HYDROMETALLURGY AND PHYTOMANAGEMENT APPROACHES FOR STEEL SLAG MANAGEMENT (HYPASS)

Approches hydrométallurgique et de phytomanagement pour la gestion des laitiers sidérurgiques.

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PROJECT SUMMARY

Metallurgical slags are major by-products generated by the steel and iron industry. Although they represent potentially important economic resources, as they still often contain significant amounts of "Strategic Metals" (SMs), slags are also considered as industrial waste that may pose public health and environmental concerns.

The goal of the HYPASS project is to propose technological innovations for both a cost-effective recovery of strategic metals and an eco-friendly management of metallurgical dumps. In this respect, HYPASS will consider the process as a whole, from by-products production to slag valorization and finally rehabilitation of contaminated landfills, with the ultimate goal of developing economically feasible and environmentally acceptable "zero-waste" processes.

The core of the project is the development, assessment and evaluation of two complementary valorization routes using: 1/ hydrometallurgical-based approaches (under alkaline conditions) to recover high SMs amounts, and 2/ phytostabilization approaches [and the beneficial role of "Arbuscular Mycorrhizal Fungi" (AMF)] to promote ecological restauration of slagheaps. Additionally, HYPASS proposes to list and to map existing dumpsites, to perform "Life Cycle Assessments" (LCA) for various processing methods and to develop a "Decision-Support Tool" (DST) to help identifying the best treatment options, both from an economical and from an environmental point of view. HYPASS technologies will be implemented at a large slagheap situated at Châteauneuf (Loire, France), which is registered in the SAFIR[1] network.

The project involves one industrial ["Industeel France ArcelorMittal" (IFAM)[2]] and two academic partners (ARMINES/SPIN[3] and BRGM[4]) and is organized into eight complementary "Working Packages" (WPs). Strong and numerous impacts are expected from the project. Technologically, the development of new approaches to recover SMs is in itself very innovative and promising, as this could allow to process large amounts of slags that are currently weakly re-used. This is very important in relation to the ambitious targets set by the "European Union" (EU) for recycling metallurgical by-products and decreasing landfilling practices.

[1] SAFIR ("Sites Ateliers Français pour l'Innovation et la Recherche pour la gestion des sols") [http://www.safir-network.com/];
[2] Industeel France ArcelorMittal (http://industeel.arcelormittal.com/industeel/where-we-are/);
[3] ARMINES ("Association pour la Recherche et le Développement des méthodes et processus industriels") [http://www.armines.net] / SPIN ("Sciences des Processus Industriels et Naturels") [http://www.mines-stetienne.fr/recherche/5-centres-de-formation-et-de-recherche/sciences-des-processus-industriels-et-naturels/];
[4] BRGM ("Bureau de Recherches Géologiques et Minières") [http://www.brgm.fr].

Environmentally, using phytostabilization as a capping strategy for slagheap rehabilitation will not only improve visual aspect of degraded lands, but this will also trigger the restauration of a local biodiversity and the construction of a technosoil. Restoring biodiversity and stimulating soil formation could give a new value to derelict slagheap, as this is directly linked to ecosystem services that a land may deliver. Additionally, HYPASS will have significant economical and societal impacts, as it could reduce the dependence of European countries to SMs importation. Finally, HYPASS could help to create new jobs in the emerging area of high added-value waste treatment and valorization.

SUMMARY TABLE OF PERSONS INVOLVED IN THE PROJECT

*Table 1 - Summary table of persons involved in the project (**Total P.M. = 117.95**).*

Partner organisation name	Name	First name	Current position	(P.M)(*)	Role and expertise used in the project
ARMINES/ SPIN	PEREIRA	Fernando	Research engineer	18	Scientific coordinator (Management, mineral processing, hydrometallurgy, waste valorization)
	DUJARDIN	Florence	Engineer	6	Communication/dissemination
	FAURE	Olivier	Associate professor	12	Phytomanagement, waste valorization
	GALLICE	Frédéric	Technical staff	7	Sampling, analytical characterization
	PARAN	Frédéric	Research engineer	7	DST, "Geographical Information System" (GIS) and spatial analyses methods, vulnerabilities
	SCATTOLIN	Mathieu	Research engineer	12	Phytomanagement, waste valorization
	XXX	Xxx	Research engineer	12	Mineral processing, hydrometallurgy, waste valorization
BRGM	MENAD	Nour-Eddine	Scientific expert	9.3	Scientific and technical leader (Physical mineral processing, hydrometallurgy, waste valorization)
	LEMIÈRE	Bruno	Research engineer	4	Sampling, analytical characterization
	LIMASSET	Elsa	Engineer	3	LCA and DST
	MULLER	Stéphanie	Engineer	3	LCA and DST
	SERON	Alain	Research engineer	2	Analytical characterization
	VILLENEUVE	Jacques	Research engineer	2	LCA and DST
	XXX YYY	Xxx Yyy	Trainees	12	Technical research
IFAM	ASTOLFI	Frédéric	Continuous improvement manager	6.5	Technical leader (Slags production/processing technologies forecasts)
	PERRET	Sophie	Environmental manager	2.15	Forecasts of processing technologies, LCA

(*) P.M: Person.Month, amount throughout the project's total duration (42 months).

I. PROPOSAL'S CONTEXT, POSITIONNING AND OBJECTIVES

I.1. Objectives and scientific hypotheses

Steel slags are major by-products produced by the steel and iron industry. While they are considered as industrial waste, slags represent an important potential economic resource because they often contain significant amounts of valuable SMs. These metals are essentially used as alloying elements in the steel industry as well as in catalysts and pigments in the chemical industry and as raw material in green technologies (photovoltaic cells, wind turbines and electric motors). During the last decade the global steel production driven by China has doubled and the development of renewable energies (wind and solar) and electrics cars has dramatically increased. This has sharply affected global SMs demand, and there is no doubt today that production and consumption of SMs will must face a major economic pressure in upcoming years. In this context, the importance of hydrometallurgy in production and recycling of SMs cannot be stressed enough. However, improving or even optimizing these processes is clearly required.

In addition, although steel slags are classified as non-hazardous thermal waste according to the decree 2002-540(1) and US EPA[5], it is well known that most metals they contain are quite toxic to living organisms and may pose serious environmental issues. In France, the CTPL[6] estimated that the total available stock of slags (including all slag families) was about 17 480 600 tons at the end of 2015. Thus, reusing steel slags appears the option of choice to ensure their sustainable management as well as to decrease their environmental concerns. Consequently, **the goal of the HYPASS project is to promote more consistent approaches for steel slag management**. Particularly, HYPASS will focus on technological innovations for both an eco-compatible and cost-effective recovery of SMs. At its core is the development of a novel recovery process integrated within a policy of safeguarding the environment. HYPASS will be tested on a selected case study: **the IFAM site, situated at Châteauneuf (Loire), with an estimated stock of 500 000 tons of EAF ("Electric Arc Furnace") slags, whose principal SMs are: Cr_2O_3 (± 2,4 %), V (± 1500 ppm), Mo (± 500 ppm) and Zn (± 500 ppm)**. Notice: this slagheap belongs to the SAFIR network and, as such, is easily available for research programs.

The project will be essentially developed at two levels:

- technologically: research will be performed at a "laboratory scale" to develop a process based on physical (pre-concentration of the mineral matrix) and hydrometallurgical principles (under alkaline conditions) for extracting a significant fraction of SMs from slags. In the case the mineral matrix resulting from the hydrometallurgical process would not meet the environmental acceptability criteria for a safe re-use in the civil engineering field(2, 3, 4) [defined by SETRA(5)], HYPASS will promote the use of **a phytomanagement approach to reduce the environmental risk of secondary waste**;
- environmentally: through the application of multidisciplinary integrated methodologies, direct field techniques, and acquisition of preliminary informations, to reduce the geological uncertainty and evaluate the possibility of SMs (Cr, V, Mo, *etc.*) recovery at a large scale. The data analysis will allow understanding the geographical scenario (far and near-field analysis) of slag deposits at a national scale, collect the information of mineralogical association in terms of SMs recovery and incorporate the mineral related research to understand how this information can be used in exploitation and environmental impact assessment. To help identifying potential treatment methods and economically viable solutions for re-use, HYPASS will develop **a tool enabling decision-makers and operators to simulate steel slag management** and test the consequences of different treatment options in terms of financial costs (direct/indirect) and environmental impact.

The overall HYPASS objectives are related to SMs recovery and slagheap reclamation and rehabilitation. They can be splited into three categories, as listed below:

1. Technical objectives:

- to evaluate the twofold sustainable and cost-effective technologies (hydrometallurgy/phytostabilization) that HYPASS will promote for an eco-friendly recovery of valuable elements (SMs);
- to conduct LCA(6) for processing methods and assessing long-range sustainability;
- to develop a DST to help identifying new waste treatment methods and economically viable solutions.

2. Social and societal objectives:

- to increase public awareness and to inform, advice and/or invite stakeholders, media, policy makers and

[5] US ("United States") EPA ("Environmental Protection Agency") [https://www.epa.gov];
[6] CTPL ("Centre Technique de Promotion des Laitiers sidérurgiques") [http://www.ctpl.info].

experts through the channels of symposia, conferences, workshops;
- to assess the social impact of existing steel slag dumpsites on the local communities and their attitudes and interests related to the proposed valorization of these waste;
- to set up a "Project Advisory Board" (PAB) consisting of the HYPASS partners, the steelmaking industry and experts of research institutes;
- to reduce the dependence of import of SMs to European countries and increase industrial competitiveness;
- to create new jobs due to the possibility to economically operate the dumpsites.

3. Safety, health, environmental and quality objectives:

- to assess the environmental context in which the exploitation of old tailings will take place in terms of environmental impact, industrial viability and as a possible socio-economic resource;
- to monitor the environmental impact of the newly steel slag processing technology;
- to optimize the material cycle (minor use of natural resources for road construction and their substitution with recycled EAF slag, minor quantity of EAF slag dumped and costs of slag handling);
- to reduce the environmental impacts associated to steelmaking activities and waste disposal;
- to increase the efficient re-use of steel slags and hence reduce CO_2 footprint;
- to identify and reduce the potential health hazards and sanitary risks for directly involved personal and urban environments.

I.2. Originality and relevance in relation to the state of the art

The metals, oxides and/or hydroxides recovery from slags has long been, and still is, the subject of numerous studies. Today, a number of technical options are available to extract SMs from contaminated mineral matrices (such as slags). The techniques implemented are generally using the principles of hydrometallurgy and involve mechanical, magnetic, chemical(8) and/or physicochemical (flotation) separation processes in various combinations(9). In the ANR ECOT ORLA [7] (10, 11), ERA-MIN EXTRAVAN [8] (12) and HORIZON 2020 CHROMIC [9] (13) research programs, successful comminution techniques have been explored by Swerea MEFOS(14) [ERA-MIN EXTRAVAN(12)], VITO(15) [HORIZON 2020 CHROMIC(13)] and BRGM [ERA-MIN EXTRAVAN(12) and HORIZON 2020 CHROMIC(13)]. Mechanical processing technologies that can be used are: smart fragmentation with a rotating drum, smart magnetic, reverse magnetic and high gradient magnetic separation for magnet material(16), electrostatic separation for fine particles.

Up to now, the solutions reported in the literature for the dissolution of the metallic parts are almost exclusively by an acid route(17, 18, 19, 20). Incorporated into mineral matrices and sometimes committed in the form of ferrites type, SM-based non-ferrous oxides (Cr, V, Mo, *etc.*) have rarely been the subject of specific treatments. However, when keeping the mineral matrix intact is desired for its subsequent valorization, processing technologies using acid leaching are inapplicable and clearly to be avoided. During acid leaching, the release of lime presents a major inconvenience. Hence, this causes an overconsumption of reagents and an excess of salt production. By contrast, the alkaline environment (soda ash, ammonia, *etc.*) offers several advantages. Particularly, soda ash's weak corrosion power and selectivity has many benefits(21). Iron and calcium, present in slags, are poorly leached at the end of alkaline treatment. Moreover, adding lime in a soda ash solution precipitates the silicates and carbonates and thus returns the leaching solution to its initial state.

Precedents for the alkaline process(22) proposed exist but they differ from this proposal as they were applied on substantially different materials [steel dust or metal hydroxide sludge with REZEDA® and EZINEX® processes(23, 24)]. Notice: the utilization of alkaline solutions for SMs recovery from slags is in itself innovative. Even if the nature of the mineral by-products is foreseeable ["Calcium Silicate Hydrate" (CSH), brucite, Si-Al gels, *etc.*], neither their grain-size distribution nor the yield of metal recovery are easily predictable or completely understood. Thus, the hydrometallurgical challenge is to evaluate the alkaline process, for which the major scientific problem is to predict properties of the precipitated solids (crystallization).

The main objective of HYPASS is to propose new approaches for an eco-compatible and sustainable slag management, and not to simply recover SMs from primary slags, while generating secondary waste. Therefore, HYPASS includes the "downstream" environmental concern of the fate of slags and secondary waste products.

[7] ANR ("Agence Nationale de la Recherche") ECOT ("ECOtechnologies et développement durable") ORLA ("Optimisation du Recyclage des Laitiers d'Aciérie de conversion");
[8] ERA-MIN ("European Research Area - Network on the Industrial Handling of Raw Materials for European Industries") EXTRAVAN (innovative EXTRAction and management of VANadium from high vanadium iron concentrate and steel slags");
[9] CHROMIC ("effiCient mineral processing and Hydrometallurgical RecOvery of by-product Metals from low-grade metal contaIning seCondary raw materials").

If some slag types are not relevant matrices for hydrometallurgical processing or if the resulting secondary mineral matrix does not meet the environmental acceptability criteria for a safe use in the field of civil engineering(2, 3, 4), **HYPASS will implement a containment strategy for limiting wind and water erosion of metallurgical dumps and to prevent leaching and run-off of contaminants**. In a context of increased awareness of the importance of soils as a finite and non-renewable natural resource, capping of metallurgical dumps using a geo-membrane liner covered by a layer of clean soil is definitely not the best option, neither economically, nor environmentally. By contrast, pollution containment using **aided-phytostabilization** is a growing field of research and a relevant approach for the sustainable ecological management of large polluted sites(25, 26). As such, phytostabilization relies on concepts and approaches that are now quite common. However, its application for on-site management of metallurgical waste dumps has never been implemented to date. In fact, the establishment of a plant cover onto steel slagheaps must overcomes a number of issues. First, besides the potential toxicity of metal elements (*e.g.*, Cd, Cr, Mo, Ni, Pb, *etc.*), slags are almost devoid of organic matter and essential macronutrients (N, P, K). They also have very low water holding capacity and a high pH (> pH 9), that greatly reduce the phyto-availability of essential trace metals (*e.g.*, Fe, Cu, Zn). Second, steel slags can hardly fulfill the functions of a living soil (*i.e.*, nutrient cycling, organic matter decomposition, carbon sink, habitat for biodiversity, *etc.*), as they lack most, if not all, of the key engineer species (bacteria, fungi, protozoan, nematodes, annelids, arthropods, plants, *etc.*) involved in soil biological processes. Therefore, these overall very particular characteristics make metallurgical slags a very bad substrate for plant development. However, Bouchardon *et al.*(27) [2014] demonstrated [at an experimental plot field scale (50 m^2 plots)] that phytostabilization of slag dumps was still feasible, provided to use an appropriate organic fertilization and an adapted plant community. Although the methodology proposed was successful in obtaining a dense plant cover that reduced pollutant transfer via wind erosion by almost 95 %, some metal elements and, particularly, those forming oxyanions (mainly, Cr and Mo) were accumulated in above ground plant parts at relatively high levels. Therefore, decreasing Cr and Mo accumulation in plants used for phytostabilization of slag dumpsites remains an important research issue. In this respect, a key-factor for the success of phytostabilization of steel slags could rely on stimulating the development of an active and diverse soil microbial community. Among the huge diversity of soil organisms, the beneficial role of "Arbuscular Mycorrhizal Fungi" (AMF) as promoting factors for plant establishment, is increasingly acknowledge, both for agricultural practices and for phytostabilization purposes. AMF establish symbiotic associations with plants roots thereby improving mineral nutrition and water acquisition of their host. In addition to a better tolerance to soil nutrient deficiencies and drought stress, there are a growing number of evidences that AMF may decrease the accumulation of toxic metals in plants(28, 29) and particularly Cr(30), thus improving the efficiency of phytostabilization. Starting from these results, HYPASS will precise the best conditions for an efficient phytostabilization both of primary slags and of secondary mineral matrix resulting from the hydrometallurgical process.

I.3. Critical risks, relating to project implementation

The risks associated to a successful implementation of the HYPASS project can be summarized for each WP as follow:

WP0 - Project coordination and management - in the case of conflicts, members of the entities involved in the project will organize a meeting with the "Project Management Board" (PMB) to find solutions. Anyway, the risk that a single partner could be not able to perform its tasks is negligible, because all partners are large institutions that have participated in numerous national or international projects. There is enough redundancy in the partner’s capabilities that the defaulting partner’s responsibilities can be met by the Consortium.

WP1 - Baseline: strategies, trends, assessments and forecasts of slags production/processing technologies state - this task does not present any risk in itself, only those related to unsuccessful work that would not provide sufficient data regarding fixed goal. This risk is however limited due to the involvement of all partners in this task. They will work together in search of useful data to fully meet the needs of the task.

WP2 - Sampling, preparation, screening and characterization of suitable slags for further processing - no risk has been identified for this task, because the equipment for characterization required in the project are very complementary within partners. This task uses in particular tools to measure that exist in the university laboratories ARMINES/SPIN but that are also available in other laboratories at the project partners.

WP3 - Pre-concentration of the mineral matrix - the risks of this task are related to the potential difficulties to recover the totality of metals and concentrate SMs before leaching. These risks will be minimized because the partner responsible (BRGM) is a large engineering department with an extensive technical experience.

WP4 - Development of an innovative hydrometallurgical laboratory process - the difficulties in laboratory pilot construction for the steel slag processing are very low, because individual experiments and experience by the partners involved (ARMINES/SPIN, BRGM) indicates a high possibility of success.

WP5 - Phytostabilization of primary slags and secondary waste resulting from hydrometallurgical treatment - the risk associated to this WP essentially lies in an unsuccessful plant mycorrhization, but anyway the phytostabilization of primary slags will still be feasible, since the process has previously been implemented at a field plot scale. Regarding phytostabilization of secondary steel slags, the main risk resides in the suitability of this substrate for plant growth. However, HYPASS will explore other routes for the management of this kind of waste [*e.g.*, its use in the field of civil engineering(2, 3, 4)], and it is very unlikely that both management strategies be unsuccessful.

WP6 - DST design - this WP is iterative and transversal. Therefore, it is greatly dependent on other WPs results or data. It also depends on territorial stakes that may change during the project. The DST content will have to be adjusted and regularly up-dated all along the project duration.

WP7 - Communication, dissemination and exploitation of the results - the possible lack of interest of the steelmaking sector could be seen as a risk. The latter remains nevertheless very low, as we have already received a strong response from industry regarding our proposal. In terms of proposed risk-mitigation measures, the partnership, which already has numerous contacts in the concerned industry, will extend its network to reach a wider audience.

II. PROJECT ORGANISATION AND MEANS IMPLEMENTED

II.1. Consortium description, relevance and complementarity

II.1.1. Consortium as a whole

HYPASS aims to examine all levels of the value chain, including processing and recovery of valuable trace elements, waste by-product valorisation and management, economic feasibility and environmental impacts with the goal of developing an economically feasible, "zero-waste" approach. To address such a wide range of different topics, a Consortium (ARMINES as project leader, BRGM and IFAM) with the needed experience, expertise and capability in these areas has been assembled. There is little overlap between the partners and each has well-defined tasks and contributions within the project. These partners belong to government research institutes and industry, thus ensuring high quality results that are focused on eventual exploitation in the real world. Synergies could be developed with the GIS PILoT[10]. The operating unit of ARMINES within the proposed activity will be the SPIN centre, common research centre of ARMINES and Mines Saint-Étienne(31).

II.1.2. Partners' complementarity

HYPASS brings together partners, who have long and proven expertise in different mineral processing techniques, process design and engineering aspects in general. Their collaboration will result in extensive integration of new knowledge amongst the partners and greatly increased innovation capacity due to the multi-disciplinary approach that will be implemented.

SPIN carries out chemical engineering studies and research that contributes to the dissemination of knowledge on the conversion of matter and energy and is equipped with all facilities and software to carry out all activities required by HYPASS. The PEG[11] department (CNRS UMR EVS 5600[12]) from SPIN/Mines Saint-Étienne(31) organizes its research inter alia in the fields of the treatment and re-use of solid mineral matrices and of the water/soil/plant transfers of trace elements. The HYPASS project will allow PEG to acquire more expertise in one of its fields of competence: the rehabilitation of brownfield sites by its involvement in previous or current studies: ANR PRECODD PHYSAFIMM [13] (27) and FUI 18 TARANIS [14] (32) projects developing phytomanagement(27, 33) or hydrometallurgical(32, 34, 35) techniques for the redevelopment of mining and

[10] GIS PILoT ("Groupement d'Intérêt Scientifique du redéploiement Post-Industriel: Loire Territoires urbains") [https://gispilot.univ-st-etienne.fr/fr/index.html];

[11] PEG ("Procédés pour l'Environnement et les Géo-ressources") [http://www.mines-stetienne.fr/recherche/departements/procedes-pour-environnement-et-georessources-peg/];

[12] CNRS ("Centre National de la Recherche Scientifique") UMR ("Unité Mixte de Recherche") EVS ("Environnement, Ville et Société") 5600 [http://umr5600.ish-lyon.cnrs.fr/];

[13] PRECODD ("PRogramme ECOtechnologies et Développement Durable") PHYSAFIMM ("la PHYtoStabilisation: méthodologie Applicable aux Friches Industrielles Métallurgiques et Minières");

[14] FUI 18 ("18ème appel à projets du Fonds Unique Interministériel") TARANIS ("Valorisation de la matrice minérale issue du traitement hydrométallurgique de laitiers "inox" et aciers spéciaux").

metallurgical wastelands.

BRGM has considerable experience too in the areas of mineral processing, soil/effluent/groundwater decontamination, waste management, recycling(36), valorization(37), risk analysis and LCA. BRGM is able in HYPASS to leverage its expertise(3, 8, 16, 38, 39, etc.) (in terms of sampling, matter pre-concentration, physical and/or physicochemical treatment, DST conception) thanks to its participation to the ANR ECOT ORLA(10, 11), ERA-MIN EXTRAVAN(12), HORIZON 2020 FAME[15](40) and CHROMIC(13) programs.

Industeel France is a subsidiary of ArcelorMittal, the world's leading steel and mining company. The HYPASS project will provide IFAM new and economical solutions for developing cleaner processes and greener products for a more sustainable environment. ARMINES/SPIN, IFAM and the GIS PILoT have collaborated over decades [ANR PRECODD PHYSAFIMM(27) and SEM NAGIS[16] programs(41)].

Table 2 - Summary table of partners involved in other research programs.

Partner organisation name	Source of funding	Title of the call for proposals	Project title	Name of coordinating entity	Grant amount	Starting date/end date
ARMINES/SPIN	ADEME[17]	ANR PRECODD	PHYSAFIMM(27)	ARMINES/SPIN	480 k€	2009/2014
	FUI	FUI 18	TARANIS(32)	Harsco Minerals France(42)	2,8 M€	2015/2018
	SEM	SEM	NAGIS(41)	"Université Jean Monnet" (UJM) de Saint-Étienne(43)	82 k€	2009/2011
	ADEME	GESIPOL[18]	APPOLINE[19](44)	LEB Aquitaine transfert(45)	280 k€	2013/2016
BRGM	"European Union" (EU)	H2020-SC5-2016-B	CHROMIC(13)	VITO(15) (Belgium)	5 M€	2017/2020
	FP7-NMP	ERA-MIN	EXTRAVAN(12)	Swerea MEFOS(14) (Sweden)	1,2 M€	2015/2017
	EU	H2020	FAME(40)	Wardell Armstrong International Ltd(46) (United Kingdom)	7,5 M€	2015/2018
	ANR	ECOT0014	ORLA(10, 11)	BRGM	1,2 M€	2008/2010

II.1.3. Project coordinator and main partners' presentation

A "Project Coordinator" (PC) and a PMB, who will work closely together with a PAB, will govern HYPASS. The PC will act as a central contact point for inquiries from the ANR, from the project partners and also from third parties. The PAB, consisting of eminent external scientists in the fields addressed by HYPASS, will also include representatives of end-users, helping to keep project results in line with relevant industry expectations and strategies. The PMB will play a major role and will take care of the following: providing project with strategic management, approving technical, financial and administrative decisions taken by the PC, controlling the quality of the project's work and advising on the exploitation of results and common strategies.

ASTOLFI Frédéric (PMB member), with more than 25 years spent in the ArcelorMittal group, is at present "Continuous Improvement Manager" on the IFAM site of Châteauneuf. In his day-to-day activity, he identifies and delivers service improvement activities across IFAM business through employing process improvement methodologies; works with key-business stakeholders to build a continuous improvement environment to support an on-going program of change; identifies trends and process variations as part of establishing a continuous improvement monitoring system; assists in the development and implementation of a "best in class" continuous improvement strategy; set-up programs and run projects.

[15] FAME ("Flexible And Mobile Economic processing technologies");
[16] SEM ("Saint-Étienne Métropole") NAGIS ("Nappe Alluviale du Gier à partir des Isotopes Stables");
[17] ADEME ("Agence de l'Environnement et de la Maîtrise de l'Energie") [http://www.ademe.fr];
[18] GESIPOL ("GEstion Intégrée des SItes POLlués");
[19] APPOLINE ("APplicabilité à l'étude des sites POllués du bio-marqueur LIpidique des végétaux et du bio-indicateur NEmatofaune").

FAURE Olivier (PMB member) is a plant physiologist and an Assistant Professor at the UJM(43) and Mines Saint-Étienne(31). He does research on the general field of soil pollution including the development of new pollution assessment approaches (bio-indication) and treatment methods (phytostabilization) for contaminated soils. His current work essentially focuses on the eco-dynamics of "Trace Elements" (TE) in polluted sites undergoing phytostabilization. He is the author (or co-author) of more than 80 articles and scientific communications and participated (as coordinator or partner) to a number of national research programs mainly dedicated to phytomanagement and bio-indication approaches [*e.g.*, ANR PRECODD PHYSAFIMM(27), ADEME GESIPOL APPOLINE(44), *etc.*].

MENAD Nour-Eddine (PMB Member) is a scientist expert at BRGM since 2006. He earned an M.S. at the Saint Petersburg School of Mines (Russia) on mineral processing and a PhD at the National Polytechnic Institute of Nancy (France). He is a project leader in physical and physicochemical processes at BRGM. Before that, he was Associate Professor at Lulea University of Technology in Sweden. He was teaching and supervising several PhD students. He focused on metallurgical waste (slags, dust, *etc.*), in collaboration with Swedish and European industries. His technology development led to the publication of more than hundred articles in scientific journals, conferences and communications and several patents. He participated in different European projects: FP6 BioMinE[20](47), BRITE-EURAM DGXIII on industrial waste and metallurgical waste recycling, CHROMIC(13), EXTRAVAN(12), HORIZON 2020 MSP-REFRAM[21](48) and WEEE[22] recycling REWARD. He was honored at TMS Annual Meeting & Exhibition 2001. He is/has been the leader of the following ANR projects: ECO-TS EXTRADE[23](49), ORLA(10, 11), PRECODD Valoplus[24](50) and Reforba[25](51).

PEREIRA Fernando, mainly industrial experienced**,** will serve as the coordinator (*i.e.*, as Project Manager and PMB chairman) for ARMINES/SPIN. Holding a PhD degree in Process Engineering, he is a senior researcher in Mines Saint-Étienne(31) since June 2014. He specialized himself in the conception/design, the definition and the realization of projects of creation and/or improvement of chemical, mineral and hydrometallurgical processing from the initial idea to the modalities of elaboration of industrial implementation. He is experienced in leading successful process improvement industrial projects (*i.e.*, at gypsum plants in France and Brazil for Millennium Inorganic Chemicals(52), a Cristal Global Company) and in the design of processes in a sustainable development perspective at laboratory/industrial scale. His principal key achievements: cut processing costs after carrying out a full-scale at a TiO_2 plant in Brazil, increased white gypsum production with a marked improvement in quality, developed an innovative process for producing phosphoric acid with rare earth elements recovery, developed a process at a semi-industrial scale for the decontamination of dredging sludge. During his activity at CTP[26] as Project Manager, he has been the leader for the aforementioned entity the following R&D projects: SOLINDUS[27](53) and ValSOLINDUS[28](54) (FEDER[29] 2007-2013 funds) and GeDSeT[30](55) (INTERREG IV program).

The detailed Curricula Vitae of the key persons involved in HYPASS are provided in Annexes.

II.2. Work plan - "Work Packages" (WPs) and deliverables

II.2.1. Scientific program and project structure

HYPASS has for guideline a DST design for operators dealing with steel slag dumpsites to help identify new steel slag treatment methods and economically viable solutions. The project (over a period of 42 months) integrates eight distinct WPs, each having a well-defined scope within a logical structure. It will be mainly developed at a TRL of 3-4 (technology demonstration at laboratory scale), although the phytostabilisation's efficiency will also be studied at site scale, *i.e.* at a TRL of 6-8. The organizational relationships between the different WPs are shown in Figure 1.

[20] FP6 ("The Sixth Framework Program") BioMinE ("Biotechnologies for Metals bearing in Europe");
[21] MSP-REFRAM ("Multi-Stakeholder Platform for a Secure Supply of ReFRActory Metals in Europe");
[22] WEEE ("Waste of Electrical and Electronic Equipment");
[23] ECO-TS ("ECOtechnologies & EcoServices) EXTRADE ("EXtraction des Terres Rares dans les Aimants permanents des DÉchets des équipements électriques et électroniques");
[24] Valoplus ("Valorisation des poudres de luminophores usagés");
[25] Reforba ("Recyclage de la fraction organique issue des résidus du broyage automobile");
[26] CTP ("Centre technologique international de la Terre et de la Pierre") [http://www.ctp.be/fr/];
[27] SOLINDUS ("SOLutions INtégrées et DUrables pour Sédiments et matières assimilées");
[28] ValSOLINDUS ("Validation environnementale des technologies SOLINDUS de traitement de sédiments");
[29] FEDER ("Fonds Européen de DÉveloppement Régional");
[30] GeDSeT ("Gestion Durable des Sédiments Transfrontaliers").

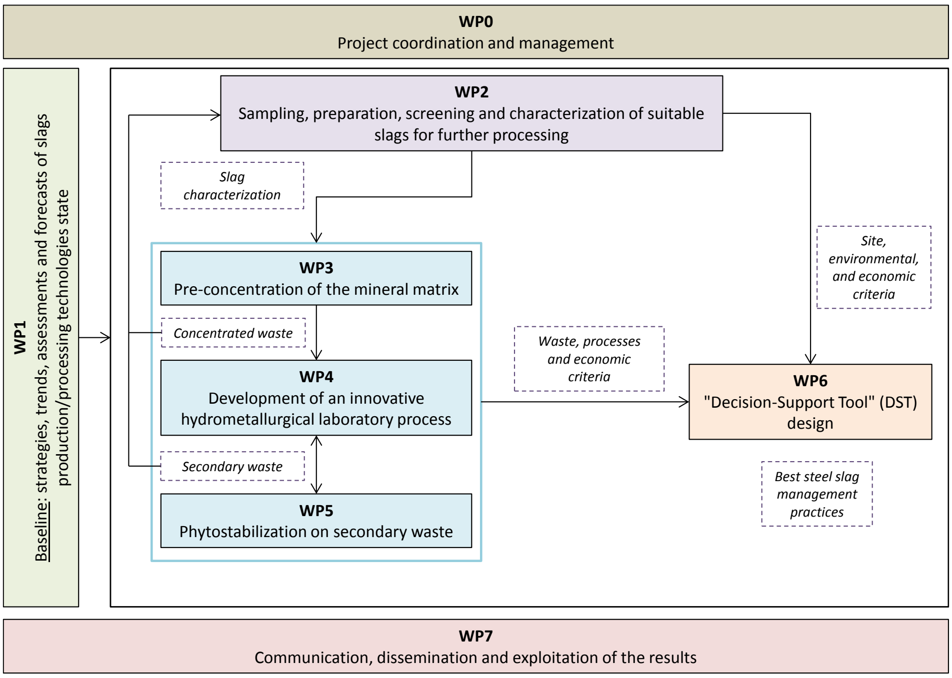


Figure 1 - Pert chart showing how the WPs are interconnected.

II.2.2. Project coordination and management

As coordinating entity, ARMINES/SPIN will be responsible for overall monitoring and smooth running of the project, guaranteeing sound financial, good communication with the ANR, timely submission of project deliverables and dynamic exchange and problem solving between partners. Although the bulk of personnel costs will be borne by the PC, all partners will be involved to ensure time for compliance.

The organizational structure is relatively simple considering the limited number of partners and is meant to make decision-making process lean, fast and effective. The relationships amongst the partners, their roles, rights and obligations will be regulated by a "Consortium Agreement", which will be signed by all partners in order to ensure efficient project management/implementation, rapid resolution of conflicts or problems and correct and equitable "Intellectual Property Rights" (IPR).

II.2.3. WPs description

For each WP, a leader will be identified according to technical and organizational skills. Tasks have been assigned with full ownership and responsibility to each participant. The WPs leaders will be responsible for the performance of their WPs and for delivery of associated reports. The WPs leaders will be supported in their work by the task leaders, whom they supervise. In particular, the WPs leaders will: ensure the accomplishment of the technical objectives of his/her WP, report regularly on the status and risks related to the WP activities, ensure timely preparation of the WP deliverables, control the quality and schedule of the work and organize technical meetings with task leaders when needed, prepare WP reports as part of the scheduled formal reporting to the ANR.

Close collaboration between partners will be critical for HYPASS success. In particular; regarding the steel slag technology development (WP3/WP4, WP5), background databases (WP1), owned by respective partners, will be merged to facilitate knowledge exchange between partners. The IFAM site of Châteauneuf will be sampled together (WP2). Once the project will proceed to the stage of integration and testing of small laboratory pilot (WP4), the partners will meet and work together to implement and conduct initial tests. The mineral processing partners (WP3/WP4) and the WP5 leader will work closely with the scientists involve in the WP6 to provide them with data for LCA calculations. All partners will then collaborate in exploitation, dissemination, writing of articles, protection of IPR, *etc.* (WP7). The detailed description of each WP is given below.

<u>WP0 - Project coordination and management</u>

<table>
<tr><td>WP leader</td><td colspan="2">ARMINES/SPIN</td><td>Starting date</td><td>"Month1" (M1)</td><td>End date</td><td colspan="2">M42</td></tr>
<tr><td colspan="2">Participant short name</td><td colspan="2">ARMINES/SPIN</td><td colspan="2">BRGM</td><td colspan="2">IFAM</td></tr>
</table>

Objectives: the purpose of this WP is to provide the coordination and overall management of the project with the following objectives: project leadership, coordination and management; the smooth running of the project, ensuring it is planned and executed effectively, implementation of each WP and efficient coordination and integration between WPs, ensuring correct technical and financial accounting and reporting, ensuring protection of IPR and compliance with ANR open access and archiving policies, completion of the project on due time and within budget.

Description of work: the project coordination and management WP will be chaired by the project coordinator, represented by ARMINES/SPIN. The project management structure is defined in sections II.1.3. and II.2.2. and will be laid in detail in the "Consortium Agreement". Work will be organized into the following three tasks, all led by ARMINES/SPIN with input and contributions from all participants.

Task 0.1. - Administrative management (M1-M42) - this task, to be fulfilled primarily by the PC, comprises the following high-level management activities: interfacing with the ANR, providing full and timely compliance with administrative, legal, financial and administrative issues, supporting partners with issues related to ANR framework.

Task 0.2. - Operational and technical coordination (M1-M42) - this task will address the day-to-day running of the project, such as verifying technical quality of the work performed, ensuring integration and communication between partners to attain the project goals and ensuring that possible risks and conflicts are identified early and solved. Activities will include: to activate the PMB and a "General Assembly" (GA), to organize PMB meetings once every 3 months (mainly, web conferences) and GA/PAB meetings every 12 months, to ensure the technical quality of all outputs and guarantee submission of deliverables to the ANR on due time, to monitor the progress of HYPASS based on milestones, deliverables and financial reporting and to take corrective action if necessary.

Task 0.3. - Exploitation and dissemination coordination (M1-M42) - this task will address management of open access policies, data archiving/sharing and IPR. While the actual work will be performed in WP7, this task will oversee compliance and progress of various related topics, such as: safeguarding of IPR, helping partners to determine exploitation or sharing paths, guaranteeing that the ANR open access requirements are met, both in terms of publishing as well as the archiving of publications, reports, *etc.*; forming a cluster between HYPASS and other relevant projects to maximize its impact and the efficiency of resource used.

Deliverables:

D 0.1. - "Consortium Agreement" (ARMINES/SPIN, BRGM, IFAM) [M6].
D 0.2. - Project periodic report years 1, 2 and 3 (ARMINES/SPIN, BRGM, IFAM) [M12, M24, M36].
D 0.3. - Final project report (ARMINES/SPIN, BRGM, IFAM) [M42].

WP1 - Baseline: strategies, trends, assessments and forecasts of slags production/processing technologies state

WP leader	IFAM	**Starting date**	M1	**End date**	M24
Participant short name	ARMINES/SPIN	BRGM	IFAM		

Objectives: the overall objective of this WP aims first of all at consolidating the various databases previously created by the Consortium partners into a single project database that details existing knowledge of the chemical characteristics, production statistics, stocks and re-uses of steel slags (including all steel slag families) in Europe and second to identify existing and/or emerging technologies for steel slag processing.

Description of work:

Task 1.1. - Steel slag knowledge database (M1-M18) - partners have already gathered substantial information on the subject. To up-date this information, an additional complete and up-dated review of available information sources (scientific literature, published company reports, *etc.*) will be conducted for the creation of a unified project database detailing existing knowledge of the chemical characteristics, production statistics, stocks and re-uses of steel slags in France and in Europe. Once created, this database will be up-dated using the data produced during the project.

Task 1.2. - Forecasts of processing technologies (M1-M24) - this prospective step, which will involve all HYPASS partners, will be performed on a technical plan and reported on year 2 (with regularly up-dates until the end of the project).

Deliverables:

D 1.1. - Steel slag knowledge database (ARMINES/SPIN, BRGM and IFAM) [M18].

D 1.2. - Report on existing and emerging processing technologies (ARMINES/SPIN, BRGM and IFAM) [M24].

WP2 - Sampling, preparation, screening and characterization of suitable slags for further processing

WP leader	BRGM	**Starting date**	M1	**End date**	M12
Participant short name	ARMINES/SPIN	BRGM	IFAM		

Objectives: the overall objective of this WP is to create common project protocols for the experiments to ensure worker and environmental safety, collect small volume samples from the IFAM site of Châteauneuf to assess the material potential for subsequent separation techniques (WP3 and WP4) and define site vulnerabilities and critical parameters.

Description of work:

Task 2.1. - Safety and environmental protocols (M1-M3) - environmental and safety risks will be managed by defining rigorous experimental monitoring, waste disposal and safety protocols. Because Consortium members already have many years of experience in such type of work, this will essentially be a standardisation of protocols already existing at the individual institutions. Documents will be produced and up-dated over the project lifespan.

Task 2.2. - Sampling and assessment of the material potential (M1-M6) - the investigated metallurgical materials are EAF slags provided by IFAM. These materials will be characterized and screened on site with "Portable X-Ray Fluorescence" (PXRF), and then sampled according to standardized sampling methods [*e.g.*, NF ISO 10381(56)] in order to provide representative samples for further testing and experimental work. Analyses will be carried out on multiple samples for each material stream to find out the inherent variability and select representative samples for further analyses. Besides that, analyses regularly performed as quality control on the slag materials by IFAM, the producer, will be used. A combination of chemical and mineralogical analyses will be performed on selected slag samples, in order to obtain the required information to design an optimal pre-concentration and leaching scenario. Chemical composition of all materials will be determined using "X-Ray Fluorescence" (XRF) and "Inductively Coupled Plasma - Optical Emission Spectrometry/Mass Spectrometry" (ICP-AES/MS). For the identification of crystalline phases, mineralogical analyses by "X-Ray Diffraction" (XRD) and Raman spectrometry will be performed. Cathodoluminescence and "Scanning Electron Microscopy/Energy Dispersive X-Ray spectroscopy" (SEM/EDX) measurements will be carried out on selected samples to determine the morphological aspects. Particle size analysis will be performed by sieving and laser diffraction analysis. A complete "Thermo-Gravimetric Analysis/Differential Thermal Analysis" (TGA/DTA) study will also be performed. Additional analyses such as "Mineral Liberation Analysis" (MLA) will be carried out to determine the liberation degree and association of different elements contained in steel slags to further map the potential for leaching and to determine the full potential for metal recovery. These analyses will be conducted by BRGM and ARMINES/SPIN in collaboration with IFAM.

Task 2.3. - Site vulnerabilities mapping and critical parameters (M1-M12) - following the task 2.2., significant parameters will be mapped at site scale using "Geographical Information System" (GIS) and spatial analyses methods (*e.g.*, interpolation method as kriging). Then, it will be possible to spatially map metal contents, leaching or bioavailability potential of slags. This mapping of polluted zones will be crossed with other environmental variables in order to define site vulnerabilities and risks. A particular attention will be brought to the water and pollutants fluxes at low flow and high flow periods. Spatial groundwater vulnerability and risk will be defined taking into account vadose zone thickness, slag thickness, hydraulic gradient, hydraulic conductivity, flow direction, slag water retention [data from the PHYSAFIMM(27) project]. Spatial river vulnerability and risk(57) will be defined by characterizing groundwater/surface water interactions (*e.g.*, flow direction, water flow) with GIS simplified model(58). Another data [set out also from the ANR PRECODD PHYSAFIMM(27) program], that cannot be spatialized, will be used to complete the diagnosis (*e.g.*, air emission, wind, rainfall or river floods). This site vulnerability diagnosis at local scale will also be integrated in the WP6 global LCA.

Deliverables:

D 2.1. - Project safety and environmental protocol report (ARMINES/SPIN, BRGM and IFAM) [M3].
D 2.2. - Assessment of the material potential (ARMINES/SPIN, BRGM and IFAM) [M6].
D 2.3. - Seasonal vulnerability maps at site scale (ARMINES/SPIN, BRGM and IFAM) [M12].

WP3 - Pre-concentration of the mineral matrix

WP leader	BRGM	Starting date	M6	End date	M18
Participant short name	/	BRGM	/		

Objectives: the overall objective of this WP is to investigate different methods of crushing, milling as well as disintegration of steel slags by microwave heating. This is mandatory to achieve the liberation of individual phases from matrix required for physical separation and to increase reaction area for leaching by mechanical activation. To facilitate the leaching and the recovery of SMs (Cr, Mo, *etc.*) from steel slags, BRGM will perform physical separation techniques to recover metallic alloys in coarse fraction by using magnetic(16) and density and gravity separation techniques.

Description of work:

Task 3.1. - Comminution (M6-M12) **-** in general, comminution(59) includes crushing, milling and other routes of fragmentation of a material, such as "MicroWave" (MW) pretreatment or electrical fragmentation. This step of preparation of material is an energy-intensive process and then it is evident to choose the optimized type of comminution technique for cost-effectiveness of a process. MW pre-treatment may facilitate the grinding process by reducing work index and improves the liberation of particles. To avoid the production of fine particles during grinding process, there are other innovative techniques. In this project, different methods of comminution routes will be compared, in order to achieve the liberation of individual phases from matrix required for physical separation:

1. smart size reduction or soft grinding (sequential grinding), using grinding followed by classification to recover metals each step;
2. electrical fragmentation(60): this technique has been used on ore aggregates and generated a higher percentage of liberated particles and lower percentage of fine material than that obtained by mechanical comminution.

Crushing, milling and MW heating will be carried out at BRGM on laboratory scale level. Electrical fragmentation will be tested by BRGM on equipment located in Switzerland. The work index will be determined. The reduced material will be characterized by MLA, combined with conventional analyses, to evaluate the comminution efficiency. These analyses will allow to measure, aside from the comminution efficiency, the influence of the comminution process on the physicochemical properties of the material (liberation degree of particles, distribution of metal-bearing phases, activation). The material, obtained by the optimized comminution processes, will be further treated in task 3.2..

Task 3.2. - Processing of recovered slag metal fractions (M12-M18) - this task is dedicated to pre-concentration of the material streams by physical and physico-chemical separation technologies (mineral processing). Several separation techniques will be tested on the representative investigated sample of slag. The separation techniques suggested in this task allow separation of liberated particles at µm level. The proposed innovative techniques will significantly increase the selectivity and recovery rate. Main objectives of this task are:

1. to recover all metals from slags which can be recycled directly in the metallurgical processes;
2. to concentrate SMs as a feed material for leaching steps (WP4).

Magnetic separation(16) will be tested on the crushed slag in dry and wet technologies, using low and high intensity magnetic separators at BRGM in order to recover metals droplets and metal-oxides containing minerals. Furthermore, an innovative dry multipolar magnetic separator, which is to date the most efficient magnetic separator, will be tested. This equipment was designed to create a strong agitation of particles that allows the release of non-magnetic particles, which are entrapped with the magnetic fraction, leading to the production of a magnetic fraction of a good quality. Finally, a new wet magnetic separation process with high intensity magnets (2Teslas) will be tested on fine particles of slags in water. BRGM expects to be able to recover some magnetic fine particles at micron level. This separation technique allows concentrating SMs in the non-magnetic fraction. Regarding the electrostatic separation experiment, electrostatic and tribo-electric separation will be tested on the non-magnetic fraction obtained from magnetic separation. The objective is to concentrate the mineral phases containing SMs. Gravity separation techniques will be investigated by wet shaking table technology and Falcon concentrator to recover the heavy metallic fraction.

All products obtained from different tests will be analysed by conventional analytical methods such as XRF, ICP-AES, XRD and SEM/EDX to evaluate the efficiency of the separation experiments. Optimization of separation procedure will lead to designing cost-effective processes to recover metallic particles (used directly as a raw material) and/or to concentrate metals (as oxides, spinels) suitable for further processing (WP4).

Deliverables:

D 3.1. **-** Assessment for subsequent separation techniques (BRGM) [M12].
D 3.2. **-** Report on optimized pre-treatment and physical separation techniques EAF slags with characterization of the final products (BRGM) [M18].

WP4 - Development of an innovative hydrometallurgical laboratory process

WP leader	ARMINES/SPIN	**Starting date**	M18	**End date**	M30
Participant short name	ARMINES/SPIN	BRGM	/		

Objectives: this WP refers to the development of a processing technology based on hydrometallurgical principles at a TRL of 3-4. The overall objective of this WP is to define the final optimized hydrometallurgical circuit to achieve the highest SMs extraction yield, while preserving the mineral matrix resulting from the physical treatment applied in WP3. For that WP, expertise will be mainly drawn from ARMINES/SPIN and BRGM.

Description of work:

Task 4.1. - Optimization of the alkaline hydrometallurgical process (M18-M24) **-** this task will consist in implementing selective unit operations propped up on the chemical nature of the non-ferrous metals from steel slags. The scientific approach will consist in adapting the medium of selective lixiviation and the complexation/separation/recovery methods in order to optimize the SMs extraction yields. Special attention will be paid on choosing conditions and environments that do not present side effects and allow a minimization of the environmental impacts. Laboratory tests will be conducted on the WP3 samples collected to determine the highest recovery of SMs and the optimum hydrometallurgical circuit. Testing will be performed in the ARMINES/SPIN laboratories with additional experimentation of leaching methods by the partner also specialized in this field (BRGM). Optimum leaching conditions will be identified for each physically pre-treated (WP3) sample, related to its specific mineralogy and the SMs (Cr, V, Mo, *etc.*) to be extracted. Study of the experimental conditions will identify the influence of the main parameters. In particular, the following experimental conditions will be addressed: alkaline leaching agent concentration, particle size, leaching time, liquid/solid ratio, pulp density, pressure and/or temperature conditions and stirring rate. The process conditions will be also optimized in terms of maximizing liquid reagent recycling and extraction yields, while minimizing base consumption, energy consumption and environmental impact. To determine the leaching behavior of WP3 samples under specified conditions, European standardized methodologies [NF EN 12457[(61)] and NF EN 12920[(62)]] will be performed in batch reactors. Additional methods to determine the influence of pH on the leachibility of inorganic constituents [NF EN 14997[(63)]] will also be conducted. This step will constitute a first scale-up of the process and will form the basis for the laboratory pilot tests to be conducted in task 4.2..

Task 4.2. - Laboratory pilot testing (M24-M30) **-** to confirm the technical options, which emerged within the framework of the task 4.1., the assembly of a small hydrometallurgical laboratory pilot will be planned. The process validation on continuous flow will be performed. This stage will allow identifying the necessary adaptations of operating conditions to obtain comparable results than at 4.1. at larger-scale and to conclude on the various technical options. To verify the process robustness, trials may be performed on different WP3 batches. Performances will be judged solely on environmental quality of obtained materials (in terms of content and leachable fraction) and on the ease of implementation (adaptability).

Task 4.3. - Analytical and mineralogical characterization (M18-M30) **-** all products ("inerted" mineral matrix and solutions) obtained from tests carried out in tasks 4.1. and 4.2. will be analyzed by conventional methods such as XRF, ICP-MS, "Ionic Chromatography" (IC), XRD and SEM/EDX in order to ensure they comply with the strictest environment related requirements according to the relevant waste nomenclature.

Deliverables:

D 4.1. **-** Assessment of the hydrometallurgical techniques (ARMINES/SPIN, BRGM) [M30].
D 4.2. - Report on optimized hydrometallurgical processing technology with characterization of the final products (ARMINES/SPIN, BRGM) [M30].

WP5 - Phytostabilization of primary slags and secondary waste resulting from hydrometallurgical treatment

WP leader	ARMINES/SPIN	**Starting date**	M1	**End date**	M36
Participant short name	ARMINES/SPIN	BRGM	IFAM		

Objectives: it is possible, following WP2 and WP3 investigations, that some slag types will not be relevant for hydrometallurgical treatment. It is also foreseeable that the hydrometallurgical process applied in WP4 generates secondary waste that do not meet the environmental acceptability criteria for a safe re-use in the field of civil engineering[2, 3, 4]. Therefore, HYPASS will implement a phytostabilization strategy, for limiting wind and water erosion of steel slag dumps and to prevent leaching and run-off of contaminants, whether they are primary slags or by-products resulting from the hydrometallurgical treatment. The WP5 will address this issue at two different TRLs. A set of laboratory experiments (TRL 3-4) will study the effects of AMF both on the stimulation of plant growth and on the decrease of metals accumulation by plants. In addition, the efficiency of phytostabilization will be studied at a large scale (TRL 6-8), on the studied slagheap, where a rehabilitation project by phytostabilization will be implemented at autumn 2017.

Description of work:

Task 5.1. - The study of AMF symbiosis into primary slags in controlled conditions (M1-M12) - this task will be implemented on year 1 of the project. Pot experiments will be performed in controlled conditions to assess the influence of two AMF strains (*Funneliformis mosseae* and *Rhizofagus irregularis*) on the growth and metal accumulation of a plant community cultivated onto primary slags. The plant assemblage will be made of five species (*Medicago sativa*, *Melilotus officinalis*, *Bromus erectus*, *Festuca arundinacea* and *Achillea millefolium*), chosen from the results of the ANR PRECODD PHYSAFIMM[27] program. Likewise, slags will be fertilized using composted sludge according to the recommendations from the PHYSAFIMM[27] project. Each pot will be equipped with Rhizon samplers, in order to collect soil water at weekly intervals. After a three month growing period, plants will be harvested and root and shoot biomass (fresh and dry weighs) will be determined. Additionally, root and shoot metal contents will be determined. This experimental setup will answer the following questions:

- Does AMF inoculation improve plant growth on metallurgical slags?
- Does AMF inoculation decrease metal content in the soil solution?
- Does AMF inoculation decrease metal accumulation by plants?

Task 5.2. - The study of AMF symbiosis into primary slags in "field" conditions (M1-M12) - both AMF strains will be tested in the field, on an experimental parcel that was prepared on the IFAM site during the PHYSAFIMM[27] project. This 50 m^2 plot (10 * 5 m) has received composted sludge and has been sown in 2010. Its vegetation cover was close to 90 % in 2015. This parcel will be divided in thirty 1 m^2 subplots randomly disposed, allowing ten replicates for three modalities: 1/ control without inoculation, 2/ inoculation with *Funneliformis mosseae* and 3/ inoculation with *Rhizofagus irregularis*. Plant growth and metal accumulation in above ground parts will be determined every year during the time course of the program. For this, three plots from each modality will be harvested in June of 2018, 2019, 2020 and analyzed for plant dry weigh and metal content. This experiment will complete data from laboratory experiments and should allow identifying the most efficient AMF strain, both for improving plant growth and decreasing metal accumulation.

Task 5.3. - The study of AMF symbiosis into secondary waste resulting from the hydrometallurgical treatment (M24-M36) - this task will be implemented on year 3 of the project. As it is very likely that by-products resulting from the hydrometallurgical treatment will have very different characteristics than primary slags, a second set of pot experiments will be performed, using those secondary waste. The same experimental setup than in task 5.1 will be implemented. This will answer the issue of the suitability of secondary waste for plant growth as well as the promoting effect of AMF on this kind of substrate.

Task 5.4. - The study of plant development and metal accumulation on a large metallurgical slagheap processed by phytostabilization (M1-M36) - the 4 ha IFAM dumpsite will be processed by phytostabilization at autumn 2017. The task 5.4 will be dedicated to the annual assessment of the efficiency of this phytomanagement strategy. This will be performed from year 1 to year 3 of the project. The percentage of vegetation cover of the area will be estimated from observations made during the optimum growing season (June). For this, the study area will be divided into plots of 100 m^2 (10 m * 10 m). Recovery will be estimated on a number of plots equal to 10 % of the whole area, arranged along transects positioned according to the apparent heterogeneity of the entire site. These first results will also allow selecting a few vegetated plots differing in their percentage of plant cover and/or plant communities. These plots will be analyzed in detail with respect to the abundance/dominance of each species to calculate conventional indices of biodiversity: species richness (S = total number of species), species diversity (H = Shannon index) and equitability (EH). This study will be conducted three times in the second year of the program to include vernal, summer and fall species. The results will be used in the framework of actions foreseen in task 2.3 (site mapping). The objectives of this action are:

- identifying and characterizing the possible heterogeneities in the process of plant recovery;

- assessing the efficiency of phytostabilization of metallurgical dump at a large site scale.

Deliverables:

D 5.1. - Suitability of AMF for improving plant growth and decreasing metal accumulation onto primary slags - (ARMINES/SPIN and IFAM) [M12].
D 5.2. - Effects of mycorrhizal associations in field conditions (ARMINES/SPIN and IFAM) [M12].
D 5.3. - Suitability of secondary waste as plant growth substrate and effects of mycorrhizal inoculation (ARMINES/SPIN and IFAM) [M36].
D 5.4. - Dynamic of plant development at a metallurgical slag dump treated by phytostabilization, mapping of different plant species (ARMINES/SPIN and BRGM) [M36].

WP6 - DST design

WP leader	BRGM	**Starting date**	M1	**End date**	M42
Participant short name	ARMINES/SPIN		BRGM		IFAM

Objectives: based on the work realized in previous WPs, the overall objective of this WP will be to develop a DST, which will enable users to simulate different steel slag management routes and to choose the most sustainable treatments based on environmental impacts and financial costs.

Description of work: the DST will be developed to help comparison of different scenarios of slag management and will be applied on the IFAM site of Châteauneuf. Based on results obtained in previous WPs, on literature reviews and on on-site interviews, a set of relevant criteria in the context of steel slag management will be identified. These criteria will then be assessed and quantified, on an environmental and an economical basis, in order to implement these data in the DST and to enable the decision-makers to choose the best steel slag management routes among the status quo, the classic option or the HYPASS innovative solution.

Task 6.1. - DST concept design (M1-M24) - this task will consist in better understanding global and local stakes of steel slags management. If global stakes can be found by a bibliographic review, local stakes knowledge requires meeting local actors(64). Therefore, several interviews will be conducted with local stakeholders (*e.g.*, industrialists, ADEME, DREAL[31], local authorities, non-governmental organizations, *etc.*). This stakes characterization, alongside the identification of DST users, will permit to define the DST conceptual framework(65).

Task 6.2. - Environmental LCA (M20-M30) - environmental LCA quantifies the potential environmental impacts a system has throughout its whole life cycle(65). The LCA will be performed on the different steel slag management options by following ISO 14040:2006 standard. The local vulnerabilities identified and assessed in WP2 will be included, when possible, in the LCA to take into account the specificities of the local context. The LCA results, both in terms of environmental impacts and on major contributors to these impacts, will then be potential criteria for the DST.

Task 6.3. - Economic aspects (M20-M30) - the economic assessment will be based on the same systems defined in task 6.2 and will consist in a cost-benefices analysis(65) where the direct and indirect costs associated to the different slag management routes will be quantified as well as the benefices associated, for example, with SMs recovery.

Task 6.4. - DST development and implementation (M24-M40) - in parallel with the work performed and the results obtained in the previous tasks, the most important criteria to consider in the DST will be stressed(66, 67). At this point, a particular attention should be paid on the reliability of the information available to assess and quantify these specific criteria. The criteria will then be compiled in the DST, which will include techniques such as multi-criteria analyses(65, 68, 69) to help users determine the best steel slag management route. The functioning of the tool will be illustrated with the case of the IFAM site.

Task 6.5. - Technical handbook (M36-M42) - the main objective of this last task is to organize, enhance and disseminate the work done in the HYPASS project. This task will help answer to this question: what is the best solution for the management of steel slags and co-produced waste? The transfer of knowledge to the industrial actors (and other actors involved) will be ensure with a technical guideline(69, 70, 71), based on the DST development, which will mainly focus on the best steel slag management practices. It will include technical specifications about: 1/ steel slags (WP1) and processes (WP3 and WP4), phytomanagement (WP5) and other remediation methods or re-uses options (WP1), 2/ global and local environmental stakes (WP6.1) and impacts

[31] DREAL ("Direction Régionale de l'Environnement, de l'Aménagement et du Logement") [http://www.auvergne-rhone-alpes.developpement-durable.gouv.fr/].

(WP2 and WP6.3) - *i.e.*, on the different aspects used to develop the DST. The information contained in this technical handbook could be organized as conceptual decision trees[(72)] including, when data are available, quantitative aspects.

Deliverables:

D 6.1. - Report on DST conceptual framework (ARMINES/SPIN, BRGM and IFAM) [M24].
D 6.2. - DST illustrated with the IFAM site case (ARMINES/SPIN, BRGM and IFAM) [M40].
D 6.3. - Technical handbook (ARMINES/SPIN, BRGM) [M42].

WP7 - Communication, dissemination and exploitation of the results

<table>
<tr><td>WP leader</td><td>ARMINES/SPIN</td><td>Starting date</td><td>M1</td><td>End date</td><td>M42</td></tr>
<tr><td>Participant short name</td><td colspan="2">ARMINES/SPIN</td><td colspan="2">BRGM</td><td>IFAM</td></tr>
</table>

Objectives: one of the HYPASS objectives is to ensure the largest possible visibility and long-term impact of the project outcomes. Communicating and disseminating the project results will be a necessary condition to make environmental managers and people aware of the potential economic, environmental and strategic advantages of the integrated techniques developed within HYPASS for steel slag processing. Specific objectives include: the creation of branding material and the project web site (with a public part and a secure part, for communication between partners and the ANR, up-load of files and reports, *etc.*), increased visibility via social media, high-level dissemination via publications and newsletters and participation in trade-shows and conferences, project archiving on a guaranteed, long-term repository, creation of training material based on the multidisciplinary results (metallurgy, mineral processing, phytomanagement, environment, *etc.*) of the project.

Description of work:

Task 7.1. - Project website and branding (M1-M42) - the HYPASS website will be operational within the first 6 months of the project and will be organized on three main themes: introduction of the HYPASS project, objectives and team; timely up-dates of HYPASS work progress and results and a password-protected section for partners only (plus the ANR officer), where confidential data exchange and communication can take place. In addition to being a showcase for the project and its results, the site will aim to be a "one-stop" portal giving a complete range of information (and, links) on the potential economic, strategic and environmental advantages of "zero-waste" steel slag processing. The partners will endeavour to the HYPASS site embedded in external sites (industry and/or environmental associations), as well as past and on-going related projects to increase visibility. All partners will be responsible to provide to the PC, on a regular basis, short texts and interesting graphics to be up-loaded. An internet forum application will be installed and structured, which will enable closed communication including up-loading/down-loading of project documents between partners. This forum will serve as a dynamic project tool to facilitate exchange and networking between partners.

In tandem with the creation of the web portal, project branding will take place in the first three months of the project. During this work, a project logo will be chosen as well as associated fonts, colours and styles for official project documents like presentation and posters template.

Task 7.2. - Project visibility via social media (M1-M42) - HYPASS will use the following tools to increase visibility of the project and its results:

- Twitter - new tweets will be up-loaded at least once a month from the beginning of the project, with all HYPASS researchers contributing short comments highlighting research progress and results. The PC will tweet regarding major events organised by the project (such as meetings). The tweets will also be used to highlight completed milestones, deliverables or publications;
- LinkedIn - LinkedIn is a networking site for professionals and industry. Thus, it will be an important outlet for the project results. A LinkedIn account will be established together with a blog that will give technical results. The account will follow various related groups (*e.g.*, Mineral Processing, Mining/Mineral Processing & Metallurgy, *etc.*).

Task 7.3. - Dissemination and exploitation of the results via publications, newsletters, tradeshows and conferences (M1-M42) - HYPASS will be highly active and dynamic in its effort to disseminate and exploit the project results via the following mechanisms:

- Peer-review, scientific publications - technical publications on the HYPASS project will be presented in trade and scientific journals with high "Impact Factors" (IF) [Hydrometallurgy, Waste Management, Journal of cleaner production, *etc.*];

- Project newsletter - an electronic technical newsletter will be published twice yearly. It will be posted on the project website and will be distributed to appropriate stakeholders. These mailing lists will first consist of partner contacts but will rapidly expand during the project via contacts made with social media, at conferences and direct communication made with appropriate industrial associations. The newsletter will describe the research progress taking care to protect partners IPR;
- Tradeshows and conferences - project researchers will attend 1-2 tradeshows or conferences a year. Tradeshows will give the opportunity to make relevant industrial contacts and expand the potential for exploitation of the results. Scientific conferences will permit increased visibility, diffusion of the technical results and exchange of ideas with peers. Targets events will include those focused on the steelmaking sector (*e.g.*, AFOCO[32] technical days, *etc.*) as well as more general events addressing mineral processing (*e.g.*, Minerals Engineering Conference, International Mineral Processing, *etc.*);
- Workshop - a Workshop will be organized at the end of the project in tandem with the final project meeting. All beneficiaries will present their results and other researchers (outside of HYPASS, but working on related topics) as well as relevant industry will also be invited to participate.

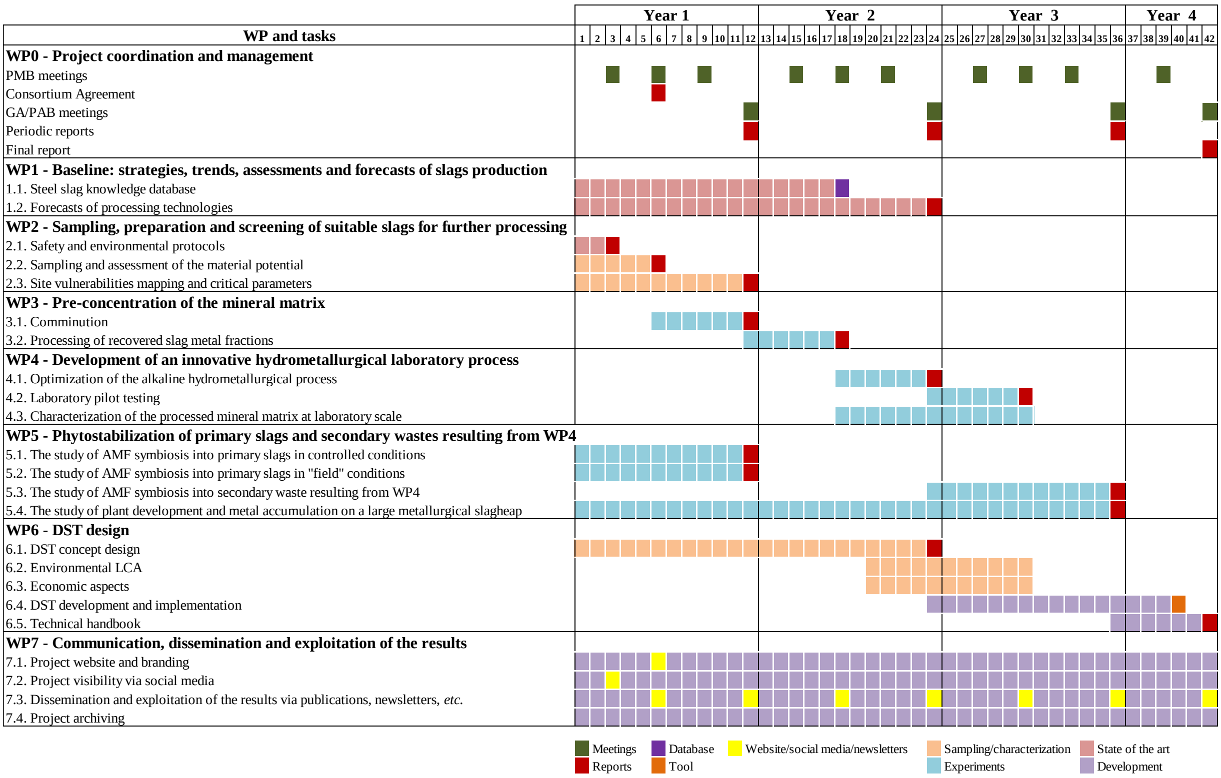
Task 7.4. - Project archiving (M1-M42) – Zenodo(73), initially created and still supported by "European Commission" (EC) funds, will be used to guarantee longevity of the results after the conclusion of the HYPASS project. All partners will be responsible to up-load their reports, data and other material to the repository. Project products up-loaded onto Zenodo will include reports, journal and conference publications, presentations, posters, *etc.* including all project deliverables (with appropriate access levels). The PMB will oversee this process, monitoring partner compliance, providing advice and resolving conflicts.

Deliverables:

D 7.1. - Website creation and selection of branding products (ARMINES/SPIN, BRGM and IFAM) [M6].
D 7.2. - Establishment of web presence on social media sites (ARMINES/SPIN, BRGM and IFAM) [M3].
D 7.3. - Annual dissemination report detailing dissemination events (including publications, conference proceedings and tradeshow attendance) and other material (reports, deliverables, data, *etc.*) (ARMINES/SPIN, BRGM and IFAM) [M12, M24, M36].
D 7.4. - Final dissemination report (ARMINES/SPIN, BRGM and IFAM) [M42].

II.2.4. Tasks schedule

Table 3 - HYPASS tasks schedule and dependence. Deliverables and annual reports scheduling.



[32] AFOCO ("Association Française des Opérateurs sur CO-produits industriels") [http://www.afoco.org/].

The different phases of the project and their relationship are presented in Table 3, which equally shows the schedule of deliverables and annual reports that will be send to the ANR.

II.3. Technical and scientific justification of requested resources

The program requirements are given in Table 4.

Table 4 - Means used and requested funding.

Partners	ARMINES/SPIN	BRGM	IFAM
Non-permanent personnel	57 478,46 €	8 215,20 €	0 €
Permanent personnel	241 692,73 €	166 589,19 €	64 000 €
Equipment	76 000 €	19 655,90 €	11 000 €
Buildings and lands	0 €	0 €	0 €
Subcontracting and intellectual property costs	0€	10 045,70 €	15 000 €
Other goods and services	6 000 €	4 012,50 €	1 000 €
Indirect costs	209 176,41 €	0 €	0 €
Global cost	590 347,60 €	417 036,97 €	91 000 €
Total requested funding/partner	295 173,80 €	208 518,49 €	22 750 €

The total aid requested by HYPASS partners is about 526 k€, that represent 50 % of the total costs involved by ARMINES/SPIN and BRGM and 25 % by IFAM and distributed as follow:

ARMINES/SPIN

Instrumentation and material (76 000 €)

- equipment costs of 80 k€, amortized for 10 k€ during the 42 months of HYPASS, will cover the acquisition:
  - ✓ of various reactors, assembly parts, joints, controller (cryothermostat), instrumentation, pumps, probes, flowmeters, pH and temperature sensors, *etc.* necessary to the hydrometallurgical laboratory pilot design, provided in the WP4 (*estimated cost*: 50 k€);
  - ✓ of a growth chamber for plant cultivation (WP5) [*estimated cost*: 30 k€].
- *scientific consumables (6 000 €)*: mainly, reagents and glassware for chemical analyses (WPs 2-3-4-5).

Staff (299 171,19 €) - ARMINES/SPIN provides 74 P.M.: an assistant professor (12 P.M.), for which no ANR funding is sought; one technician (7 P.M.) and four research engineers (43 P.M.). Moreover, ARMINES/SPIN will recruit in the year 2 of the HYPASS program one post-doctoral position (12 P.M), specialized in the mineral processing, to cover the WP4 (design of an effective hydrometallurgical process to recover SMs).

Operating costs (215 176,41 €) - the ARMINES/SPIN operating costs are divided as follow:

- *travels and accommodations (6 000 €)*: devoted to PMB, GA/PAB meetings, conferences/Workshops, field trips, sampling, networking and dissemination activities;
- *indirect costs (209 176,41 €)*: management and structure fees are amounted to 203 436,41 €. Environment costs are of 5 740 €.

BRGM

Instrumentation and material (19 655,90 €): BRGM provides for the purchase of sampling and magnetic susceptibility measurement tools, amortized for 8,1 k€ during the 42 months of the project. Crucibles used for high volume thermal analyses, that will be implemented in the project to characterize the targeted steel products, will be amortized around 2 k€ for a period of three years. 9 513 € will cover all consumable materials.

Staff (174 804,39 €) - permanent personnel cost, about 166,6 k€, will cover the researchers and technicians costs mobilized during HYPASS for the amount of 23.3 P.M.. 8,2 k€ will be allocated to the expenses of two trainees for six mounts in the second and third year of the project for the amount of 12 P.M..

Operating costs (14 058,20 €): the BRGM operating costs are divided as follow:

- *subcontracting - external service delivery (10 045,70 €)*: subcontracting some analyses (MLA, *etc.*);
- *travels and accommodations (4 012,50 €)*: the missions are planned for PMB, GA/PAB meetings, visits to

industrials, campaigns of sampling and working meetings, as well as participation in national and/or international conferences and symposia.

IFAM

Instrumentation and material (11 000 €) - 11 k€ will be allocated to the installation of two additional piezometers (6 k€) and to the refurbishment of the experimental space and the weather station (5 k€).

Staff (64 000 €) - this permanent personnel cost will cover the two managers mobilized during the 42 months of the research program for 8.65 P.M..

Operating costs (16 000 €) - the IFAM operating costs are dived as follow:

- *subcontracting - external service delivery (15 000 €)*: 15 k€ will be directed to the rehabilitation of the "PHYSAFIMM"[(27)] experimental field plots area and annual maintenance of the area (WP5);
- *travels and accommodations (1 000 €)*: missions are essentially planned for PMB, GA/PMB meetings as well as participation in national events (AFOCO technical days, *etc.*).

III. IMPACT AND PROJECT BENEFITS

III.1. Project impact

The HYPASS project responds to the Challenge 1 ("*Lean resources management and adaptation to climate change*") of the 2017 ANR action plan, and more precisely to those of Axis 4 ("*Scientific and technological innovations to accompany the ecological transition*"), where the following text is indicated: "*it also concerns the social, political and technological innovations avoiding or reducing impacts, rehabilitating environments, focusing on ecological compensations, and adapting to the new constraints and opportunities*".

The main goal of the project is to improve environmental performance of operations (including a reduction in waste and a better recovery of resources from the latter) and to move towards "zero-waste" systems for steel slag processing, that have a significantly reduced environmental impact. This will be accomplished by recovering valuable SMs and a bulk by-product [an inerted mineral matrix for re-use in the civil engineering[(2, 3, 4)] field]. Technologically, the Consortium will furnish innovative services and technologies (evaluation of SMs in terms of contents, mineralogical forms, *etc.* in steel slags based on an adaptive methodology demonstrating the feasibility of the proposal, development of a DST for the steel slag management sustainably; design assistance for steel slags, cost effective management using simultaneously a DST and a portfolio of technologies). To improve the health and safety performance of the operations, tests and laboratory research will be conducted according to the European and national norms safeguarding health and safety of researchers, which plan to develop technical standards for the equipment and work involving harmful substances.

Communication/dissemination (WP7) will begin immediately after the start of the project and will continue beyond its completion. Initial work will address project branding, Web-portal creation, Twitter tweets, LinkedIn, *etc.* in the early months of HYPASS. The Web-portal will be hosted on an institutional server to guarantee longevity beyond completion of the project. The HYPASS website will be monitored to quantify the project impact on internet users. Tweets will be at least once a month to announce events, results and progress. A project technical newsletter will be released every six months starting from M6. The newsletter will be made available on the web site and will be sent to a mailing list (industry, researchers, *etc.*) that will continue to grow during the project lifetime. LinkedIn content will be focussed at providing technical information for a professional/industrial audience. Networking will also be necessary to acquire contacts, information and helpful advice regarding results obtained with other similar projects, as well as to strengthen the relationships among the needs of stakeholders and end-users. The monitoring of different impact indicators, established considering that the main target audience of the HYPASS project consists of environmental managers and all operators dealing with steel slag dumpsites, is a necessary requisite to evaluate the socio-economic impact of the overall project. HYPASS is also addressed to all citizens, raising public awareness on the problem of contamination and on the way to find environmentally friendly solutions.

Project members will attend 1-2 trade association meetings a year for networking and visibility, and 2-3 scientific conferences for research exchange. Since, the partners of the Consortium are involved in other diverse networks; it will be easier to publicize the research results within HYPASS towards an expended Consortium for future submissions to European calls (HORIZON 2020 and EIT Raw Materials[33], for example).

By giving high visibility to the project's work and progress using both mass dissemination tools (like internet) as well as focused contact and exchange with stakeholders in the steelmaking industry (through trade-shows,

[33] EIT ("European Institute of Innovation and Technology").

exhibitions and conferences), the HYPASS partners plan to highlight the significant strategic, economic and environmental advantages of their technical approach.

Exploitation of the results will take many forms. Longevity and availability of the project results will be guaranteed by using the on-line repository Zenodo and by publishing all scientific works in trade and scientific journals. Patents may be filed on any new steel slag processing techniques. The principle mechanism for regulating all IPR issues will be the "Consortium Agreement", which will lay down all rules regarding partner's rights and responsibilities. HYPASS partners will defined foreground "Intellectual Property" (IP) and the rules governing its use by the Consortium and define the procedures and rules for use and exploitation of project results.

III.2. Scientific, technical, industrial, economic and policy impacts

Technical impacts

Previous tests carried out at BRGM showed that sequential grinding followed by multipolar magnetic[16] separation is a promising approach to recover high percentage of metals from numerous mineral matrices. Indeed, as compared to currently applied practices, this recent technology allow to achieve an optimal degree of liberation for targeted critical metals. Developing and adjusting this approach for slag processing, in combination with hydrometallurgy, is very innovative and promising as this could make more effective the treatment of large amounts of slags that are currently weakly re-used.

Industrial impacts

Landfilling has long been and is still used to dispose off large volumes of slags. However, increasing legal and environmental constraints progressively lead to limiting this practice. This gives "entrepreneurs" a margin for processing slags to recover valuable contents, while decreasing the total volume for disposal and turning waste into a re-usable material [*e.g.*, in the civil engineering[2, 3, 4] field], thus saving landfill costs. In addition, this will create revenues from the recovered metals and save resources for future generations.

Economic impacts

The economics of metal recovery from by-products such as metallurgical slags depends on many variables, in particular on metal prices. However, the new line of processing guarantees the recovery of considerable amounts of metals and materials with additional resource savings (preservation of materials, keeping metals within the materials cycle) and could ensure the sustainable supply of raw materials and particularly SMs.

The development of a more efficient of a more efficient, strategically sound, and environmentally friendly system for processing steel slags will give steelmaking industry a technology that they can potentially in the future market, build and operate, which in turn would create jobs in Europe to process the large number of slagheaps throughout the European Union.

Additionally, using phytostabilization as a capping strategy for slagheap rehabilitation will also trigger the restauration of a local biodiversity and the construction of a technosoil. Restoring biodiversity and stimulating soil formation could give a new value to derelict slagheap, as this is directly linked to ecosystem services that a land may deliver.

Policy impacts

The present project could help to reach the ambitious French and European recycling targets set in the Directives 2008/98/EC[74] on waste ("Waste Framework Directive") and 1999/31/EC[75] on the landfill of waste. They are still low in ascending European countries where the largest gains are possible.