PEPR EXPLORATOIRES
PROJET CIBLE
2022

PROGRAMME PEPR SOUS-SOL

DOCUMENT PRESENTATION PROJET

TAEF

Acronyme	**TAEF**		
Titre du projet en français	*Prévision technique et économique*		
Titre du projet en anglais	**Technical and economic foresight**		
Mots-clefs	Economie, modélisation, minerais, produits-joints, externalités		
Établissement porteur	Université Savoie Mont Blanc		
Responsable du projet	**Aude Pommeret, professeur des universités**		
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Durée du projet	84 Mois		
Aide totale demandée	1.528k€	**Coût complet**	3 146k€

Liste des établissements du consortium :

Établissements d'enseignement supérieur et de recherche	***Secteur(s) d'activité***
Université Savoie Mont Blanc	***Economie***
Université de Montpellier	***Economie***
Rennes School of Business	***Economie***
Université d'Orléans	***Economie***

Organismes de recherche	***Secteur(s) d'activité***
BRGM	***Géologie***
Ineris	***Environnement industriel et risques***

Autres partenaires	***Secteur(s) d'activité***

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

L'élaboration de modèles et de scénarios dynamiques nécessite des données et une bonne compréhension du couplage entre des variables telles que les ressources énergétiques et matérielles, la consommation, le PIB/habitant, le déploiement des technologies, les impacts environnementaux et sociaux, les moteurs du marché mondial/local et enfin la réglementation et les actions juridiques/les politiques publiques. La plateforme se concentrera sur tous les aspects liés à l'extraction, à la transformation et à la consommation des ressources minérales afin d'alimenter la plateforme de modélisation dynamique. Les principaux objectifs scientifiques sont :

- Définir le concept de valeurs de référence du sous-sol pour quantifier le niveau soutenable d’exploitation du sous-sol et la valeur de référence des métaux stratégiques, les externalités qu'elle couvre et son utilisation dans les évaluations socio-économiques, en particulier des technologies décarbonées qui utilisent ces métaux comme matières premières.
- Développer une vision globale des cycles des ressources minérales et des analyses dynamiques des flux de matières liés à la transition énergétique afin de quantifier la quantité de chaque ressource minérale qui pourrait être extraite, circuler dans la technosphère et finalement être éliminée dans l'environnement dans un avenir proche.
- Intégrer l’approche économique afin de projeter les tendances des prix et les perspectives à moyen terme concernant les marchés des ressources minérales, en prenant en compte l’incertitude et l’existence de produits joints.
- Etudier le rôle de la réglementation publique, pour le développement de la géothermie couplée au captage et stockage géologique du CO_2 (CSC), de l’exploitation minière et du recyclage afférent, mais aussi lors de la conception des contrats de concession minière et de la supervision, ainsi que du droit de la concurrence, dans le but de clarifier les principaux compromis en jeu pour l’élaboration des politiques publiques accompagnant l’exploitation.

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

Building dynamic models and scenarios requires data and a fair understanding of the coupling between contrasted variables such as energy and material resources, consumption, GDP/capita, technology deployment, environmental and social impacts, global/local market drivers and finally regulation and legal actions/public policies. The platform will focus on all aspects around mineral resources extraction, transformation and consumption in order to feed the dynamic modelling platform. The main scientific issues are:

- Define the concept of subsoil reference values to quantify the sustainable level of subsoil exploitation and the reference value of strategic metals, the externalities it covers and its use in socio-economic assessments, in particular of decarbonized technologies that use these metals as raw materials.
- Develop a global vision of mineral resource cycles and dynamic analyses of material flows related to the energy transition in order to quantify the amount of each mineral resource that could be extracted, circulate in the technosphere and finally be disposed of in the environment in the near future.
- Integrate the economic approach to project price trends and medium-term prospects for mineral resource markets, taking into account uncertainty and the existence of joint products.
- Study the role of public regulation, for the development of geothermal energy coupled with CO_2 Capture and Storage (CCS), exploitation and related recycling, but also in the design of mining concession contracts and supervision, as well as competition law, in order to clarify the main trade-offs at stake during exploitation.

1. Context, objectives and previous achievements / Contexte, objectifs et réalisations antérieures

1.1. Context, objectives and innovative features of the project

As the Covid-19 and Ukrainian crises highlighted vulnerabilities in value chains, Europe must actively pursue a more strategic approach to access to resources as a key factor in reducing its dependence on critical raw materials. There is then a need for better knowledge-driven methods to improve estimation of subsurface properties, identification of potential sources of competition, tensions and conflicts, and potential technological solutions. The risks of physical disruption, rapid price changes and dependency remain at the heart of supply issues. PC3 aims at raising awareness in the economic community and its stakeholders about these issues, and at developing models and tools to integrate these risks in the management of mineral resources.

An interesting tool for both public decision on exploration/extraction (versus recycling) and complementing existing models focusing on demand would consist in a reference value of minerals, that would be broader than the market price. It would encompass the main externalities hence properly guiding socio-economic choices.

In addition, the renewed interest for investment in mining to produce a variety of underground resources, specific to a geo-site, suggests that joint extraction of multiple elements might enhance the profitability of the investment. Typically, these projects can rely on (1) the extraction of a mix of mineral resources like the lithium and kaolin (coextraction in the Imerys deposit at Échassières, Auvergne), (2) the co-extraction of mineral resources and energy (Electricité de Strasbourg and Lithium de France projects in Alsace). The potential for joint production when exploiting underground resources raises specific issues related to costs (scope economies, see Baumol, 1977), revenues' volatility and producers response to price signals. Such issues were pointed out in seminal theoretical papers in the 1970's in the context of co-production of energy (see Pindyck, 1982). The literature on the co/by-production of mineral resources (including minor metals) is more recent (see Fizaine, 2013, Redlinger et al., 2016, Nassar et al., 2015, Jordan, 2017). On the one hand, joint production of mineral or energy resources reduces the average cost of each single commodity, when fixed costs are shared on a larger output. Moreover, diversifying output is a source of internal insurance. On the other hand, joint production in mining implies that downstream markets for single elements are connected one another according to the geological characteristics of the site. Therefore, the supply in a single commodity-specific downstream market may prove to be inelastic, with implications for the volatility of equilibrium prices and firms' revenues on related mineral markets. Empirically, most recent econometric models also indicate that markets are likely to be even more complex (Jordan, 2017) and depend on the type of resources co-extracted, specific constraints of the deposits and the possibility of substitution.

Finally, public regulation could help provide the suitable incentive for the optimal use of subsoil, whether it concerns exploration and extraction, CCS and/or geothermal energy development. Designing contracts and public policies, also accounting for other objectives, like climate targets or recycling policies, will also be considered in PC3.

1.2. Main previous achievements

We propose to provide economic elements to complete the existing DyMEMDS (Dynamic Modelling of Energy and Matter Demand & Supply) model, including price dynamics. The research will also be based on those in progress within the framework of the ANR Scarcyclet: "Materials scarcity and recycling for the energy transition (project leader: Francesco Ricci, University of Montpellier) of which the University of Savoie Mont Blanc is one of the partners. In addition, partners have been supervising PhD thesis on economics and CCS (Université d'Orléans), mineral recycling (Toulouse Business School, University Savoie Mont Blanc and Université de Montpellier), and are working on the application of environmental economics to circular economy problems (Ineris).

2. Detailed project description

2.1. Project outline, scientific strategy

The analysis of the use of the subsoil must be done not only by studying the needs for subsoil resources (cf. PC2) but also by considering the characteristics of the supply and the functioning of the markets in general in order to deduce the correct price dynamics for these resources. This step requires to take into account the technological developments to be expected but also the dynamics of the economy, not only via the existing markets, but also via the numerous externalities, linked to these resources. There are many dynamic models of this type that link infrastructure, energy and resource consumption of societies, their economies, and environmental impacts, in order to guide political decision making, particularly around climate issues, including TIMES and POLES (https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_POLES), which have also been used (see the Quinet Commission 2019) to calculate the value of climate action by 2050. PC2 aims to build a model capable of assessing the future demand for Subsoil resources for French needs by 2050, for different national evolution scenarios, with a regional declination and a measurement of environmental impacts and some socio-economic indicators. The Targeted Project PC3 "Technical and economic foresight" aims at completing this approach, by providing elements of supply, price dynamics and externalities, that will complement the demand side approach of PC2.
Building dynamic models and scenarios requires data and a fair understanding of the coupling between contrasted variables such as energy and material resources, consumption, GDP/capita, technology deployment, environmental and social impacts, global/local market drivers and finally regulation and legal actions/public policies. The platform will focus on all aspects around mineral resources extraction, transformation and consumption in order to feed the dynamic modelling platform. The main scientific issues are:

- Define the concept of subsoil reference values to quantify the sustainable level of subsoil exploitation and the reference value of strategic metals, the externalities it covers
- Guide the use of such subsoil reference values in socio-economic assessments, in particular of decarbonized technologies that use these metals as raw materials.
- Develop a global vision of mineral resource cycles and dynamic analyses of material flows related to the energy transition in order to quantify the amount of each mineral resource that could be extracted, circulate in the technosphere and finally be disposed of in the environment in the future.

- Integrate the economic approach to project price trends and medium-term prospects for mineral resource markets, taking into account uncertainty and the existence of joint products.
- Study the role of public regulation, for the development of geothermal energy coupled with CCS, exploitation and related recycling, but also in the design of mining concession contracts and supervision, as well as competition law, in order to clarify the main trade-offs at stake during exploitation.

2.2. Scientific and technical description of the project

WP1: Constructing reference values for mineral resources
IREGE-USMB: general framework, accounting for biodiversity, geopolitics
INERIS: accounting for pollution (PC6), decommissioning of mines (PC8)
Rennes School of Business: biodiversity (Andy Dobson?)
City University of Hong Kong: geopolitics

Managing resources in a more sustainable way suggests the establishment of "reference values" representing the cost, for society as a whole, of the use of these strategic resources (environmental damage, resource scarcity), in order to integrate them into the evaluation of public policies in the same way as has been done for carbon and air pollution. This is consistent with the roadmap on the Circular Economy.[1] It is therefore a question of establishing "reference" values for resources, inspired in particular by the Quinet Commissions 1 and 2, which dealt with greenhouse gases, in order to properly value these resources and optimize their use. Hence, we will define the concept of the reference value of strategic metals, for it to be used in socio-economic evaluations, particularly of decarbonized technologies that use these metals as raw materials but also when choices need to be made between extraction and recycling.
We will first focus on some scope issues. This will first require some reflections (with PC1, PC7, and any part of the PEPR linked with Human Science) on the concept of common good. Second, we will determine the externalities to be considered in the reference value. We suggest the following task list:

Task 1: Impact on biodiversity
We will first study how to construct reference values for biodiversity (in relationship with PC6), to account for them when exploiting subsoil as called for by the Chevassus report (2009), that already contributed to its construction with a bottom-up approach and a cost-benefits analysis.
Task 2: Geopolitical effects
Local versus international extraction has some value as it reduces protectionism and/or military risk. However, it requires rising social capital at the local level to secure cooperation and improve acceptance and increase R&D.
Task 3: Environmental impacts:
We will gather environmental impact assessments of the extraction (in line with work done in PC6). The impacts will probably not be available for single minerals but for mining activities as a whole, and their impacts will need to be apportioned to the mineral being studied. Impacts will be monetized

[1] https://www.ecologique-solidaire.gouv.fr/sites/default/files/Feuille-de-route-Economie-circulaire-50-mesures-pour-economie-100-circulaire.pdf

into a single value to be integrated into the external cost of the mineral. This environmental component of the external cost of the mineral is likely to be context and case specific.
Third, we have to determine the economic evaluation methodology to be used. For instance, shall it be a cost/efficiency or cost/benefit framework? In the case of carbon, the tutelary value is calculated by adopting a cost/effectiveness approach as the cost to be paid to encourage the use of an alternative technology to achieve a given emission reduction. It can certainly be inspired by the value of carbon, though keeping in mind that contrary to carbon emissions, there is a “spontaneous” market price for mineral resources.

For instance, regarding biodiversity, the first step is to be able to measure biodiversity. CDC Biodiversité (from the Caisse des Dépôts et Consignation in France) and Carbon4 Finance have developed a Global Biodiversity Score that assesses the biodiversity footprint (or impact) using a simple metric: mean species abundance (MSA) per km². MSA describes the mean abundance of species in a given ecosystem relative to their abundance in the same ecosystem that is not disturbed by human activity. It ranges from 0%, corresponding to a completely destroyed ecosystem to 100% *i.e.* a pristine ecosystem. MSA.km² integrates MSA with the surface area and is read as follows: x MSA/km² is comparable to the loss of x km² of pristine nature. In addition, the GLOBIO model (developed by a consortium with the PBL, UNEP GRID-Arendal1 and UNEP-WCMC) can be used to provide pressure-impact relationships (also called cause-effect or dose-response relationships) for a number of pressures on biodiversity, referred to as the “GLOBIO cause-effect relationships”[2] and also scenarios of future global biodiversity loss. The Mean Species Abundance (MSA) is the metric used in GLOBIO cause-effect relationships.
Second step is to use a policy objective for biodiversity to derive a shadow price (our reference value) for biodiversity. Based on a politically defined objective for biodiversity conservation for France (or a smaller territory), the shadow price path for biodiversity that allows reaching this objective in a cost-efficient way will determine the reference value. This is in contrast with the partial attempts of the Chevassus report (2009) which was based on a cost-benefit approach. A parallel with the trajectory of the tutelary value for carbon (see Quinet, 2019) that has been set for France can be drawn. This top-down approach is opposed to the one initiated with the Chevassus report (2009) or used in the Efese (2018) sectoral reports that cannot provide a relatively unified evaluation. Our approach will be very rough in the sense that very strong assumptions will be needed, and it strikingly differs from the one consisting in counting species. However, we do believe that such an approach is needed to be operational and really obtain a value for biodiversity. In addition, it does not prevent from many refinements that could be later introduced in this framework, to improve the measure.

Finally, we will implement the defined methodology on a previously defined list of strategic resources.
One 2-year Post-doc USMB (A. Pommeret)
1 thèse USMB (A. Pommeret)+? (foreign university). Funding: ½ USMB

WP2. Price and mineral flows/stock projections
Université de Montpellier : theory, joint products
PSE : theory, joint products

[2] The pressures covered include for instance land conversion, fragmentation, encroachment, eutrophication and climate change for terrestrial biodiversity (Alkemade et al. 2009; Schipper et al. 2016).

Université de Pau: theory, joint products, IO
IREGE, USMB : joint product empirical approach, IO and empirics
RSB: joint product, IO and empirics
BRGM : new uses/technologies

Task 4: Extraction under recycling opportunities: theory and empirics

The development of recovery of metals from scrap and end-of-life products and their recycling raises new issues. Recyclers too, as raw materials producers, are confronted with the possibility to produce several chemical elements out of the composite end-of-life products (the urban mine). Hence, recycling as well is characterized by economies of scope and joint production. However, the composition of the urban mine is function of the design of industrial products, while the composition of primary mines is set by nature.

Even if there is currently no recovery of several chemical elements from a manufactured product hence generating by-products from recycling, this remains to be investigated for the future, in particular using projections which economists do, using dynamic modeling. Indeed, as recycling develops, urban mines may significantly replace primary mine which may drastically change the picture of joint production of chemical elements, i.e. their supply and prices. This is true even though first, perfect recycling loop for end-of-life manufactured products is not possible (see Valero et Valero 2019), and second, metals in low quantities in metal alloys currently exhibit very low recycling rates (see Graedel & Miatto, 2022). According to Vidal *et al.* (2021), aluminum, for instance, is currently nearly only primary product in China while the share of primary products in consumption would reach around 60% by 2050 according to their projections; it is already at 50% currently in the US. This would happen in the long term, after stabilization of the demand and once there is enough stock of secondary materials.

Hence, if the product design is stable over time, it can be expected that commodity prices volatility should diminish with the development of recycling activity: the share of the urban mine in total mineral production increases, resulting in an improved matching between the composition of the basket of minerals demanded and the composition of the total stock from which minerals are produced (the urban mine plus the geological mine). Such effects may significantly affect the commodities markets or even create the suitable incentives for the creation (or destruction) of some financial markets (with the corresponding contracts). Such projections need to be integrated in the computations of financiers and industrials like smelters, for them to derive their valuation computations based on capex, opex primary and secondary material costs, and plan their operations. That will cause the feedback effects responsible for the new equilibrium.

This would require working in collaboration with material flow experts from BRGM/Ofremi. Recent literature explores the combined sourcing of primary and secondary aligned with the objectives of energy transition material needs (see Ba and Soubeyran, 2023). Different methods, between the industrial ecology and economics fields, are used such as the dynamic material flow analysis (MFA), economic models and also input-output tables. For example, Northey et al. (2023) explores to model the primary exploration, mining and metal supply, in other words, it is one of the rare models of the metal supply and not metal demand.

Moreover, given the importance of fixed investment costs, mineral resource markets can feature imperfect competition, so that the joint production of output in the industry raises new opportunities for intertemporal strategic actions, such as market foreclosure. Hence, we aim at studying the role of public regulation, in the form of design of mineral concession contracts and supervision, as well as competition law, in the aim of clarifying the main trade-offs at stake.

This conceptualization shall produce empirically testable predictions, and may allow us to speculate on the impact of the most common policy regulations affecting product design, waste sorting, collection and treatment, and recycling. Currently, data on recycling allowing to design a straightforward test of the theory are unavailable. Therefore, our team plans to collect empirical data on the recovery and recycling activity, by building data sets from publicly available information provided by the industry and public administrations, while also promoting access to new data and information from actors of the sector by conducting case studies.

1 PhD : Montpellier (Francesco Ricci)+PSE (Mouez Fodha) (Florian Fizaine, Carole Haritchabalet and Raphaël Soubeyran in the PhD committee)

Task 5: Accounting for uncertainty

Commodities prices dynamic dependence structure between primary products and co-products has been extensively studied in the resource and agricultural economics literature (see Zhou et al., 2023; Song et al., 2022; Kim, 2020; Marowka and al., 2020; Shammugam et al., 2019; Jordan, 2018). Several commodities in agriculture and mining are indeed physically related to each other under two different circumstances: they are either jointly produced or jointly consumed (see Marowka and al., 2020 and Shammugam et al., 2019 for empirical studies on respectively agricultural commodities and metals markets). Such prices relationships systematically lead to arbitrage strategies from the producers which then influence in return the joint dynamics of the commodities prices (see Afflerbach et al., 2014).

In our project we would like to enrich the by-products economics literature by considering the effect of information heterogeneity about multivariate asset price dynamics (as done in Zhou et al., 2023) on the profit-maximizing extraction behaviour of mining companies. This would help in understanding the strategic decisions made by these companies under uncertain price joint dynamics or in presence of non-synchronous demand shocks on either the base or the minor metals considered in the Sous-sol global project.

1 PhD : BRGM +RSB (Guillaume) (A. Pommeret dans le comité de thèse). Funding: BRGM

Task 6: New uses/technologies

The dependence on metals induced by energy transition is pointed out by many studies including the recent reports from the IEA. New technological development is one factor that is considered by these models but with a high degree of uncertainty and with a heavy impact on material demand results. Any dynamic model that estimates the material demand in the future, as developed in PC2, has to be based on some assumptions of future technologies and its material content. This task expects to assess a technological watch of new devices/equipment/technologies and its material content and a systematized data collection stored in a harmonized way such as the ProSUM data model. Even though the PEPR sous-sol is a French project, European initiatives such as the FutuRaM project, the work done by Liang et al. (2022) and the ODYM model cannot be neglected (Pauliuk et al 2020), as well as work done in other PEPR such as hydrogen and TASE and AIDHY (whose partners include Ineris, with Jean-Marc Brignon's team).

The SURFER project (Monfort et al. 2021; Le Boulzec 2021) did a first significant work of compilation of material intensities for all energy sector equipment as well as recent works such as Liang et al. (2022). These works do not include new sectors such as the hydrogen and CO_2 storage and have

partial data on geothermal plants. Moreover, technologies such as the Li-ion batteries, e-mobility batteries in general, PV panels and the permanent magnets present significant changes in terms of material composition according to different subtypes and technologies. This fact can induce strong dependencies on some critical raw materials.
The goal of this task is to feed the dynamic model done in PC2 and ensure a technology watch of material composition. A particular attention will be done to uncertainties and the likelihood of some assumptions.
1.5 year Post-doc: BRGM. Funding: BRGM.

WP3. Public regulation
Université de Montpellier : contract design
University of Pau: contract design
ESSEC: contract design
Toulouse Business School and TSE : second-best effects of climate policies
INERIS : second-best effects of climate policies
Université d'Orléans : geothermal energy and CCS
BRGM : CCS & geothermal energy

Task 7: Exploration contract design

The design of mineral concession contracts and supervision of mineral projects raises a number of well identified economic issues. Mineral concession contracts can experience a hold-up problem where one party is unable to capture the full value generated by the project. There may be a lack of information regarding the quality and quantity of mineral reserves, making it difficult to determine the value of the concession and set appropriate terms for the contract (Martimort et al., 2018). Mineral projects also have significant environmental and social costs, which must be considered in the design of the concession contract and the supervision of the project. The allocation and supervision of mineral concessions can be prone to corruption, which can result in suboptimal contracts being awarded and ineffective supervision of projects. The potential for joint production when exploiting underground resources raises new issues in the design of concession contracts.
In a context where there is imperfect knowledge on the ecosystem as well as on the production potential, how should concession contracts be designed to ensure that firms have incentives to reveal the information that they gather by investing in exploration and development of the sites? This information concerns two distinct dimensions: on the one hand the production potential and its costs (the potential market value), on the other hand any other data allowing to improve the assessment of the environmental impact of the investment by the public administration (Hiriart et al., 2008, 2010). If the concessionaire finds out that the environmental hazard could be very high, but also that the market return from exploitation is high, how could the license be designed to ensure it reveals the information on environmental risks?
The problem is particularly severe and challenging when the scientific public knowledge about the ecosystem is imperfect. Then, the concessionaire's exploration activity could improve the public understanding of the ecosystem. Any hard evidence provided by the firm could contribute to progress in scientific knowledge. It would thus improve the potential assessment of environmental impact of future concession contracts. Hence, we aim at characterizing the optimal contracts by considering

experimentation or learning issues that play an essential role in structuring dynamic incentives (see Halac et al., 2016, DeMarzo and Sannikov, 2016, S He et al, 2017, Haritchabalet and Renault, 2006, Casamatta and Haritchabalet, 2007, Soubeyran and van Long, 2014). The improved understanding of the environmental and social impacts of mining from WP1 shall contribute to this Task.

1 PhD : U. Montpellier (Francesco Ricci)+ U de Pau (Carole Haritchabalet) (Jérôme Pouyet, Raphaël Soubeyran and Wilfried Sand-Zantman in the PhD committee)

Task 8: Extraction and recycling

Motivations for developing recycling activities are generally twofold. First, recycling allows relaxing various constraints on non-renewable resource use: scarcity, limitation imposed by climate change mitigation policies when extraction of these resources has a high carbon intensity or has potential environmental impacts. The second objective is to reduce waste production, which generates local or dispersed environmental degradations and whose management is costly for society, and which can also be unmanageable and cause irreversible damage. On the other hand, recycling minerals leads to renewed exposures, emissions and risks from these minerals, whereas technological progress might lead to the use of novel virgin less hazardous chemicals or materials. There is therefore a potential tradeoff between risks and benefits of recycling that needs to be integrated in the modelling of the circular economy of minerals to ensure better decisions on recycling policies for minerals.

These trade-offs do not seem to have been studied so far for minerals but have been to a limited extent for additives in plastics (see Brignon, 2021). Should expanding recycling found to be the optimal decision, its capacity and its efficiency are subject to technical constraints: substitutability between virgin raw materials and recycled materials, quality downgrading at each new recycling iteration… Some of these limits can be mitigated or relaxed thanks to dedicated R&D investments. Under a normative point of view, the regulator can implement a set of policies that can incentivize – directly or indirectly – the deployment of recycling devices. Direct actions are, for instance, waste management policies (waste tax…) or promoting policies for a circular economy (recycling subsidies, extended producer responsibility, norms…). However, alternative public actions, such as the climate policy through a carbon tax or R&D policies, can indirectly have positive impacts on recycling. The objective of this research project is to investigate, in a general equilibrium dynamic framework, the second-best effects implied by the implementation of such a policy-mix.

This task will generate some collaboration and cross-fertilization with WP1 and WP2, task 4.

1 PhD : TBS+INERIS

Task 9: Heterogeneous resources and optimal resource management

There is a large empirical literature documenting the relationship between natural resources and economic development (see Vanables, 2022 for a review). In particular, whether the endowment of natural resources is a curse or a blessing is still debated (Badeeb et al., 2017). The impact of natural resources is therefore multifaceted (Berman et al. 2021). In particular, the proper use of natural resource endowments requires the right mix of private investment, fiscal regimes and public spending to capture the benefits and mitigate the externalities of natural resource extraction.

This project aims to better understand the drivers of an optimal public management of natural resources, taking into account the heterogeneity of potential benefits and costs. In particular, agents

are likely to be affected in a different way depending on whether they are affected only by the extraction activity, only by the use of the extracted material, or both.
Specifically, the project will take advantage of two complementary strands of the economic literature. On the one hand, the large existing empirical literature on the economic impact of natural resource extraction (both at the cross-country and the within-country levels -- see Van Der Ploeg and Poelheke, 2019 and Lashitew et al., 2021) will help build and discipline an economic model by identifying and quantifying some key mechanisms at play. Second, the recent literature on optimal public policy design in heterogeneous-agent models (LeGrand and Ragot, 2022 and LeGrand et al., 2023) will be used to design optimal resource management policies in this quantitatively relevant model. Such a modeling will be useful to understand the issue of local (lack of) acceptability for an otherwise socially desirable projects such as a mineral exploitation, a deep geothermal energy project or CCS.
1 paper: no student but expenses

Task 10: The economics of CCS and geothermal energy

The CCS-geothermal coupling, which combines an energy resource with CO_2 capture and storage, is attractive. It is also suitable for 'small' CO_2 emitters (e.g. municipal incinerators), but raises the issue of matching CO_2 sources and geothermal reservoirs. In addition, the issue of space availability in urban areas must be considered in order to find an operator to implement these projects (see Galiègue et al., 2017). Our aim is to design an appropriate contract, with the right incentives, so that CCS-geothermal coupling can develop. Like any project involving the subsurface, the exploration and exploitation of geothermal installations are subject to risks (achievable water flow rate or fluid temperature below expectations, seismic risk in some specific contexts - e.g. Alsace). Such risks are already taken into account by insurance (and reinsurance) companies and should be integrated into exploration/development decisions. A real options approach may be appropriate, as the project can be broken down into several steps, each of which provides additional information.
1 PhD : BRGM+U.Orléans. Funding: BRGM.

2.3. Planning, KPI and milestones

WP	Task	Année 1	Année 2	Année 3	Année 4	Année 5	Année 6	Année 7
WP1	1							
	2							
	3							
WP2	4							
	5							
	6							
WP3	7							
	8							
	9							
	10							

Lecture notes:
Immediate start and long duration:

Defining reference values for minerals in Task 1 is a long-term project hence requiring the full 7years, with first a post post doc and then a PhD student on the topic. However, the study of the environmental consequences can start slightly later once the methodology has been determined.
The same is valid for Task 6 in which BRGM has to estimates the material demand for the future energy transition.
Immediate start:
Université d'Orléans has already started to work on CCS and geothermal energy and could immediately be operational on the topic.
Task 8 links Ineris and TBS that are already for collaboration. Beginning might be delay for 1 year to have enough time to recruit the PhD student.
Delayed start:
Université de Montpellier is very involved in ANR Scarcyclet, which is very valuable for this platform. However, for a time management reason, they would rather start working on Task 4 once Scarcyclet is over.
Task 5, 7 and 9 are new collaborations that may require some time for student recruitment and operationalization.

3. Project organisation and management / Organisation et pilotage du projet

3.1. Project manager

POMMERET Aude

50 ans, professeur des universités en science économique, 1re classe. Conseiller scientifique à France Stratégie, Membre du bureau de l'IMPT (Institut des Mathématiques pour la Planète Terre) et de la CNE2 (Commission Nationale d'Evaluation des recherches et études relatives à la gestion des matières et des déchets radioactifs). Editeur associé de la European Economic Review et co-éditeur de Resource and Energy Economics.

2021- : Scientific director for IREGE (=Co-Investigator) of the ANR ScarCyclet "Materials scarcity and recycling for the energy transition" (amount controlled 200k€).
2016-2018: Principal Investigator for the GRF project "Implementing environmental policy in a politically-constrained world Second best under uncertainty" funded (HKD 602k) by the Research Grant Council of Hong Kong.
2015-2017: Principal Investigator for the GRF project "Irreversible decisions and thresholds under specific uncertainty- Designing the energy source mix for electricity generation" funded (HKD 311k).by the Research Grant Council of Hong Kong.
2014-2018: Scientific director (= Principal Investigator) for the ANR project (200 K€) "Sustainably reducing energy poverty" linking 4 French universities, research teams in the US and in Canada.
2008-2011: Scientific director (= Principal Investigator) for the PREBAT project on « Greenhouse Gases Emissions Reduction and Energetic Efficiency in Buildings: Economic and Financial Dimensions », linking 5 research teams in economics and one research team in physics. This project is financed (80K€) by the French Ministry of Ecology and Sustainable Development and Planning.
2010-2011: Scientific director for IREGE (=Co-Investigator) of the ANR CLEANER (ChalLEnges for the long term economic ANalysis of Environment and natural Resources) (amount controlled: 40K€).
2011-2014 : Scientific Director for IREGE of ANR UNCERSD (taking into account UNCERtainties for Sustainable Decisions), (amount controlled: 30K€). The objective of this project is to define and use methods that allow taking into account the uncertainties surrounding decisions for cities management.

For BRGM Daniel Monfort would be the copilot of the project. He is already participating in projects about raw materials needs for energy transition (coordinator of HE MaDiTraCe project) and circular economy (ANR Scarcyclet, HE FutuRaM). By the past he participated to SURFER project with Isterre and ADEME.

3.2. Organization of the partnership

Partenaires : Établissements d'enseignement supérieur et de recherche

Partenaire 1 : Université Savoie Mont Blanc :

Economics modeling ; econometrics ; critical raw materials; recycling.

Aude Pommeret : responsable WP1 (et responsable du projet)
Description : voir plus haut
Université Savoie Mont Blanc
Professor at the Université Savoie Mont Blanc
Fields : environmental and energy economics; uncertainty ; macroeconomics.
Gilles Lafforgue, TBS Education and Toulouse School of Economics
Professor at TBS Education
Fields: environmental economics; innovation; recycling.
Florian Fizaine, Université Savoie Mont Blanc
Associate Professor at the Université Savoie Mont Blanc
Fields: critical raw materials; recycling; applied econometrics.
Mouez Fodha, Paris School of Economics and University Paris 1 Panthéon Sorbonne
Professor
Fields: macroeconomics; environmental economics; recycling
Lin Zhang, City University of Hong Kong
Associate Professor at School of Energy and Environment
Fields: political economy; applied econometrics; sustainability economics
Benteng Zhou, University of Luxembourg
Associate Professor in the Faculty of Law, Economics and Finance
Fields: Critical raw material, competition, recycling

Partenaire 2: U. de Montpellier

Microeconomics; Environmental and resource economics; Regulation; Industrial organization*
Francesco Ricci : responsable WP2
Université de Montpellier
UMR 5211 Center for Environmental Economics – Montpellier (CEE-M)
Professor at the Université de Montpellier
Fields: Environmental and resource economics; Critical raw material and recycling; Macroeconomic long-term dynamics.
Raphaël Soubeyran, INRAE
UMR 5211 Center for Environmental Economics – Montpellier (CEE-M)
Directeur de recherche at INRAE
Fields: Political economics; Microeconomics; Development economics
Carole Haritchabalet, Université de Pau et des Pays de l'Adour (UPPA)
UMR 6031 CNRS-UPPA Transitions énergétiques et environnementales (TREE)

Professor at the Université de Pau et des Pays de l'Adour
Fields: Industrial Organization; Economics of risk and insurance; Corporate finance; Environmental economics
Jérôme Pouyet, ESSEC Business School & THEMA-CNRS
CR au CNRS and associate professor at ESSEC Business School
Fields: Industrial Organization; Regulation; Incentives Theory.
Wilfried Sand-Zantman, ESSEC Business School
Associate professor at ESSEC Business School
Fields: Industrial Organization; Regulation; Incentives Theory.

Partenaire 3 : Rennes School of Business
Commodity markets, models with heterogeneous agents
Guillaume Bagnarosa, Rennes School of Business
Associate professor at Rennes School of Business
Fields: commodity markets analysis; applied econometrics
François Le-Grand, Rennes School of Business
Associate professor at Rennes School of Business
Fields: macroeconomics; theory; heterogenous agents' modeling.

Partenaire 4 : U. d'Orléans
Econometrie appliquée, CCS
Xavier Galiègue, Université d'Orléans
Associate professor at Université d'Orléans
Field : real options; microeconomics; CCS
Camelia Turcu, Université d'Orléans
Professor at Université d'Orléans
Field : applied econometrics; environmental & resource economics; international macroeconomics;

Partenaires: organismes de recherche
Partenaire 1 : Ineris
Environmental Economics
Health and environmental externalities of circular economy/recycling
Jean-Marc Brignon
Valentin Chapon

Partenaire 2 : BRGM, French geological survey
Geology, mineral resources, mineral intelligence, industrial ecology, CCS, geothermal
Daniel Monfort Climent
Geologist engineer, project manager.
Field: minerals for energy transition, environment footprint, material stock analysis
Christophe Kervevan
Geochemist
Field: CCS, geochemistry, geothermics

Partners' publications, in relationship with the project:

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Berman, N., Couttenier, M. & **R. Soubeyran** (2021). Fertile Ground for Conflict, Journal of the European Economic Association 19(1): 82–12.

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3.3. Management framework

General meetings every 6 months
No risk is anticipated, except for data collection. Back-up plan would be to rely on the existing literature for parameters' values.

Milestones consist in reaching the defined objectives. That will consist in

- A reference value built task by task,
- a price dynamics when accounting for joint products and uncertainty,
- an estimate of the need for minerals in the energy transition,
- public policies,
    - for optimal exploitation under agents' heterogeneity,
    - for optimal exploitation coupled with recycling,
    - for the development of CCS joint with geothermal energy,
- the design of exploration contracts when the environment is an issue

Valorisation will consist in:

- Publications in highly ranked journals: general science journal and specialized ones.
- Communication of the results in seminars and conferences as well as more broader audience events (printemps de l'économie etc.).
- Train researchers (postdoc and PhD students) that will become experts on the topic.
- Take part in the public debate: already in contact with the European Investment Bank on the topic

3.4. Institutional strategy

University of Savoie Mont Blanc: Partner of the research network UNITA stressing renewable energies and circular economy. The research team IREGE is already involved in ANR Scarcyclet: "Materials scarcity and recycling for the energy transition The IREGE researchers collaborate closely around the unifying theme "Environmental Choices and Innovations" within two main multidisciplinary thematic axes: Environment, Sustainable Consumption, Tourism and Innovation & Development of Organizations. They continue their actions around four main missions: produce knowledge about their scientific area of knowledge, enhance the knowledge produced in particular in the socio-economic world, provide support to the community, train in research through research.

U. de Montpellier: already involved in ANR Scarcyclet: "Materials scarcity and recycling for the energy transition". The research unit UMR5211 Center for Environmental Economics – Montpellier (CEE-M) is structured around four research fields. The project id relevant for two of such axes: "Preserving natural resources and biodiversity" and "Toward effective and equitable environmental governance". The University and the CEE-M operate within a collaborative framework I-SITE MUSE structuring research locally around three objectives. The current proposal fits with the aim of "Protecting: favoring the transition to an environmentally sustainable society". In the MUSE consortium research units specialized in fields beyond economics are also involved in the larger PEPR Sous-sol bien commun. The project allows the CEE-M and the University of Montpellier to promote the collaboration with three distinguished researchers, experimented in the methodologies that we plan to mobilize, strengthening the ability to train young researchers locally.

Université d'Orléans: Université d'Orléans (UO): leads the LABEX VOLTAIRE, which brings together the University of Geosciences and the CNRS laboratories, BRGM and INRAE, on exchanges between the subsoil and the atmosphere. It has enabled the financing of numerous doctoral and post-doctoral theses in the fields of energy, mineral resources and environmental economics, with a particular focus on critical metals and the impact of environmental regulations on international trade. The Laboratoire d'économie de l'Orléans (LEO) is also involved with the BRGM in national (ANR) and regional (APR) projects in the field of carbon capture and storage (CCS), geothermal energy and CCS combined with CCS, in which it has provided socio-economic assessments and expertise through doctoral and post-doctoral work and a dedicated junior chair.

Ineris has been commissioned by the French government to develop its activity around several axes, among which the energy transition and the safety and environmental impacts of the circular economy are major ones. Therefore Ineris develops its participation to research projects under these two areas. Within Ineris, the EDEN Unit (Economics and Decision Support) will be involved in the project. The EDEN unit (Economics and Decision-making for the Environment) carries out economic studies and develops decision-making tools in the environmental field, using such methods as cost/efficiency analysis and multi-criteria analysis. The Unit has carried out research to adapt these economic methods to circular economy problems, in the framework of European H EUROPE R&D Projects (CIRCULAR FLOORING, BLACKCYCLE).

BRGM is the French reference institution for subsoil sciences. The project will develop scientific knowledge and expertise on the economics and ecology of mineral resources and underground resources in times of climate crisis. An important objective of PC3 will be to explore the possible futures of technologically advanced societies, particularly on a French scale. Thus, the scientific results of this project will be of major importance to inform industrial and political decisions that will ensure an efficient, sustainable and responsible use of subsoil resources. BRGM is already engaged in ANR Scarcyclet project and Horizon Europe projects such as FutuRaM.

4. Expected outcomes of the project / Impact et retombées du projet

The four key contributions the project will provide are:
- a methodology for calculating reference values for mineral resources,
- elements affecting price dynamics that incorporate recycling and joint products,
- some desirable features of exploration contracts.
- data on material that are necessary for the development of new technologies (hydrogen, electric mobility…)

These four key contributions are intended to complement the "geologist" approach of the PEPR (notably PC2). They can also be used independently, i.e., they can be re-appropriated for other projects. In particular, the reference value could guide public decisions on exploration or extraction independently of its use in DyMEMDS, for example.

Finally, the low carbon national strategy is concerned with building the energy infrastructure essential to achieving greenhouse gas emission reduction targets, which requires substantial amounts of mineral resources need to be mobilized: an energy system powered by low-carbon energy technologies needs significantly more minerals, notably copper, silicon and silver for solar PV. There is currently no shortage of these mineral resources, but this project, by focusing on the value and the price dynamics of minerals and on CCS will help understanding how to keep pace with world's climate ambitions.

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