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LCA-SUB

PLATEFORME SUR L'ÉVALUATION ENVIRONNEMENTALE ET LA PENSÉE CYCLE DE VIE POUR UNE UTILISATION DURABLE DU SOUS-SOL

FRANCE 2030

PROGRAMME DE RECHERCHE

SOUS-SOL

Résumé du projet en français (Non Confidentiel – 4000 caractères maximum, espaces inclus)

Dans le passé récent, l'Analyse du Cycle de Vie (ACV) a été de plus en plus largement mise en œuvre pour évaluer les impacts environnementaux potentiels des utilisations du sous-sol. Dans ce contexte, LCA-SUB (PC6 du PEPR SousSol) entend améliorer significativement à la fois les méthodes et les données mises en œuvre dans la Pensée Cycle de Vie, pour une évaluation environnementale cohérente, complète et représentative des utilisations du sous-sol. Cinq lots techniques (WP), et tâches associées, sont distingués dans LCA-SUB. Les WP1 et WP3 (développement de méthodes) traiteront des limites de complétude et de représentativité de l'étape d'Inventaire du Cycle de Vie (ICV), en particulier grâce à la combinaison innovante d'approches classiques de compilation d'ICV avec d'autres approches de modélisation et de collecte de données environnementales (par exemple par simulation de procédés, par télédétection, etc.). Les méthodes nouvellement développées seront testées dans les WP4 et WP5 sur des études de cas associées à l'exploitation des ressources minérales et d'énergie géothermique, et au stockage de CO_2. Elles permettront ainsi de développer des ICV et des extensions environnementales des tableaux Entrées-Sorties largement améliorés par rapport aux standards actuels de la littérature scientifique et des bases de données majeures de l'ACV et de l'Analyse Input-Output. Par ailleurs, les WP2 et 3 permettront de dépasser les limites actuelles de l'étape d'évaluation de l'impact du cycle de vie, essentiellement associées à l'incomplétude et l'incertitude des méthodes existantes (empreinte eau, impacts sur la biodiversité et les services écosystémiques, etc.). Les développements des WP2 et WP3 sur les méthodes de caractérisation des impacts environnementaux seront mis en œuvre sur les études de cas des WP4 et WP5.

LCA-SUB permettra ainsi de faire progresser de manière significative les méthodes de la Pensée Cycle de Vie pour l'évaluation environnementale, grâce à une combinaison innovante d'approches et d'outils. La mise en œuvre des méthodes développées dans LCA-SUB (dans les WP1, 2 et 3) à des études de cas de l'utilisation du sous-sol (dans les WP4 et 5) permettra d'élaborer de nouvelles données ACV complètes, cohérentes, et représentatives. LCA-SUB permettra par ailleurs de rassembler, structurer et renforcer la communauté de recherche ACV en France. Ce projet développera en particulier des approches et des modèles qui s'appuieront sur l'interaction avec d'autres PEPR, et auront des applications potentielles dans ces derniers.

LCA-SUB fournira ainsi une évaluation environnementale des perspectives offertes par l'exploitation potentielle future du sous-sol français. Cette évaluation prendra en compte, et discutera, des menaces et des opportunités en ce qui concerne les défis environnementaux à la fois locaux et globaux. LCA-SUB livrera en particulier une analyse sur les potentiels transferts d'impacts qu'impliquerait une telle exploitation du sous-sol français, dans une approche multidimensionnelle; c'est-à-dire en tenant compte de potentiels transferts d'impacts respectivement i) entre diverses catégories d'impact environnemental, ii) dans le temps et iii) entre les régions du monde. LCA-SUB développera des méthodes et des connaissances qui à terme soutiendront l'Observatoire français des ressources minérales pour les filières industrielles (OFREMI). En conclusion, LCA-SUB s'inscrit dans l'ambition du PEPR SousSol de poser les bases de ce que pourrait être une Stratégie Nationale d'utilisation et de préservation *durable* du sous-sol, lui permettant de jouer son rôle dans la transition écologique.

Résumé du projet en anglais (Non Confidentiel – 4000 caractères maximum, espaces inclus)

In the recent past, Life Cycle Assessment (LCA) has been increasingly widely implemented to assess the potential environmental impacts of the use of the subsurface. In this context, LCA-SUB (PC6 of the PEPR SousSol) intends to significantly improve both the methods and the data implemented in Life Cycle Thinking, for a consistent, complete and representative environmental assessment of the uses of the subsurface. Five technical Work Packages (WP), and associated tasks, are distinguished in LCA-SUB. WP1 and WP3 (method development) will deal with the limits of the Life Cycle Inventory (LCI) stage, in terms of completeness and representativeness, in particular thanks to the innovative combination of classical LCI compilation approaches with other approaches to modelling and collecting environmental data (for example by process simulation, remote sensing, etc.). The newly developed methods will be tested in WP4 and WP5 on case studies associated with the exploitation of mineral resources and geothermal energy, and CO_2 storage. They will thus make it possible to develop LCIs and environmental extensions of Supply-Use tables that are greatly improved compared to the current standards of the scientific literature and major databases of LCA and Input-Output Analysis. Furthermore, WP2 and 3 will make it possible to overcome the current limits of the Life Cycle Impact Assessment (LCIA) stage, essentially associated with the incompleteness and uncertainty of existing methods (water footprint, impacts on biodiversity and ecosystem services, etc.). The developments of WP2 and WP3 on environmental impacts characterization methods will be implemented on case studies in WP4 and WP5.

LCA-SUB will thus make it possible to significantly advance Life Cycle Thinking methods for environmental assessment, thanks to an innovative combination of approaches and tools. The implementation of the methods developed in LCA-SUB (in WP1, 2 and 3) to case studies of the use of the subsurface (in WP4 and 5) will make it possible to develop new, comprehensive, consistent and representative LCA data. LCA-SUB will moreover bring together, structure and strengthen the LCA research community in France. In particular, this project will develop approaches and models that will rely on interaction with other PEPRs, and have potential applications in them.

LCA-SUB will thus provide an environmental assessment of the perspectives offered by the potential future exploitation of the French subsurface. This assessment will consider, and discuss, threats and opportunities with respect to both local and global environmental challenges. LCA-SUB will in particular deliver an analysis of the potential impact transfers that such exploitation of the French subsurface would imply, in a multidimensional approach; that is, taking into account potential transfers of impacts respectively i) between various categories of environmental impacts, ii) over time and iii) between regions of the world. LCA-SUB will develop methods and knowledge that will ultimately support the French Observatory of Mineral Resources for Industrial Sectors (OFREMI). As a conclusion, LCA-SUB aligns with the whole PEPR SousSol ambition to lay the foundations of what could be a National Strategy for a *sustainable* use and preservation of the subsurface, allowing it to play its part in the ecological transition.

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1. Context, objectives and previous achievements

1.1. Context, objectives and innovative features of the project

In the context of Europe's ambition to deliver the Green Deal, access to mineral resources has been reaffirmed as a strategic security question by the EC[1]. In particular, the recent CRM Act[2] aims at establishing a framework for ensuring a secure and sustainable supply of critical raw materials, ramping up production in a "sustainable manner" and bringing the EU closer to their climate ambitions. Raw materials have a twofold role with respect to the 17 Sustainable Development Goals established by the United Nations (UN) 2030 Agenda (UN General Assembly, 2015), both hindering and contributing to their achievement (Mancini et al., 2019). In this context, there is nowadays a necessity to bring transparent and reliable data and methods to address the actual sustainability (here considering its environmental dimension) of such large-scale change of the potential production and supply of raw materials on the EU territory. It is required to anticipate the environmental assessment of the mineral resources extraction methods, and more generally of the subsurface use such as geothermal energy or gas storage, in order to contribute to the debate on the sustainable use of the subsurface potential.

In the last 20 years, Life Cycle Assessment (LCA) has been ever more widely implemented to assess the potential environmental impacts of the use of the surface in a cradle-to-gate perspective. Regarding mineral resources, LCA studies in particular enable: i) to provide an overall quantification of the potential environmental impacts of metals production, considering large-scale (regional, or even worldwide) data from operating plants; ii) to identify and discuss environmental impact hotspots along the process chains either at a fully operating stage or at a development stage; iii) to further analyse the environmental benefits of potential actions on these hotspots; and iv) to support the comparison between several options of processing routes, based on their environmental performance (e.g. Beylot et al., 2021a; Beylot et al., 2022; Lai et al., 2021a; Lai et al., 2021b; Bodin et al., 2017).

Yet LCA implementation in the context of the use of the subsurface faces overarching limitations, especially pertaining to 1) the Life Cycle Inventory (LCI) and 2) Life Cycle Impact Assessment (LCIA) steps (e.g. regarding mining and metal production: Beylot, 2021).

1) *Current limitations on LCI*

Recent scientific literature on the LCA of the production of raw materials (e.g., battery-grade graphite, lithium carbonates from brines) demonstrated that inventories, including in both scientific literature and standard LCI databases such as EF (Environmental Footprint), GaBi and ecoinvent, have so far led to underestimated carbon footprint values (Schenker et al., 2022; Surovtseva et al., 2022). LCAs of metal production generally currently lack completeness, consistency and representativeness (technologically, temporally, geographically), with insufficient granularity to account for the diverse impacts induced by diverse production routes in diverse geographical contexts (Beylot, 2021). Regarding CO_2 storage, a particular limitation of current LCAs moreover pertains to undetected or unmonitored CO_2 leakages over time, and the consideration of their impact in a dynamic approach. During the CO_2 storage stage, classical inventory data needed to perform standard LCA (e.g. utilities consumption, materials for infrastructures etc.) are expected to bring a relatively low impact over the very long storage duration, yet a specific focus needs be put on CO_2 emissions due to late-detected leakage. To the best of our knowledge, this aspect has never really been fully considered in LCA. Furthermore, LCAs are increasingly being performed at the earliest stages of processes development. Early assessments provide the greatest opportunity to influence design and ultimately

[1] EC, 2019. Communication from the Commission to the European Parliament the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions - the European Green Deal. COM(2019, p. 640 final.
[2] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661

environmental performance of a process. Yet, it is the stage with the least available data (e.g. regarding energy and reagents consumption) and greatest uncertainty, with so far only limited software capabilities to support such an assessment (Beylot et al., 2019). Finally, LCAs are generally often conducted based on aggregated average data that do not fully account for the effects of uncertainties and variability on the results (Pérez-López et al, 2020).

Limitations on LCI may be tackled through innovative approaches to couple LCA with other modelling approaches. This was recently successfully initiated in the context of LCA of raw materials production, e.g. with implementing process simulation and reactive transport modelling in order to derive more complete, consistent and overall robust LCI data (Beylot et al., 2021a; Beylot et al., 2022; Muller et al., 2022; Bodin et al., 2017). The development of satellite imagery over the past decade moreover provides access to a range of information on land use and transformation (including on the quality of vegetation via multispectral images, urbanization, differentiation of piles of waste, etc.). The analysis of satellite images has been successfully applied in the recent past, for example in the case of artisanal mining in West Africa (Ngom et al., 2022; 2023), or generally in a more global approach on mining worldwide (Maus et al., 2022). To our knowledge, there only exists few studies that aimed to use satellite images in the context of LCA; in particular, Islam et al. (2020), in a study that focused on a single case study of a copper-silver-gold mine. Satellites allow rapid, reliable, precise and objective monitoring, within the framework of a follow-up that can be done on a regular basis, with a level of detail (of disaggregation) that goes far beyond the "global average" classically (only partly) captured in LCA. The use of satellite images to complement LCI databases associated with mining activities therefore appears extremely promising to fill LCI data gaps in terms of representativeness (geographical, temporal), disaggregation and completeness.

2) *Current limitations on LCIA*

Limitations in impact assessment in the LCA field, in particular regarding the use of the subsurface, especially relate to uncertainties in current existing impact assessment methods (regarding toxicity, ecotoxicity, water use, mineral resource use) and incompleteness in methods (regarding biodiversity and ecosystem services).

Improvement is particularly needed for proper consideration of metal toxicity and ecotoxicity, in order to make their associated assessment more relevant and robust. Although multimedia fate models were developed for organic substances (best suited), the USEtox® method also uses this model to calculate characterization factors (CFs) for cationic metals. It should be noted that the following aspects are currently not addressed in the fate modelling of metals via the USEtox® model: i) existence of a background concentration due to natural presence of metals in ecosystems; ii) essentiality of some metals for life and iii) complex dynamic speciation of some metals in the environment. Until these specificities are not addressed, the potential toxicity impact assessment of metals (in LCIA) is to be taken with caution (Saouter et al., 2018).

Moreover, while mineral resource depletion has long been addressed through LCIA, recent methods have instead tried to capture the contribution of products and systems to mineral resource “losses” (or dissipation), either at the LCI stage and/or at the impact assessment stage (Charpentier et al, 2022 ; Beylot et al., 2021b). These methods pave the way towards more robust impact assessment relative to mineral resources, yet with simplifications or on the contrary complexity in implementation which make these methods still unfit for standardized implementation in the LCA field.

Moreover, LCA should not be misunderstood as a complete assessment of all environmental impacts. There is for instance an urgent need to come up with a widely usable LCIA method to evaluate impacts on biodiversity. The topic of biodiversity is clearly the second most relevant environmental challenge next to climate change, as has been demonstrated in the recent discussion at the United Nations Biodiversity Conference (COP15) that ended in Montreal, Canada, on 19 December 2022 with a landmark agreement. Further research is urgently required to continue the integration of biodiversity impacts into LCA by the means of ecosystem services (Pastor et al, 2022), with LCA needing predictive spatial modelling for biodiversity and ecosystem services (Chaplin-Kramer, 2017).

Furthermore, if temporality was carefully taken into account, the effects of greenhouse gases (GHGs) delayed emissions or CO_2 temporary storage in materials (e.g. CO_2-based chemicals) on climate change could be more impactful (Shimako et al., 2018). Leakage occurring in CO_2 geological storage might, at least conceptually, lead to similar effects and dynamic climate change indicators should be properly used to provide representative climate change impacts over a long time, representative of geological storage.

Finally, there is still need for development to actually capture – through LCA - how far production and consumptions compare to so-called planetary boundaries (PBs). The PBs represent a well-known concept, which helps identify whether production and consumption systems are environmentally sustainable in absolute terms, namely compared to the Earth's ecological limits and carrying capacity. Current studies (e.g. Sala et al., 2020) are affected by uncertainty mainly due to: (a) the intrinsic uncertainties of the different LCA modelling approaches and indicators; (b) the uncertainties in estimating LCIA-based PBs, due to the difficulties in identifying limits for the Earth's processes and referring them to LCIA metrics.

1.2. Main previous achievements

LCA-SUB will build on previous and on-going work of partners on Life Cycle Thinking (LCT) applied to the use of the subsurface.

BRGM was the leading partner on the environmental assessment of technologies for the extraction and processing of mineral resources, in four H2020 projects ended in 2019-2020:

i) INTMET (Integrated innovative metallurgical system to benefit efficiently polymetallic, complex and low grade ores and concentrates. https://www.intmet.eu/)
ii) ITERAMS (Integrated Mineral Technologies for More Sustainable Raw Material Supply, http://www.iterams.eu/);
iii) IMPACT (Integrated Modular Plant and Containerised Tools for Selective, Low-impact Mining of Small High-grade Deposits. https://cordis.europa.eu/project/id/730411);
iv) SLIM (Sustainable Low Impact Mining solution for exploitation of small mineral deposits based on advanced rock blasting and environmental technologies. https://cordis.europa.eu/project/id/730294/fr)

This led to several developments on LCA of metals production, including innovative approaches to couple LCA with other modelling approaches (process simulation and reactive transport modelling) in order to derive more complete, consistent and overall robust LCI data (Beylot et al., 2021a; Muller et al., 2022; Lai et al., 2021a; Lai et al., 2021b).

BRGM and UB are moreover currently collaborating in two other European projects pertaining to LCA of metals production: i) HiQ-LCA (EIT-funded; High-Quality Life Cycle Assessment for Battery Industry; 2023-2025), in particular in tasks dedicated to innovative and prospective LCI datasets compilation; and ii) TranSensusLCA (Horizon Europe; Towards a European-wide harmonised transport-specific LCA Approach; 2023-2025). Regarding mineral resources/metals production, LCA-SUB will also build on results from two projects involving CEA: respectively REPUTER (2020, French ANR) on the techno-economic (TE) and environmental assessments of NiMH batteries recycling; and a project with SNAM on the recycling of Li-ion batteries (2021-2022) in which the coupling of TE/LCA enabled the industrial to choose the best option in a multi-criteria approach.

Moreover, regarding mineral resources, LCA-SUB will build on achievements beyond the classical LCA scope. This particularly relates to:

- Achievements from IRD, namely in the following projects:

- LMI MINERWA: International and interdisciplinary project, led by David Baratoux, and involving several French and West African Laboratories (Côte d'Ivoire, and Senegal). Major research achievements relate to the development of AI techniques to monitor the footprint of artisanal mining activities in West Africa, and an interdisciplinary reflexion on the use of remote sensing techniques to support the regulations of small scale mining in West Africa (Abass Saley et al., 2021; Ngom et al., 2022; Ngom et al., 2023). The LMI MINERWA is strongly connected to the Africa Center of Exellences in Mining Environments (CEA-MEM/INPHB);

- ORVA2D: French project funded by the French Agency for Development (AFD) aimed at precisely characterizing the economic model of the value chain of post-consumer objects in six cities: Antananarivo (Madagascar), Bogotá (Colombia), Delhi (India), Lima (Peru), Lomé (Togo) and Surabaya (Indonesia).

- Achievements from Ineris. For years, Ineris has studied the physicochemical behavior of pollutants in wastes and in the environmental compartments, among others of metals from mining residues. Research results from different disciplines are used to develop assessment methodologies and tools and to provide environmental impact assessments of industrial activities, e.g. mining activities (Brunel et al., 2004; Munoz et al., 2009).

Regarding carbon storage, LCA-SUB will build on results from the terminated H2020 STRATEGY CCUS project, which aimed to support the delivery of carbon capture, utilisation and storage (CCUS) in eight regions identified as promising because they feature strategic elements, such as clusters of industry, potential CO_2 storage sites, opportunities for CO_2 usage, and options for hydrogen production and use. IFPEN was involved to perform economic and environmental studies. As a second core project in the field, the France Nord project (sponsored by the French Agency for Ecological Transition - ADEME - and major industries, as Total, GDF Suez, EDF, Air Liquide) studied the potential of geological storage of CO_2 in the Paris Basin. Under the project, partners (including BRGM) developed a method to estimate the geological capacity of storage in deep saline aquifers.

Regarding geothermal energy, LCA-SUB will build on the H2020 GEOENVI project (https://www.geoenvi.eu/), in which MINES Paris and BRGM were partners. GEOENVI aimed at assessing the environmental impacts and risks of geothermal projects operating or in development in Europe. The methodological framework and environmental approaches proposed in GEOENVI resulted in the development of a set of recommendations, as well as four parameterized LCA models for different geothermal systems (Blanc et al, 2020a, 2020b; Douziech et al, 2021; Parisi et al, 2020). LCA-SUB will build on two main outcomes of GEOENVI, namely the methodological guidelines for harmonized assessments of environmental impacts through LCA, and the protocol to build parameterized LCI and perform LCA for reference cases.

Finally, LCA-SUB will build transversally (that is, for mineral resources, geothermal energy and carbon storage) on the INCER-ACV project (MINES Paris, ended in 2021, ADEME-funding) which developed a protocol and a library in Python language (https://github.com/oie-mines-paristech/lca_algebraic) to build parameterized LCA models and to conduct uncertainty and sensitivity analysis in energy production systems.

2. Detailed project description

2.1. Project outline, scientific strategy

LCA-SUB intends i) to significantly improve methods, and ii) to tackle data gaps, for consistent, comprehensive, and representative environmental assessment of underground and mineral resources use in a life cycle perspective. The limits of current LCT methods, and in particular LCA as extensively described in the above section 1, will be tackled in LCA-SUB.

LCA-SUB is developed in five technical Work Packages and associated Tasks (see Figure 1 and following section 2.2 for a complete description). Limitations on the LCI step will be tackled in WP1 and WP3 (method development), in particular through the innovative combination of classical LCI compilation approaches with other modelling and data harvesting (e.g. through remote sensing) approaches. The newly developed approaches will be tested on case studies (in WP4 and WP5) leading to significantly improved LCI datasets and environmental extensions of Supply-Use tables; that is improving LCT methods beyond LCA only. Moreover limitations on the LCIA step will be tackled in WP2 and WP3, and further implemented on case studies (in WP4 and WP5).

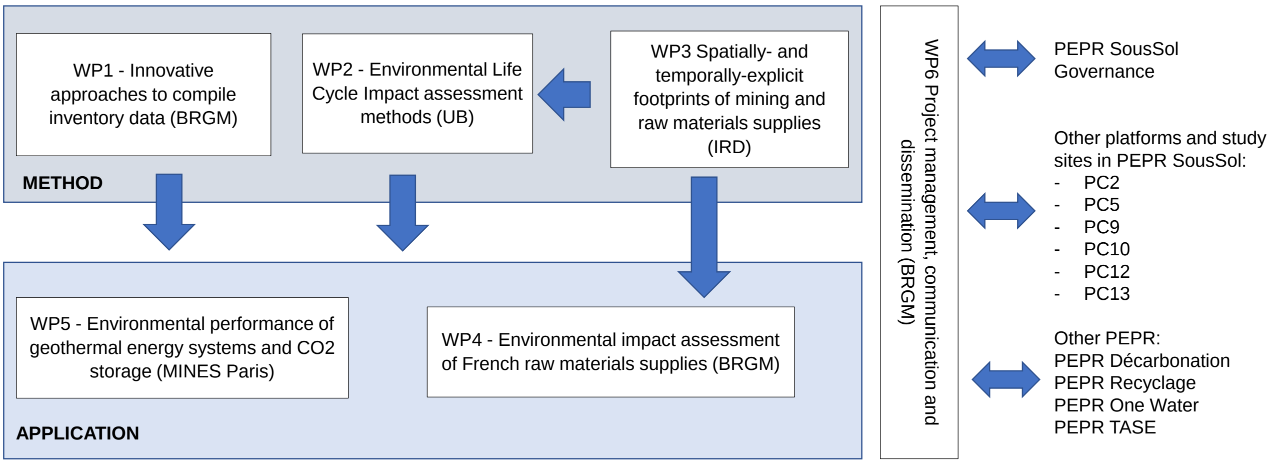

Figure 1: LCA-SUB project outline

The scientific challenges related to LCI that this project will tackle can be summarized as follows:
- developing predictive LCI-models to support the eco-design of processes at low-TRL for metals production;
- developing prospective LCI-models for geothermal energy and metals production;
- assessing unmonitored or late-detected CO_2 leakage from geological storage, in a dynamic framework;
- comprehensively and accurately assessing the emissions and resulting impacts of tailings management in the LCA framework;
- developing approaches and data for spatially- and temporally- explicit land and water footprints of mining at regional and world scales, and their implementation in LCT methods and tools (in particular, LCI datasets and Supply-Use tables);
- comprehensively and accurately capturing the impacts of underground and mineral resources use, with significant developments regarding the consideration of impacts associated with land and water use, biodiversity, ecosystem services, toxicity and ecotoxicity, mineral resources.

The implementation of these innovative methods will support:

- quantifying the environmental impacts of French raw materials supplies, putting in perspective case studies and scenarios of extraction in France and current impacts of French supplies, currently essentially outsourced;
- discussing perspectives offered by potential future exploitation of the French subsurface, both in terms of environmental threats and opportunities as to both local and global challenges.

Close interlink with other PC in PEPR SousSol has already been identified and promoted in this project proposal, in particular with:

- PC5 on “Innovative and *sustainable* technologies” (through WPs 1 and 4). LCA-SUB (PC6) intends to support the eco-design of the low-TRL technologies developed in PC5, driving them towards increased sustainability. Collaboration will be ensured through a post-doc position (BRGM) and a short-term contract (CEA) shared between PC5 and LCA-SUB.
- study sites, and in particular PC9, 12 and 13. Interlink with PC5 will ensure interlink with PC13 (Massif Central) and possibly PC9 (Rhine Graben), as samples will be drawn from these PC and processed in PC5. Case studies addressed in WP5 regarding CO_2 storage and geothermal energy production will be based on data from case studies in Aquitaine Basin and Rhine Graben, therefore potentially also opening the door to collaborations with associated PC12 and 9.
- PC2 on “Dynamic modelling of energy-economy-resources”, as it is LCA-SUB intention to develop life cycle environmental data and knowledge that may subsequently feed other types of modelling approaches, including economy-wide dynamic modelling approaches.
- PC10 Paris Basin study site, Task “Sustainability / LCA”. In this specific case it was agreed with the PC10 project manager (Isabelle Halfon, BRGM) that at least two meetings will be held between the team involved in the PC10 Sustainability task (Laboratoire Navier, Ecole des Ponts ParisTech) and the LCA-SUB core team.

2.2. Scientific and technical description of the project

WP1 Innovative approaches to compile inventory data (BRGM)

*Task 1.1 Predictive modelling to support eco-design of low-TRL processes (**BRGM**, CEA, UB)*

Firstly, a communicating pathway between process simulation and environmental LCA softwares will be created, in order to support eco-design of processes as developed in PC5. BRGM (in particular one post-doc position, shared with PC5) will combine existing simulations developed in previous projects (e.g. USIM PAC for mineral processing and/or SysCAD for biohydrometallurgical processes) with LCA software such as GaBi or SimaPro. The (CEA) PEPS numerical tool, currently under development, will be used to simulate a number of chemical process unit operations (with the help of one short-term contract engineer shared with PC5). The final objective is to combine both BRGM and CEA approaches from mineral processing to downstream processes simulations with LCA tools, in order to support eco-design of PC5 processes at early stage of development, through multi-criteria optimization. The developed predictive models and tools will be applied to case studies in WP4.

Secondly, UB will use and introduce to the consortium the process simulation software HSC Chemistry that has already been linked to OpenLCA software and related LCA databases in the recently finalised EIT-funded project TripleLink as support to the development of inventories, in contexts of limited knowledge on processes beyond literature data; e.g. exploitation of deposits of Lithium in Massif Central (link to PC13), using literature-based data on operating conditions. This sub-task will be led by UB (one post-doc position, also working on T1.3 and T4.1). These simulation models and tools will be additionally used as support to development of prospective inventory datasets in Tasks 1.2 and 4.1.

*Task 1.2 Prospective modelling to support decision-making (**MINES Paris**, BRGM, UB)*

BRGM and UB will first provide inputs on prospective LCI modelling as per their involvement in a parallel EIT-funded project (HiQ-LCA; 2023-2025). HiQ-LCA will in particular seek to perform i) a review of data, methods and tools for future-oriented LCI datasets, and ii) the development of future-oriented LCI datasets associated with e-mobility (including, battery raw materials). MINES Paris will build on this State-of-the-Art to propose a methodological framework to assess the sensitivity of uncertainty and sensitivity analyses in LCA to the characterization of inputs' uncertainties and variability. To do so, the steps to build a parameterized model for the flexible evaluation of potential environmental impacts of a system will be first specified. Then, an approach to assess the influence of the characterization of input parameters' uncertainty on the sensitivity analysis results will be developed, in order to ultimately support the identification of the key influencing input parameters based on global sensitivity analysis (GSA) approaches. Features of existing LCA tools, such as Brightway2 and the complementary library lca_algebraic, will be explored and adapted if needed to allow the computational implementation of the approach within a general GSA framework.

Outcomes of T1.2 will be implemented on mineral resources extraction and production in WP4 (BRGM and UB) and geothermal energy production in WP5 (MINES Paris).

*Task 1.3 Dynamic life cycle inventories to assess CO_2 leakage from geological storage (**IFPEN**, BRGM)*

This task aims at integrating CO_2 emissions due to leakage in LCA of geological storage, which so far are classically disregarded in the scientific literature. An alternative to the European Guidance on carbon leakage is to adopt a probabilistic approach to model leakage risks and their associated uncertainties to be propagated to the LCI, and therefore to the dynamic climate change impact calculations (interlink with Tasks 2.5 and 5.2). Unmonitored or late-detected leaks is a serious climate issue and new comprehensive estimators will be derived in this workflow to account for it in LCA. In addition, simple analytical models – based on Darcy flow in model porous media – and recently developed metamodels of CO_2 geological storage[3] could be used. If properly informed, the latter will provide an estimation of the storage dynamic response, and more precisely of the CO_2 leakage, in response to a given set of geological and physical criteria. Developments carried out in this task will help assessing any current or planned CO_2 geological storage project, potentially at the interface with study sites within the PEPR SousSol project (in particular Aquitaine Basin).

*Task 1.4 Long-term emissions from tailings management (**INERIS**, BRGM)*

This task first aims to carry out a critical analysis of current approaches to model emissions from tailings final disposal in LCA, in view of analysing: relevance of the emissions considered, parameters (composition, climate, etc.); nature of the residues and properties of the substances (solubility, mobility, etc.), data to estimate the quantities emitted (origin, uncertainties, distribution and expression of results, representativeness, etc.); evolution over time; consideration of operating practices and discharge reduction measures, including European requirements and "good practices". The analysis will focus in particular on i) the origin of the data and their relevance in view of European practices, and on ii) the identification of the most uncertain values. This work will support the development of improved models, in particular capturing the influence of improved practices on

[3] Duwiquet H. et al. 2023. ACT ACT!ON project, Deliverable 1.1 (*In preparation*)

tailings management, which is key to properly assess future mining projects in Europe. Task 1.4 will closely interconnect with Task 2.1 (on toxicity and ecotoxicity LCIA), and outcomes from these two tasks will feed the case studies “from mine to metals” in Task 4.1.

WP2 Environmental Life Cycle Impact assessment methods (UB)

*Task 2.1 Toxicity and ecotoxicity impact assessment (**INERIS**, UB, BRGM)*

A PhD student hired by UB will do a review of existing toxicity and ecotoxicity impact assessment methods, including USEtox®, for metals with regard to four questions: a) adequateness for assessing metals and coverage of which metals, b) which key specificities reported in scientific literature (see section 1 above: existence of a background concentration, essentiality of some metals for life, complex dynamic speciation) are addressed or not, c) possibility to extend to site-dependent archetypes-based characterisation factors, d) integrability into the mining footprint approach foreseen to be developed in T4.3. Based on this review the most promising methods, including USEtox®, will be used in at least one case study from mine to metals from those available in T4.1. This test in one or more case studies will allow UB and BRGM to come up with recommendations on which method to use in which situation in LCA applied to metal mining and refinery activities.

Once the initial review has been carried out, INERIS (post-doc on Tasks 1.4 and 2.1) will focus either on the issue regarding the potential regional impact assessment as defined as relevant for the PEPR SousSol “study sites” Massif Central (PC13), Rhine Graben (PC9) and French Guiana (PC11) or develop site-generic characterisation factors for metals not yet well covered and of relevance particularly for batteries or other applications for the energy transition. In the first case, a critical analysis will be conducted on French site-dependent archetypes of USEtox® based characterisation factors for metals and the toxicological and ecotoxicological impact assessment methods identified in the initial review by UB. In the second case, missing site-generic characterisation factors of metals will be identified and conditions for improvement will be determined. Other basic documents will be considered such as guidance documents and data developed and used for the evaluation of metals in the context of the European regulation on chemicals (REACH), e.g. Appendix R.7.13-2: Environmental risk assessment for metals and metal compounds (Echa 2008), REACH Metals Gateway (information system by Eurometaux). This task will closely interconnect with Task 1.4 in order to support the development of improved models useful for tailing management, and outcomes from these two tasks will feed the case studies “from mine to metals” in task 4.1. This work will be carried out in cooperation with UB and BRGM.

*Task 2.2 Water and land use (**UB**, BRGM)*

Water and land use are relevant impact categories in LCA but the maturity and overall acceptability of related LCIA methods are lower in comparison to e.g. Global Warming Potential. Therefore, a PhD student hired by UB will do a review of existing methods with regard to three questions: a) adequateness for assessing mining and refinery activities, b) alignment with the biodiversity and ecosystem services methodology used in T2.3, c) integrability into the land footprint and water footprint approaches foreseen to be advanced in T3.1 and T3.2. Based on this review the most promising methods will be tested by BRGM jointly with the land footprint and water footprint approaches in at least one case study from mine to metals from those available in T4.1. This test in one or more case studies will allow UB and BRGM to come up with recommendations on which method to use in which situation in LCA applied to metal mining and refinery activities.

*Task 2.3 Biodiversity and ecosystem services (**UB**, BRGM)*

In this task, a PhD student at UB will review existing efforts for the establishment of a methodology on how to integrate ecosystem services and driver of biodiversity loss for the LCA framework jointly with the review of *water and land use* impact assessment methods. This work will be implemented in interconnection with the LCA-TASE project (part of the PEPR TASE on renewable energies) if this project is funded, and then will enable to assess impacts on biodiversity within the LCA framework developed in LCA-TASE by INRAE in collaboration with UB. The methodology to be developed aims to be global and generic. The specific tasks of T2.3 will be to:

- Do a review of the State-of-the-Art of methodologies integrating ecosystem services and biodiversity into LCA for mining and refinery activities;
- Adopt a generic framework and test it for the case of mining and refinery activities. Options for the applications exist in T4.1;
- Give a special focus on the spatial dimensions of the applicability of the method ensuring close links with T2.1 and 2.2 as well as 3.1 and 3.2.

*Task 2.4 Mineral resources (**BRGM**, UB)*

This task will continue the joint work by BRGM and UB to derive an up-to-date approach to assess the impacts induced by mining and metal production on mineral resources, on the geological stock and in terms of losses to tailings and environment. T2.4 will build on the concepts of accessibility and quality of mineral resources, and on on-going work regarding innovative approach to account for mineral resource flows in LCIs (in particular in the context of the HiQ-LCA project; 2023-2025), and will address the topic of resource productivity.

*Task 2.5 Considering temporality in dynamic climate change indicators (**IFPEN**)*

Based on recent research[4,5] the purpose of this methodological task is to implement specific development of the Global Warming and Temperature Potential characterization factors (CFs). This will enable improved interpretation of the CO_2 leak impacts from geological storage for different and relatively long-time storage duration, on a yearly or 5-years basis, when combining these CFs with dynamic LCIs as developed in T1.3 and applied in T5.2.

WP3 Spatially- and temporally-explicit footprints of mining and raw materials supplies (IRD)

WP3 will develop approaches and data for spatially- and temporally- explicit land and water footprints of mining at regional and World scales (in Tasks 3.1 and 3.2). These approaches and data will be implemented to study a number of key metals including those key for the energy transition, in particular to feed standard LCI and Supply Use datasets (in T3.3., in interlink with WP4 and PC2).

*Task 3.1 Land Footprint (**IRD**, BRGM, UB)*

This Task aims at significantly improving the way land occupation and transformation are addressed in LCT approaches, taking advantage of the use of satellite images. T3.1 will be based on the time series of the Sentinel 2 satellites (visible and near infrared, Copernicus program of the EU) which

[4] Ventura A. 2022. Conceptual issue of the dynamic GWP indicator and solution. Int J Life Cyle Assess (2022). https://doi.org/10.1007/s11367-022-02028-x

[5] Batôt G. et al. 2023 Temporal Inconsistencies in LCA : Dynamic Climate Change Characterization Factors. SETAC Dublin 2023.

make it possible to study the dynamics of a mine site over time (potentially > 1 image/month) in the vicinity of the mine and on a regional scale. In general, satellite imagery is expected to provide data with a level of completeness and precision (including temporal representativeness) far superior to current standards of LCI datasets and environmentally-extended Supply Use Tables (used in Input Output - IO - Analysis). IRD aims to produce a database of the land footprint as a function of time (every two years) in two countries (in West Africa and South America) for selected metals. The database will also qualify the type of environmental degradation (classes to be defined).

This task will initially draw a conceptual framework for the integration, within LCT methods and tools (LCA, IO Analysis, MFA) of data derived from satellite images. This framework will cover issues of i) nomenclatures of land flows in LCT, ii) capabilities from satellite imagery to derive information of relevance for environmental assessment, building on studies at large-scale and at the scale of some sites, and iii) ultimately, constraints and potentials for integration within LCI and IO datasets (e.g. in terms of update). Regarding ii) on capabilities of satellite imagery, this work will start from (and go beyond) occupied land surfaces as already studied in the literature at large scale, e.g. exploring issues of land transformation, harm to vegetation, coverage of illegal mines, etc. The conceptual framework and interlink with LCI and IO databases (in T3.3) will be led by BRGM (one PhD student). This framework will be tested on metals required for the energy transition (in particular, metals for batteries), in order to derive a spatially-explicit footprint associated with their exploitation.

In parallel, IRD will provide complements regarding dedicated sites (gold and energy transition metals), with more comprehensive and refined indicators. IRD will compare the physical flows entering and leaving the mining environment (water, energy, pollutants, ore extracted) with the impact of the mine, seen from space, at different scales. Footprint on vegetation cover (deforestation in forest areas), on surface waters, and on soils in savannah areas, will be assessed considering temporal variations. Approaches will also be developed to quantify the impact on soil quality, based on recent developments of onboard hyperspectral sensors (Ngome et al. 2022).

Finally UB will ensure a link with the work done in T2.2 and T2.3. Land footprint indeed means the generation of environmental impacts and has implications for the ecosystem services provided by the land use for mining. Moreover, a systemic approach based on a geographic information system (GIS), as done in T3.3, is needed to treat land and water footprint in a consistent way with regard to data management and footprint communication on mining and refinery activities as input for T4.3.

*Task 3.2 Water Footprint (**UB**, BRGM, IRD)*

On a global and even national scale, consumption of freshwater for mining and refining activities accounts only for a small portion of the overall water use, particularly compared to agricultural water consumption as well as other industrial sectors such as the energy supply industry. However, on regional and even local scale there are significant impacts on freshwater resources to be observed from the mining industry. This is the challenge that this task will address by applying a GIS to set up a comprehensive water footprint accounting and water scarcity assessment of lithium and other metals for batteries (in line with T3.1) to quantify the influence of mining and refining of metal production on regional water availability and water stress. This task is inspired by the work of Meissner (2021)[6] and will be carried out by a PhD student to be hired by UB to work in collaboration with IRD and BRGM. The scope of the GIS application will be in France, and for lithium and selected metals for batteries at international level for the most relevant parts of the respective supply chain. Important linkages exist to T2.2 and 2.3: through its effects on the quantity and quality of freshwater available, mining and refining causes environmental impacts and an adequate water management

[6] Meissner, Simon. 2021. The Impact of Metal Mining on Global Water Stress and Regional Carrying Capacities—A GIS-Based Water Impact Assessment. Resources 10, 12: 120. https://doi.org/10.3390/resources10120120

is essential to sustaining ecosystems and environmental services. Cooperation will be established with the PEPR One Water - project PC4[7] - that works on water footprint as well but with a focus on other water uses than from the mining sector. The first 18 months of the PEPR One Water PC4 will be devoted to workshops dedicated to the development of the concept of water footprint. Partners of T3.2 of LCA-SUB will take part to these workshops.

*Task 3.3 Linking material flows with land and water footprints in a LCT perspective (**BRGM**, IRD, UB)*

IRD will deploy a cross analysis of the physical flows and value chain (cf. Danino-Perraud 2021) of metals consumed in France and extracted in countries of the South. This contribution, which mobilizes methodological tools from both the physical sciences and the social sciences, will shed light on the growing tensions over mineral resources through a politico-industrial ecology (Newell and Cousins, 2015; Pincetl and Newell, 2017) of the energy transition. This work of territorialization of stocks and flows would focus primarily on lithium, but also potentially on other critical metals such as copper, nickel, cobalt and certain rare earths.

This T3.3 will characterize the socio-ecological hotspots of the supply chains considered. The approach combines ex-situ and in-situ work. For the ex-situ part, a data scientist will be recruited as a post-doc (2 years) to extract, analyze and model data from existing databases (ecoinvent.org, prosum.geology.cz, panorama.brgm.fr, minerals4eu.brgm-rec.fr, etc.; and other databases in preparation: FutuRaM, HiQ-LCA, etc.) with a view to reconstructing the sectors. Close interaction will be ensured with BRGM, which has co-developed several of these databases. The fieldwork will be based in particular on the ARTEMIS interdisciplinary research project, which focuses on the impact of lithium extraction on the Peruvian altiplano, in order to finely characterize the impacts on human and environmental health. In West Africa, the project will be able to rely on the multi-actor network and the data collected within the framework of the Laboratoire Mixte International MINERWA (https://miner-wa.org), an interdisciplinary project on the impacts of mining activity in West Africa (mainly gold).

In addition, BRGM (in collaboration with UB and IRD) will implement the data associated with land and water footprints within environmental extensions of Supply Use Tables. The most recent version of Exiobase (currently version 3) and PANORAMA tables will be considered for this implementation, at the time of start of this Task (that is, in 3 years from now). The full PANORAMA tables are not in a public version so far, but BRGM and UB were partners in the EIT-funded PANORAMA project and have engaged discussion with the lead partner (University of Leiden) for use of the PANORAMA tables in diverse projects, including in LCA-SUB. A similar approach will be adopted regarding the ecoinvent LCI database (current collaboration of BRGM and UB with ecoinvent in HiQ-LCA) and potentially other databases (e.g. EF).

Results from this T3.3 are intended to feed modelling in PC2 of the PEPR SousSol and help ground this modelling in specific territorial contexts. Moreover, links will be explored with study sites (Massif Central PC13 and French Guiana PC11) co-managed by IRD colleagues in order to reconstitute the supply chains corresponding to some of the metals targeted by these projects (W, Li, Ta, Au).

[7] PC4 OWMS: OneWater Multiple Sources Qualitative and quantitative water footprint, impacts on ecosystems and society for a comprehensive approach of cycles, interactions and monitoring

WP4 Environmental impact assessment of French raw materials supplies (BRGM)

WP4 aims to quantify the environmental impacts of French raw materials supplies, putting in perspective case studies and scenarios of extraction in France (LCA case studies in T4.1, in close interaction with PEPR SousSol PC5 and study sites), and current impacts of French supplies, currently essentially outsourced (as assessed in T4.2). Results will be eventually integrated (in T4.3) in order to discuss perspectives offered by potential future exploitation of the French subsurface, both in terms of threats and opportunities as to both local and global environmental challenges.

*T4.1 LCA case studies from mine to metals (**CEA**, BRGM, UB, INERIS)*

T4.1 will build on developments on predictive modelling to support steering the novel PC5 processes towards environmentally preferable outcomes at an early stage of development. This T4.1 is intended to support both i) process development in PC5 WP5 during the project, and ii) future upscaling of the technology after the project, providing with a solid basis on environmentally optimal design characteristics.

Predictive modelling approaches as developed by BRGM and CEA in T1.1 will be implemented on case studies, developed in close interlink with PC5, in particular on: scheelite (tungsten; PC5 and PC13 Massif Central); sulfidic ores (PC5 and Massif Central); and possibly Rare Earths (interlinked with PC9 Rhine Graben). The main case study considered by CEA will be the development of an alternative process proposed in PC5 WP3 & 4 for tungsten recovery from scheelite, including grinding and flotation steps to concentrate the ore followed by new approaches for leaching and purification. This new process will be compared to the conventional one (pressure leaching with sodium carbonate, precipitation of impurities, fractional crystallization of APT). This case study targets both reduction of environmental burden and cost optimisation (CAPEX and OPEX) in an iterative way. It will also integrate the consideration of impacts associated with the management of tailings as generated from the new minerallurgical processes, building on outcomes from T1.4 (INERIS) on the modelling of long-term emissions from tailings.

In this task also the inventories developed through process simulation by UB in T1.1 and identified from previous projects in T1.2 will be used. This will be particularly relevant for prospective case studies, e.g. exploitation of deposits of Lithium in Massif Central, using literature-based data on operating conditions to allow to carry out the process simulation. In addition, cooperation with industry will be sought for the case studies to substitute literature data as far as possible. This task is also expected to provide case studies to allow the testing of methods reviewed in T2.1 and T2.2 and developed in T2.4 and T4.3.

*T4.2 Assessment of French supplies: ex-ante LCA, ex-post LCA, and IO Analysis (**BRGM**, UB, IRD)*

Task 4.2 will take benefits from i) developments in parallel projects (e.g. HiQ-LCA), ii) T1.2 (prospective modelling), and iii) WP3 (spatially- and temporally-explicit footprints) to develop complete, consistent, representative (technologically, temporally and geographically), and reliable LCI datasets for raw materials in a global perspective. Both current markets (ex-post LCA) and prospective production (ex-ante LCA) will be addressed, considering a number of raw materials including in particular metals for the energy transition. Impact assessment will be performed building on developments as in WP2. Beyond the impact induced by global raw materials production, T4.2 will address the share induced by the French supplies. To this end, both bottom-up approaches (building on classical process-based LCA) and top-down approaches (building on IO Analysis as in T3.3) will be implemented and compared. This work will be led by BRGM (2-year post-doc involved in T1.2, T3.3 and T4.2).

*T4.3 Threats and opportunities associated with exploitation of the French subsurface: an environmental life cycle perspective in context of planetary boundaries (**UB**, BRGM)*

A PhD student hired by UB will address the research question on how to compare the carbon footprint with the mining footprint of energy intensive products like vehicles. The mining footprint is defined similar to the water footprint in line with ISO 14046 as a way of assessing potential environmental impacts related to mining. For this the environmental impact and footprint work done in T2.1 and in particular in T3.1 and T3.2 based on input from T2.2 and T2.3 will be aggregated and evaluated in the context of planetary boundaries (Rockström et al., 2009). This work will build on case studies in T4.1 and additional efforts with regard to LCA case studies from mine to metals with national and international supply chains carried out by BRGM embedded into battery and electric vehicles LCA available at UB. The PhD student will address the threats and opportunities associated with the exploitation of the French sub-soil from an environmental life cycle perspective in context of planetary boundaries. This will be done by preparing a comparative LCA study considering the impacts on planetary boundaries of three alternative scenarios of a product in which metals help to use a new technology that reduces the carbon footprint in the use phase. The three alternative scenarios are i) the old product without the new technology, ii) the product with metals that are mined and/or refined in France and iii) the product with metals that are mined and refined outside of France. That means T4.3 will address the challenge of evaluating the transfer of environmental impacts from global due to GHG emission versus local impacts due to mining either in France or abroad.

WP5 Environmental performance of geothermal energy systems and CO_2 storage (MINES Paris)

*T5.1 LCA case studies of geothermal energy systems (**MINES Paris**)*

MINES Paris will build a parameterized LCA model of geothermal systems considering a case in the Rhine Graben site (potential link with PC9) by considering a collaboration with industrial partners as Electricité de Strasbourg or Engie. Other regions, such as the Paris Basin (PC10), may be considered if available. The built model will be used to test the methodological framework proposed in WP1 (Task 1.2) to assess the influence of the characterization of input parameters' uncertainty on the sensitivity analysis results. Several alternative probability distribution functions representing the range of variation for each input parameter will be proposed. GSA will be conducted to identify the key influencing input parameters affecting the results on the model and provide recommendations on where data collection should focus to obtain relevant estimates of environmental impacts, in particular as support to future technologies currently at a low TRL.

*T5.2 Dynamic LCA case studies of CO_2 storage (**IFPEN**, BRGM)*

Task 5.2 will ensure integration of results from T1.3 and T2.4 in order to build a comprehensive dynamic assessment framework, either on a yearly or 5-years basis, for a few model case studies. Different storage and leakage scenarios will be considered (potential link with the PYCASSO project[8] and Aquitaine Basin Study site; PC12).

[8] Territory project in the South West France launched by the Pole Avenia in 2021

2.3. Planning, KPI and milestones

The tasks described in the above section 2.2 are organized according to the calendar below. The corresponding deliverables are listed, with the responsible organization and deadline in parenthesis.

		Year 1		Year 2		Year 3		Year 4		Year 5		Year 6		Year 7	
WP1	**Innovative approaches to compile inventory data**														
T1.1	Predictive modelling to support eco-design of low-TRL processes										D1.1				
T1.2	Prospective modelling to support decision-making					D1.2									
T1.3	Dynamic life cycle inventories to assess CO2 leakage from geological storage							D1.3							
T1.4	Long-term emissions from tailings management										D1.4				
WP2	**Environmental Life Cycle Impact assessment methods**														
T2.1	Toxicity and ecotoxicity impact assessment				D2.1.1		D2.1.2					D2.1.3			
T2.2	Water and land use														
T2.3	Biodiversity and ecosystem services						D2.3								
T2.4	Mineral resources									D2.4					
T2.5	Considering temporality in dynamic climate change indicators								D2.5						
WP3	**Spatially- and temporally-explicit footprints of mining and raw materials supplies**														
T3.1	Land Footprint							D3.1.1		D3.1.2			D3.1.3		
T3.2	Water Footprint								D3.2						
T3.3	Linking material flows with land and water footprints in a LCT perspective										D3.3				
WP4	**Environmental impact assessment of French raw materials supplies**														
T4.1	LCA case studies from mine to metals												D4.1		
T4.2	Assessment of French supplies: ex-ante LCA, ex-post LCA, and IO Analysis													D4.2	
T4.3	Threats and opportunities associated with exploitation of the French subsurface: an environmental life cycle perspective in context of planetary boundaries													D4.3	
WP5	**Environmental performance of geothermal energy systems and CO2 storage**														
T5.1	LCA case studies of geothermal energy systems					D5.1									
T5.2	Dynamic LCA case studies of CO2 storage												D5.2		

Table 1: LCA SUB Gantt chart

Deliverables

D1.1 Predictive models to support eco-design of low-TRL minerallurgical and metallurgical processes (BRGM, M60)

D1.2 Methodological guidelines for the application of sensitivity analysis in prospective modelling contexts (MINES Paris, M30)

D1.3 Report on “probabilistic” LCI based on risk assessment for CO_2 storage (IFPEN, M42)

D1.4 Final critical analysis report on specific cases identified as environmental impact hotspots of tailings management by LCA (INERIS, M60)

D2.1.1 Review of existing toxicity and ecotoxicity impact assessment methods submitted to scientific journal (UB, M24)

D2.1.2 Toxicity life cycle impact assessment characterisation factors for metals developed (UB, M36)

D2.1.3 Critical analysis of toxicologic and ecotoxicologic metals impact assessment and report on conditions for development of regional impact assessment or for improvement of site-generic characterisation factors of metals in Usetox® (INERIS, M66)

D2.3 Review of water and land use as well as biodiversity and ecosystem services impact assessment methods submitted to scientific journal (UB, M36)

D2.4 Report on mineral resources indicator in LCA (BRGM, M54)

D2.5 Methodological report on dynamic climate change characterization factors for long time assessment (IFPEN, M48)

D3.1.1 Map of the spatial extension of the mining activities footprint in two countries (Côte d’Ivoire, and Perou, for selected metals), with qualifications of the nature of land degradation (IRD, M42)

D3.1.2 LCI datasets of selected metals with improved land use accounting (BRGM, M54)

D3.1.3 Update of database on mining land footprint (IRD, M72)

D3.2 Paper on water footprint accounting and water scarcity assessment of lithium and other metals for batteries, submitted to a scientific journal (UB, M48)

D3.3 Land and water use in environmental extensions of Supply Use Tables (BRGM, M60)

D4.1 Coupling process simulation and LCAs - Report on methodology + case study (CEA, M72)

D4.2 Paper on impacts induced by the production of raw materials supplied to France, submitted to a scientific journal (BRGM, M78)

D4.3 Deliverable: PhD thesis on the threats and opportunities associated with the exploitation of the French subsurface from an environmental life cycle perspective in context of planetary boundaries (UB, M78)
D5.1 Parameterized model for the LCA results of geothermal systems in France (MINES Paris, M30)
D5.2 LCA report for a few model case studies (IFPEN, M72)

KPIs
KPI1: "SUB LCA LCIA method" (for toxicity, ecotoxicity, land, water, biodiversity, ecosystem services, mineral resources and climate change impacts) for implementation to case studies
Means of verification: set of characterization factors published in scientific journals and in reports

KPI2: at least 5 LCA case studies associated with the use of the subsurface (mineral resources, geothermal energy, and CO_2 storage)
Means of verification: published in reports and scientific articles

KPI3: Processing pipeline and tutorial for continuous monitoring of the spatial extension of the footprint of mining activities
Means of verification: published by IRD through a report at M48

KPI4: at least 12 articles submitted to scientific journals by year 7
Means of verification: Available in specialized journals – as open access as far as possible

KPI5: presentations (poster and oral) to at least 15 international/national conferences, by year 7
Means of verification: abstracts available in conference Books of abstracts

KPI6: 3 PhD students and 137 PMs of post-docs educated and engaged on tasks of the project
Means of verification: PhD theses available on https://www.theses.fr

Identified risks and mitigation measures

Risk (Impact High, Probability High): Difficulty to hire LCA scientists (PhD, post-doc)
Mitigation: Hiring young scientists specialized in other fields connected to raw materials and energy transition that will be trained on LCA at the beginning of their contracts

Risk (Impact High, Probability High): Difficulty to get LCI data
Mitigation: Collaboration within the project partner organisations with big projects (like EU ones) and with industry and other stakeholders through advisory committee and outreach. The LCA-SUB team will moreover complete the input data with existing databases and sources in the literature (technical reports and scientific articles), as well as with the application of sensitivity analysis to understand the influence of uncertainties and variability in the LCA results.

Risk (Impact Middle, Probability Low): Lack of interactions and collaborations between WPs and partners as the project is wide and there are numerous partners
Mitigation: Most of the partners are involved in several WPs. The project structure was intentionally designed to make tasks and WPs largely interconnected. It is moreover planned that the project management will develop efforts in the organization of transversal project meetings to facilitate interactions between WPs and between partners.

3. Project organisation and management

3.1. Project manager

Antoine Beylot has been a research engineer at the BRGM since 2011. His research activities focus on LCA and Input-Output Analysis, with application to raw materials (primary and secondary) production, including metals. He is an engineer of the Ecole Centrale de Lille holding a Master in Environmental Engineering of the Technical University of Denmark (DTU). He was a Project Officer at the Joint Research Center of the European Commission (JRC-EC) in 2018 and 2019. Back in 2020 at the BRGM, he is currently in charge of EU and French research projects relative to LCT applied to raw materials.

He acted/is currently acting as the BRGM project manager of the following projects:

- REACTIVITY (co-funding ADEME ; 2014-2016): *Politique de relance de la consommation et politiques de prévention et de gestion des déchets: antagonismes et synergies?*
- PCI (co-funding ADEME ; 2015-2017): *Progrès pour l'analyse du Cycle de vie de l'Incinération des déchets ménagers et assimilés en France*
- TranSensusLCA (co-funding Horizon Europe; 2023-2025): *Towards a European-wide harmonised transport-specific LCA Approach*
- HiQ-LCA (co-funding EIT Raw Materials; 2023-2025): *High-Quality Life Cycle Assessment for Battery Industry*

At the JRC-EC (2018-2019), he was involved in the following projects (DG ENV-funding):

- Indicators and assessment of the environmental impact of EU consumption
- Environmental Footprint and Material Efficiency (EFME 3)
- Technical support for the Environmental Footprint and the Life Cycle Data Network (EF4)

At the BRGM, he has been (and currently is) involved in numerous research projects, especially at the European level. In particular:

- H2020 INTMET, ITERAMS, IMPACT, SLIM (ended in 2020; see further details in section 2.1 "Previous achievements"),
- Horizon Europe FutuRaM (Future Availability of Secondary Raw Materials)

A list of publication is available at:
https://scholar.google.fr/citations?user=fAdCmvoAAAAJ&hl=fr
Google Scholar h-index = 21

3.2. Organization of the partnership

The consortium includes leading scientists in the field of developing LCA methodology and its applications for the use of the subsurface in France, and brings together a rich variety of institutions

BRGM is the French leading public institution in the Earth Science field for the sustainable management of natural resources (including mineral resources) and surface and subsurface risks. BRGM is actively involved as a coordinator and as a partner in several European and French projects that support circular economy policies and technologies for resources efficiency and environmental impacts mitigation. In particular, BRGM has recently had a leading role in the research and development of LCA approaches in several H2020 projects, supporting the eco-design of innovative solutions in the raw materials sector.

BRGM will act as the LCA SUB project coordinator, and will lead the following WPs and Tasks: WP1, Task 1.1, Task 2.4, Task 3.3, WP4, and Task 4.2.

UB is recognized at the international level for its knowledge on LCA, and after 10 years of existence of its group CyVi it acquired a lot of experience and expertise in developing LCA methodology and data. Key references are the GeoPolRisk tool and quality assurance for databases in emerging countries, as well as applications to chemical products like organic photovoltaic cells, materials such as especially battery materials as well as recycling processes. A key aspect is the work on the integration of environmental impacts into chemists and process engineer's decision-making for more sustainable solutions. Prof. Guido Sonnemann Guido (56 years old) will act as the LCA SUB project Deputy leader. He is a distinguished professor at the Université de Bordeaux with an H-index of over 40 and around 8000 citations. He heads the CyVi group on Life Cycle Assessment for Sustainable Chemistry at the Institute of Molecular Sciences (ISM UMR 5255).

Beyond supporting the project as Deputy leader, UB will additionally lead: WP2, Task 2.2, Task 2.3, Task 3.2, and Task 4.3.

MINES Paris – PSL University, centre OIE has worked on parameterized LCA models and sensitivity analysis for a long time and developed a framework to apply these approaches to renewable technologies such as photovoltaic systems, wind power or geothermal power (Besseau et al., in press; Douziech et al., 2021; Padey et al., 2013). Furthermore, to facilitate the development of parameterized models, as well as the analysis of the uncertainties and variability on the results, the lca_algebraic library (Jolivet et al., 2021) has been recently developed by the center OIE in Python programming language and is compatible with the LCA-specific library Brightway2. These tools were applied in the GEOENVI project to assess the environmental impacts of different geothermal systems. In addition, the Center OIE works actively in the dissemination of scientific knowledge in open access.

MINES Paris – PSL University will lead: Task 1.2, WP5 and Task 5.1.

The **Institut de Recherche pour le Développement (IRD)** is an internationally recognised multidisciplinary French public research organisation, working mainly in partnership with countries in the South and in the French Overseas Territories to achieve the Sustainable Development Goals. Geosciences Environment Toulouse (GET), a joint research unit of the CNRS, IRD, Toulouse 3 University and CNES, is a multi- and interdisciplinary research laboratory in Earth and Environmental Sciences attached to the Observatoire Midi-Pyrénées. The unit has a staff of 226, including 156 permanent staff and more than 70 PhD students and researchers on fixed-term contracts.

IRD will lead: WP3 and Task 3.1.

IFP Energies nouvelles (IFPEN) is a major research and training player in the fields of energy, transport and the environment. As part of the public-interest mission with which it has been tasked by the public authorities, IFPEN focuses its efforts on bringing solutions to the challenges facing society and industry in terms of energy and the climate, to support the ecological transition. In line with its historical expertise in geosciences, IFPEN's strategy focuses on new resources and uses of the subsoil, particularly to propose solutions for large-scale and secure CO_2 storage with a validated expertise throughout the storage chain, via numerous collaborative projects including e.g. the France Nord project (ADEME), ENOS (H2020, http://www.enos-project.eu/), and more recently Strategy CCUS (H2020, https://www.strategyccus.eu/)

IFPEN will lead: Task 1.3, Task 2.5, and Task 5.2

INERIS is the French public expert on industrial and environmental risk management. Its mission is to contribute to the prevention of risks caused by economic activities to health, environment, and the safety of people and goods. It works to expand its scientific and technical capabilities in the fields of accidental risk, chronic risk, and ground-level / subterranean risks (e.g. mining), and makes them available to public authorities, local authorities, and businesses to help them make the decisions best suited to improving environmental safety.

INERIS will lead: Task 1.4, and Task 2.1

CEA, the French Alternative Energies and Atomic Energy Commission, is a key player in research, development and innovation in four main areas: defense and security, low carbon energies (nuclear and renewable energies), technological research for industry and fundamental research in the physical sciences and life sciences. Drawing on its widely acknowledged expertise, the CEA actively participates in collaborative projects with a large number of academic and industrial partners. CEA will be involved in LCA SUB through its Process Research Department for Mine and Fuel Recycling (DMRC), which has a large experience in hydrometallurgy, especially in separations of elements and simulation of processes (PAREX+). One of its laboratories (LSPS) is dedicated to simulation of processes, and is currently developing a new tool (PEPS) for assessing costs of a process (CAPEX & OPEX).

CEA will lead Task 4.1.

3.3. Management framework

The project management, communication and dissemination will be performed through a dedicated WP (WP6) that complements the five technical WPs presented in section 2. WP6 includes all LCA-SUB management activities and will last for the entire project duration (74 months). It aims at ensuring efficient project management in compliance with ANR rules and at maximizing the use of resources toward the completion of project objectives and outcomes. BRGM, as overall LCA-SUB project coordinator, will ensure the overall project management and oversee communication and dissemination activities in close connection with the whole PEPR SousSol associated activities.

Antoine Beylot (BRGM) will act as the project manager. He will also be in charge of the scientific animation of this multidisciplinary project, in close collaboration with Prof. Guido Sonnemann (UB) who will act as deputy leader. They will get the support of the project steering committee, made of all the partners that are WP leaders in this project: IRD and MINES Paris, in addition to BRGM and UB. One LCA-SUB consortium meeting (in Orléans or Paris) will be organized every year. In addition, LCA-SUB partners (either the whole partners, or only the steering committee) will participate to the global PEPR SousSol meetings when required. LCA-SUB obviously has the ambition to contribute to the overall success of the PEPR SousSol. LCA-SUB steering committee (project manager, deputy leader and WP leaders) will regularly participate to meetings with the PEPR coordination team.

For the smooth start of the project, BRGM will quickly set up the consortium agreement with all partners and will be in charge of (1) governance of the partnership; (2) interfacing with the ANR, including the Grant Agreement implementation; (3) the definition of each partner activities and commitment; and (4) the definition of a data management plan. The project manager will oversee the quality throughout the life cycle of the project, by working closely with the responsible persons for WPs, and organizing project meetings at due dates.

Regarding communication and dissemination, the LCA-SUB consortium (and especially the BRGM project manager) will work in close interlink with, and will get the support of, the global PEPR SousSol management. The BRGM project manager will monitor the valorization of the outcomes of the project produced by all partners in the form of:

- Reports published on the project website for certain tasks
- Scientific publications as main outputs as far as possible open access
- Communications (through oral presentations or posters) at relevant conferences as far as possible within the available budget

Finally, the intellectual property will be treated in a classical way. The researchers/laboratories/institutions have the IP of the models and data developed outside PEPR. IP for developments within PEPR will be based on the respective contribution of the researchers. The scientific articles and referencing of the models and data will include all the researchers having contributed with their main institute, in the order of their respective contribution and with the PhD students as first signatory.

3.4. Institutional strategy

As stated in the **BRGM** scientific strategy for the next 10 years, reducing the environmental and social impacts of the use of raw materials, and the dependency of EU economies on them, is high on the government’s policy agenda. BRGM's scientific strategy has the ambition to link global economic and environmental perspectives, by using approaches such as mineral intelligence, LCA and the monitoring of material flows, with research and expert advice on supply chains. The contribution of the BRGM in LCA-SUB is fully in line with the Strategic Axis 1 of the “Roadmap of the Mineral resources and the circular economy (MINECO) Programme" as published in 2022: "*Characterize, analyze and model the parameters governing the life cycle of mineral materials to support the co-development of the circular economy and responsible mining*”. Moreover, following the recommendations of the Varin report, BRGM (acting as lead) created the French Observatory of Mineral Resources for Industrial Sectors (OFREMI) in 2022. **CEA** and **IFPEN** are core partners in this Observatory. It is one of the objective of the LCA-SUB project to perform research and develop knowledge that will eventually support the OFREMI. LCA-SUB will develop innovative methods that will eventually be replicable routinely in the OFREMI, after the end of the project.

Moreover the **CEA** Science and Technology Institute for Circular Economy of low-carbon Energies (ISEC), created in 2020, is dedicated to different topics linked with optimisation of resources, recycling and environmental assessments as support to decision-making. The CEA contribution in LCA SUB on coupling of an economic simulation tool with LCA is obviously in the heart of its goals.

IFPEN is a major player in research and training in the fields of energy, transport and the environment. In line with its historical expertise in geosciences, IFPEN's strategy focuses on new resources and uses of the subsurface. Geological storage, whether long-term and temporary, is one of the main focuses.

Rich in its committed communities, **UB** has implemented since 2021 a roadmap of environmental and societal transitions included in its strategic plan for 2030. The LCA SUB project is seen as a contribution for UB to stand up with its commitments in contributing to better assessment methods, and transitions with lower environmental impacts.

MINES Paris – PSL University hosts the department Energy and Processes, a pluri-disciplinary research department committed to work on innovative systems for the production and consumption of energy, which responds to threats related to climate change and the overall pollution on the environment and public health by developing and accessing new energy systems with high performance and limited pollution.

Assessing risks and impacts from mines post-exploitation and conversion is one of the objectives described in the 2021-2025 **INERIS**' Contract of objectives and performance'. The new research axis CORISTE aims to improve the integrated assessment methodologies associated with soil and subsoil pollutions, notably by a better knowledge of the fate and availability of pollutants in environmental matrices.

Finally the PEPR "SousSol Bien commun" is fully in line with the study of georesources and Contaminants-Environment-Health interactions, which is one of **IRD** GET lab's main research axes.

4. Expected outcomes of the project

High-impact scientific outcomes
LCA-SUB will enable to significantly advance environmental assessment through LCT methods. It is expected that LCA-SUB will push the frontiers of LCT, and LCA in particular, through innovative combination of approaches and tools (e.g. remote sensing). These significant scientific developments are expected to be published in high-level scientific journals. These methods will be tested on case studies, which will enable to develop new, improved (complete, consistent, representative) LCA data relative to the exploitation of the subsurface in France and abroad.

Thriving a French LCT research community
LCA-SUB is moreover an outstanding opportunity to gather, structure and strengthen the LCA research community in France. LCA and LCT have long been developed and implemented in other parts of Europe (Belgium, the Netherlands, Denmark, etc.). In the recent years, several French research organizations, partners in LCA-SUB, took a leading role in the EU regarding LCT applied to the use of the subsurface, through their participation to overarching EU projects in the field. It is expected that LCA-SUB will enable/reinforce the collaboration between these institutions, and additionally further strengthen and enlarge the French research community on this topic.

Linking with other PEPR
LCA-SUB will develop approaches and models that will build on interaction with, and have potential applications in, other PEPRs; namely PEPR Recyclage, OneWater, TASE and Décarbonation, Several of the partners of LCA-SUB are also (core) partners in these PEPRs (e.g. BRGM, UB and CEA in PEPR Recyclage; BRGM and IRD in PEPR OneWater; IFPEN and UB in PEPR Décarbonation; etc.). This positions LCA-SUB at a crossroad of the National Acceleration Strategy.

Policy support
LCA-SUB intends to deliver science-based environmental assessment on the perspectives offered by potential future exploitation of the French subsurface. This assessment will account for and discuss environmental threats and opportunities as to both local and global environmental challenges. LCA-SUB will deliver an analysis on potential impact transfers that such exploitation of the French underground would imply, in a multi-dimensional approach. That is, this analysis will consider potential impact transfers i) from some impact categories to others (e.g. climate change versus toxicity issues), ii) from one region of the World to another (e.g. extraction in France rather than abroad), and iii) from one generation to another (impacts and benefits in the short-, medium- and long-term, assessed through prospective and dynamic approaches). That is, LCA-SUB aligns with the whole PEPR SousSol ambition to lay the foundations of what could be a National Strategy for a sustainable use and preservation of the subsurface, allowing it to play its part in the ecological transition.

Moreover LCA-SUB will perform research and develop knowledge that will eventually support the French Observatory of Mineral Resources for Industrial Sectors (OFREMI), led by BRGM and launched in 2022. In LCA-SUB, the OFREMI will be a key lever to ensure outreaching to policy makers. LCA-SUB will develop innovative methods that will eventually be replicable routinely in the OFREMI, in particular after the end of the project.

Communication and dissemination

Firstly, LCA-SUB will develop its own communication and dissemination approach. Several participations to international scientific conferences are planned to communicate about the project results. Moreover the detailed description of the life cycle of certain key objects in the form of data visualization could support participative sessions of collective description of our sociotechnical attachments in order to allow concrete transitions towards increased sufficiency (see TRANSILIENCE project). Such participative schemes could take place within the Zone Atelier Pyrénées-Garonne (PYGAR).

LCA-SUB will moreover build on the actions undertaken in the PEPR SousSol transversal Governance regarding Communication and outreach. LCA-SUB will engage in the diverse actions planned as part of the PEPR SousSol Governance project, whenever relevant: e.g. regarding outreaching to the EC (in particular, JRC), participation to national and international workshops organized as part of the PEPR SousSol, whether scientific or targeting national authorities/Ministries, etc.

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