and 'wear‑less' equipment and infrastructure that reduces maintenance and increases availability. - Novel and small scale processing technologies and management tools that minimise waste, increase recycling and re-use, while reducing inputs such as energy and water.
Exploration under cover	Next generation drilling technologies	- Development of faster, cheaper and more portable drilling technologies, including directional drilling and measure-while-drilling techniques which help to continuously target new provinces and mineral systems. - Advancing sensing and data collection technologies and processes, including geophysical, geological, geochemical and geometallurgical sensing, exploration at depth, sub-sea exploration, and down‑hole technologies.
Advanced extraction	Advanced drilling and cutting technologies	- Precision rock cutting and smart blasting knowledge and technologies combined with improved resource characterisation and block model resolution and interaction. - Advanced and intelligent materials that increase the strength and performance of drilling equipment, reduce weight and minimise maintenance requirements. - Rock mechanics better linked to equipment design (including customisation to local / current conditions).
	Sensors and ore sorting	- Real-time (or near real-time) sensors and methods for exploiting variations in extracted material grade and physical rock properties for early waste rejection. - Multi-resolution and attribute representations to facilitate continuous refinement of orebody block models and mine plans.
Mining automation and robotics	Machine vision, materials and robotics	- Machine vision and sensor developments / miniaturisation to allow robots to develop perception and situational awareness to safely interact with humans and their environments, particularly in underground environments.
	Control systems and algorithms	- Improved computational ability with the integration of machine learning algorithms, sensors, machine vision, big data, cloud technologies and the internet of things to allow robots to autonomously move, repair, self-calibrate and change behaviour based on complex and highly variable mining environment (surface and underground), geological conditions and changing goals. - Improved machine-to-machine communication, interoperability, positioning and signal processing for heterogeneous autonomous robots and fleets. - Intelligent / smart sensors able to process system and resource data on board, allowing real-time highly accurate decisions and corrective action.
	Virtual and Augmented Reality	- Improved solutions for haptics (integration of touch) and audio integration, such as dismissing standard keyboard and mouse for voice and gesture commands.

6.2 Workshop photos (Bled/Slovenia, January 2018)
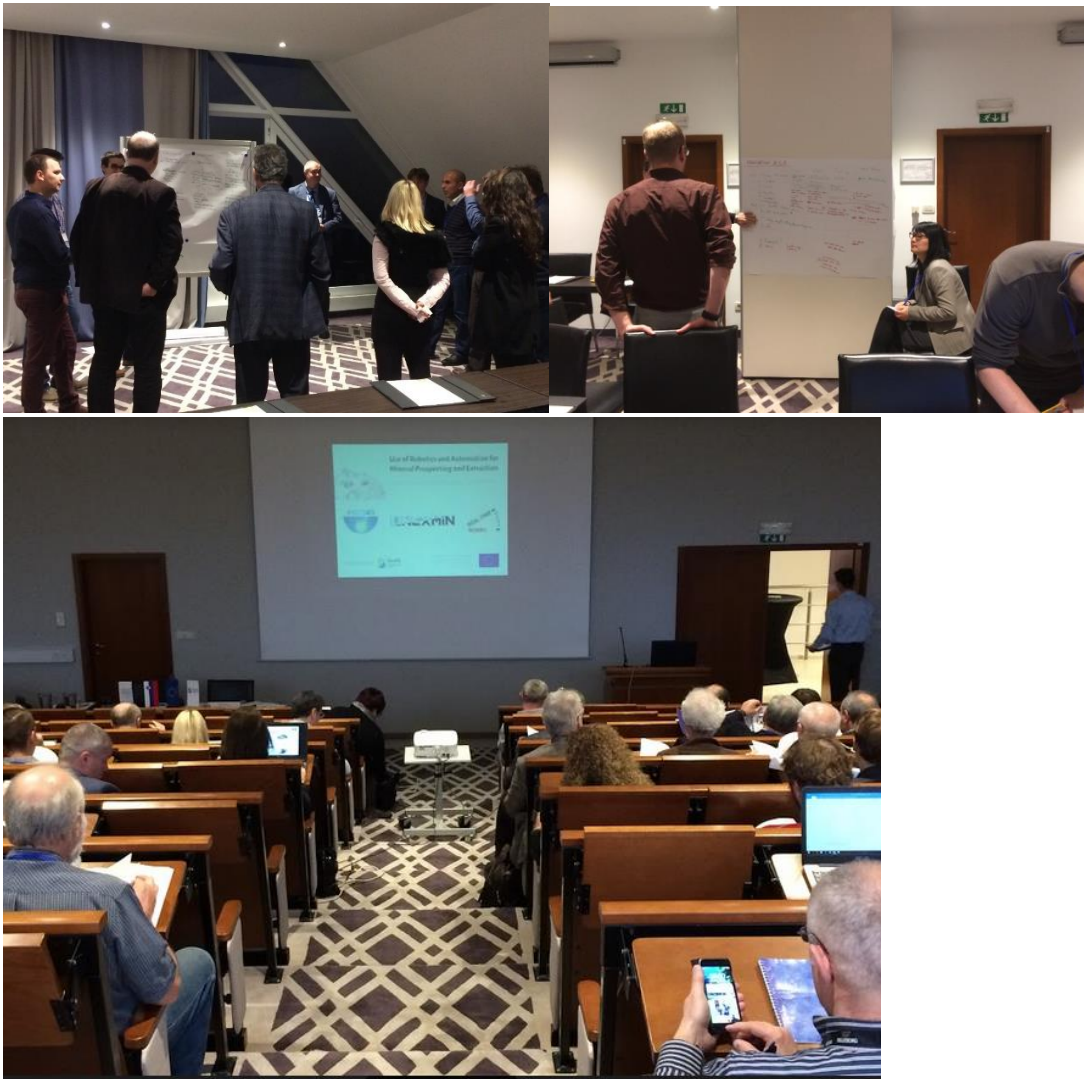
6.3 INTRAW Scenarios

The INTRAW Project (www.intraw.eu) took part between 2015 and 2018 aiming at developing new cooperation opportunities in raw materials between the EU and other reference countries i.e. Australia, Canada, Japan, South Africa and the United States, addressing specific fields:

- Research & Innovation;
- Education & Outreach;
- Industry & Trade; and
- Recycling & Substitution.

For these different fields, action plans were developed as recommendations for implementation by the European Commission and the 'International Observatory for Raw Materials', a non-profit entity launched during the 'Raw Materials Week 2017' in Brussels, Belgium.

As part of the INTRAW Project, a scenario-building exercise was undertaken producing three different scenarios for the global long-term future (2050) of the raw materials sector. The scenarios outlook is briefly described below:

- ***Sustainability Alliance***: sustainable approaches dictate the norms in the sector – circular economy, reforms focusing in increasing sustainability become reality;
- ***Unlimited Trade***: the increase in global consumption of raw materials is confirmed and addressed with increasing cooperation and dialogue for producing and trading raw materials. Access to capital lead to industry integration, technology development and productivity improvement;
- ***National Walls***: protectionist measures on a national level become more frequent, impacting the raw materials sector with diminishing progress in mining practices, lower private investments and cooperation for raw materials open supply.