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DyMod

DYNAMIC MODELING

FRANCE 2030

PROGRAMME
DE RECHERCHE

SOUS-SOL

***Résumé du projet en français** (Non Confidentiel – 4000 caractères maximum, espaces inclus)*
Le Projet ciblé « dynamic modelling » vise à modéliser et scénariser les besoins et les potentiels en ressources du Sous-sol à Horizon 2050. Il vise également à combler les faiblesses des modèles existants, en fournissant un cadre analytique clair, ouvert et permettant à toute personne intéressée d'effectuer elle-même des simulations, en gardant la complexité des couplages et interactions. **Les objectifs généraux sont les suivants :** • Bâtir un modèle capable d'évaluer la demande future en ressources du Sous-sol pour les besoins nationaux à horizon 2050, pour différents scénarios d'évolution nationale. • Faire le lien entre scénarios nationaux et leur déclinaison régionale (ressources potentielles, infrastructure) et les replacer dans une évolution européenne et mondiale • Intégrer les impacts environnementaux, leurs rétroactions, en tenant compte de certains indicateurs socio-économiques • Simuler des évolutions tendancielles, avec évolutions technologiques et sociales de rupture, ou une crise • Rendre le modèle accessible pour les non-spécialistes et mise en situation : déclinaison en jeu sérieux. • Rendre le modèle accessible et collaboratif pour les chercheurs pour enrichissement continu et collaboratif

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

The Project "Dynamic Modelling" aims at modelling the needs and potentials of the Earth's subsurface resources for the period 2050. It also aims to overcome the weaknesses of existing models, by providing a clear, open analytical framework that allows anyone interested to carry out their own simulations, while keeping the complexity of couplings and interactions.

The general objectives are the following:

- To build a model capable of evaluating the future demand for Subsoil resources for national needs by 2050, for different national evolution scenarios.
- To make the link between national scenarios and their regional declination (potential resources, infrastructure) and to place them in a European and global evolution
- Integrate environmental impacts and their feedbacks, taking into account certain socio-economic indicators
- Simulate trend changes, with technological and social breakthroughs, or a crisis
- Make the model accessible to non-specialists and put it into situation: declination in serious game.
- - Make the model accessible and collaborative for researchers for continuous and collaborative enrichment

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Abbreviations used in the document:

PC = Projet Ciblé (13 projects in the PEPR Sous-sol bien commun). The present projet is the PC2
WP = work package
PEPR = Projet d'Equipement Prioritaire de Recherche
AAP = Appel à Projet (call for proposal). There are two calls for additional financing in the PEPR, one by the end 2023, the other two years latter.
GDP = gross domestic product

CNRS = centre National de la Recherche Scientifique. Pilot institution of the PEPR (30 000 employee).
BRGM = Bureau de Recherche Géologique et Minière (French Geological survey). Co-pilot institution (1000 employee).
IFPEN = Institut Français du Pétrole et Energie Nouvelles (2000 employee)
CEA = Commissariat à l'Energie Atomique (20 000 employee)
Isterre = Institut des Sciences de la Terre (250 employee)
GAEL = Grenoble Applied Economic Laboratory (120 employee)
IRIT = Institut de Recherche en Informatique de Toulouse (

1. Context, objectives and previous achievements

1.1. Context, objectives and innovative features of the project

The lifestyles of developed societies are based on the consumption of non-renewable energy and materials. In order to limit climate change and slow down the collapse of biodiversity, the world's socio-economic metabolism is bound to undergo profound changes, which will have a strong impact on the resource needs of the Subsoil. The stakes being very high, it is necessary to study the possible trajectories. The adequacy between the needs in subsoil resources and their availability must be analyzed in long-term scenarios. This step requires the modeling of energy and material systems as a whole. For example, a massive electrification of society implies building a new infrastructure for the production, transport, storage and use of energy, which requires an intensive use of energy and materials, generating different types of positive and negative socio-environmental impacts.
The analysis of socio-economic metabolism and subsurface needs must therefore be estimated using dynamic models describing the entire infrastructure of our societies, not only the subsurface infrastructures. Many such dynamic models are available, among them MEDEAS and WILIAM: Capellán-Pérez et al. (2020), https://www.locomotion-h2020.eu/locomotion-models/locomotion-iams/; World7: Sverdrup et al (2021); MESSAGEix-GLOBIOM: https://docs.messageix.org/projects/global/en/latest/overview/index.html#; GCAM (Global Change Analysis Model): https://jgcri.github.io/gcam-doc/overview.html; TIMES: https://github.com/etsap-TIMES/; POLES: https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_POLES,; REMIND-MAgPIE: https: //www.iamcdocumentation.eu/index.php/Model_Documentation_-_REMIND-MAgPIE; WITCH: https://www.iamcdocumentation.eu/index.php/Reference_card_-_WITCH; OSeMOSYS: http://www.osemosys.org/; NAVIGATE: https://www.navigate-h2020.eu/; NAVIGATE: https://www.engage-climate.org/; INVEST: https://www.engage-climate.org/. Each of these models has been developed for a specific purpose and has its own specific strengths and weaknesses. Nevertheless, they all have commun weaknesses for the analysis of subsurface needs at the national level:

- Capellan-Pérez et al, (2020) point out the lack of transparency regarding assumptions, detail of results and coupling of variables. The models are often focused on the economic evolution governed by price mechanisms, invisibilizing the reality and the "biophysical" dynamics, and the control of subsoil resources availability onto the dynamics.
- Traditionally, transition pathways are designed by using integrated assessment models (IAMs), which are based on economic transactions and the assumption of (partial) economic equilibrium in each time interval (typically 5a or 10a). As there are less than seven years left before crossing 1.5C with 50 % probability (https://www.mcc- berlin.net/en/research/co2-budget.html), transition models that allow modeling a fast dynamic change (i.e.,a system not in equilibrium) become necessary.
- Transition models (including IAMs and others) are usually "materials blind" (Michaux,2021c), in disregarding the physical requirements of materials and the dynamics of mobilization. The available models (expect World7) have difficulty in modeling the effects of resource depletion and the decline in quality that controls production cost-reserve links.
- They take little account of the environmental and social dimensions, apart from climate change (whose feedback on the economy is mostly modeled as a simple function of damage, fully compensated by monetary flows, which is not the reality).
- The available models are used in a prospective mode. Their capacity to reproduce past energy-mineral resources-infrastructure-GDP/inhabitants-impacts evolutions, since the Second World War, is generally not tested. Modelling is based on exogenous scenarios, which are themselves based on changes in technological progress and rates of penetration of technologies constrained by short time series. However, the potential for technological improvement is ultimately limited by thermodynamic limits that are approached with technological progress. The future potential for future technological improvement is thus not the same as that of the past.
- The geographical grid is very coarse, going down at best to the national scale, whereas the study of national uses of the subsoil requires a regional analysis.
- The models are written in various languages (C++, Vensim, Stella, python, Claire, etc), few are open source with an open source database, and few are able to link with external databases (input/output databases, Ecoinvent, etc).
- Almost none of the models have a graphical interface allowing an unfamiliar user to run simulations by himself, which limits the use to a group of specialists who then provide the results they consider to be the most significant, and which are hardly reproducible.
- None of these models introduces the possibility of a decision to change the trajectory of the scenario envisaged at the outset. However, political decisions and regulatory changes will be made according to indicators that change over time and cannot be predicted at the outset. The future trajectory will therefore depend on a succession of decisions that may deviate from the trajectory envisaged at the outset.

Moreover, society is represented by categories of actors (political decision-makers, citizens, experts, laymen, institutions, industrialists, etc.) who defend different issues (e.g. ensuring economic profitability for some, minimizing environmental impacts for others). These actors will not necessarily prefer the same scenarios to satisfy their respective objectives. Each stakeholder has only a partial representation of the way in which subsoil resource needs are determined, whereas the decision on which scenario to implement must involve a societal judgment of all these possible scenarios. To help a stakeholder to build his argumentation it is useful to have a support tool that, in order to estimate the subsurface needs, would describe as far as possible the complexity of the whole system, and not only the subsurface. A dynamic model is the appropriate tool that allows the different actors to appropriate a complex system with simultaneous play of many variables (biophysical, environmental, economic, political ...) and their evolution in time. To be useful as a support for a debate between actors, the complex dynamic model must be declined in a form that can be understood by all; we are thinking in this case of a model in the form of serious role-playing games (e.g. roles: State, company, legislator, associations, citizens, market regulator...).

The project PC2 "dynamic modelling" aims at filling the weaknesses of the existing models, by providing a clear, open analytical framework allowing any interested person to carry out simulations themselves, while keeping the complexity of the couplings and interactions. An effort will be made to develop modelling approaches rooted in the laws of physics, including the relevant feedback loops in the dynamic system, and integrating knowledge from geology,

The general objectives of PC2 are the following:

- To build a model capable of evaluating the future demand for subsoil resources for national needs by 2050, for different national evolution scenarios.
- To make the link between national scenarios and their regional extension (potential resources, infrastructure) and to place them in a European and global evolution
- Integrate environmental impacts and their feedbacks
- Be able to simulate trend evolutions and introduce technological and social breakthroughs, or a crisis
- Make the model accessible to non-specialists and put them into situation: gaming mode,
- Make the model accessible and collaborative for researchers for continuous and collaborative enrichment

1.2. Main previous achievements

Different models with different modeling philosophies and strategies are available at CNRS (Isterre and GAEL) as well as at IFPEN to deal with Subsoil issues in a dynamic way. Beyond the estimation of the Subsoil resource requirements, an important objective of PC2 is to take advantage of their respective strengths:

- Isterre has been developing for 4 years the biophysical models DyMEMDS (Dynamic Modelling of Energy and Matter Demand & Supply) built in the Vensim environment, and a version under Python (MATER: Multi-regional Assessment of Technologies, Energy and Raw materials) able to link the model to internal databases in SQL format and external ones (Exiobase and Ecoinvent). The development over time of the transport, energy, urbanization and agri-food infrastructure is calculated from 1960 to 2060 and by country according to the evolution of GDP/capita (Vidal et al., 2022; Leboulzec et al., in review), or for per capita demands in transport, housing, food and services, or for exogenous scenarios of energy. The energy and material requirements to make the products consumed in the country as well as some environmental impacts (GHG emissions and local contribution to global warming, soil footprint, water consumption) are then estimated. MATER continues to be developed in collaboration with Carbone4 and the Shift Project to model the impacts of energy transition scenarios.
- An alternative approach is used by the TIMES models which propose an optimization (cost minimization under CO2 emission constraints) of the energy system, and therefore of the deployment of different technologies. IFPEN has developed its own TIMES models: TIAM-IFPEN for the global scale, MIRET-EU for the European scale. TIAM-IFPEN has been used in particular during the ANR GENERATE project to estimate the evolution of the global demand for critical metals for different CO2 emission scenarios.
- POLES (Prospective Outlook on Long-term Energy Systems) is a partial equilibrium simulation model of the world energy system up to 2050 developed at the Grenoble Applied Economics Laboratory (GAEL). It is based on exogenous assumptions for the demographic and economic evolutions, for each of the major countries or regions of the world, but an endogenization of all the variables characterizing energy

consumption, transformation, production and prices. It presents a strong technological disaggregation (e.g. fossil energies, solar, wind, geothermal), and identifies technological trajectories presenting a minimal cost for a given climate objective. It is a sectoral equilibrium model by recursive simulation whose dynamics are given, from the initial year and then from year to year, by the staggered adjustments of supply and demand variables on the one hand and prices on the other. The scenarios produced with POLES feed the IPCC scenario database and POLES is one of the reference models used internally by the European Commission (Joint Research Centre IPTS-Seville) for the economic evaluation of climate policies (Criqui et al., 2015. Desprès et al., 2017).

2. Detailed project description

2.1. Project outline, scientific strategy

The objective of the PEPR Sous-Sol PC2 is to obtain regional estimates of supply/demand of subsoil resources until 2050. For geothermal energy, gas storage and urbanization, it is a matter of "simply" quantifying the subsoil infrastructures to be deployed and converting them into subsoil use volumes. For mineral commodities, the problem is more complex because it is necessary to know in detail the installed infrastructure and products used in France, their material intensity, their lifespan and their recycling potential. This information is necessary to quantify the quantity of primary and secondary (recycling) metals mobilized. Three approaches will be possible to set the dynamics:

- Reading of scenarios produced by other actors than the PEPR community, e.g. IEA, ADEME or others, which list at least the quantities of energy used by sectors (transport, industry, housing) and in the best case the evolution of infrastructures. It is then possible to convert this information into built surfaces, numbers of vehicles, train, boat and planes per type, volume of gas to be stored, etc. using the unit consumption or storage volumes.
- Estimation of existing infrastructures from GDP/capita using logistics functions calibrated on historical data by country (Vidal et al., 2022, Leboulzec et al., 2023). This approach, successfully used in DyMEMDS-MATER, gives trend evolutions for transport, housing, food, services, etc. It is then possible to modify the energy mix (electric vs. fossil energy), the intensity of use (e.g. average vehicle mileage, use rate or modal shift to other modes of travel). The advantage here is to integrate the scenarization into the model, which avoids using scenarios that were themselves calculated with a model that is not the one used to estimate the impacts, with a risk of inconsistency.
- Addition of a cost minimization function to define the technological mixes, in trend or not. This approach is complementary to point 2 since it gives a unique evolution.

PC2 aims at combining and eventually integrating these three approaches by coupling the existing models. To our knowledge, there is no model (even at the international level) having this flexibility and being able to reproduce past evolutions, which is necessary if we want to have a chance to say sensible things about the future. This objective will be possible thanks to the collaboration between Isterre, Gael, BRGM and IFPEN laboratories. In addition, we will develop approaches to link with the other PEPR PCs, the PC2 being seen as a tool to aggregate very diverse information:

- PC1 to take into account the social aspects, with a decisional aspect: a 50-year scenario is unlikely to be strictly followed, because beyond the resource and technological constraints, there are others that can generate systematic or sporadic opposition from citizens. Legal aspects and regulations (PC8 *"Legal regulations"*) may also change over time and alter the framework of the initial scenario. Finally, trade and especially imports may also change. It is necessary to be able to include them in the model, to be able to modify the initial trajectory and to simulate abrupt changes (e.g. economic crises simulated by an abrupt change of GDP/cap or flow disruption).

- The PC3 (*"Technical and economic foresight"*) for the material intensities of the subsoil technologies that must be integrated in the model (different geothermal and storage technologies, urban structures), and for the estimation of the value of mineral resources (long term price).
- The PC6 (*"Environmental assessment and Life cycle thinking"*) to better integrate the environmental and life cycle dimensions.
- Field studies (PC9 to 13) to go down in scale and test the model at the regional rather than national level.

2.1.1 The different modelling approaches

Dynamic modelling

- A predictive model for the subsurface cannot be restricted to the subsurface. It is necessary to integrate the socio-economic and technological evolutions that will control the level of use. The sectors covered by the model will be at least energy (consumption and production), transportation, industry and construction. The level of industrial detail of subsoil technologies and resource production (primary and recycled material, fossil and renewable energy) will be specified in consultation with PC3, PC6 and the regional field studies. The social dimension is much more difficult to integrate. The strategy envisaged is to create a variation of the model in the form of a serious role-playing game (WP3); this game will be used to support the societal judgement of the scenarios (multi-actor and multi-criteria evaluation of each scenario to meet the objectives of the actors), leaving the possibility for the players, whose objectives and interests often diverge, to make decisions during the simulation in the game, before the final date of the simulation
- The calibration of infrastructure evolutions and rates of technological progress will be constrained by historical data from different regions. For the future, two types of additional constraints will be introduced: i) thermodynamic limits that limit the incremental improvement capacity of a given technology and operating costs for decreasing qualities of resources (WP1.3), ii) disruptive evolutions that deviate the future trajectories from the trend situation.
- The model must be able to be used with a "What if?" approach. This means co-constructing the scenarios with the stakeholders and then giving the user the possibility to modify the scenario narratives (type of use of the subsoil, the infrastructure, regulatory constraints, etc.). Eventually, the model could be used to simulate trajectories that the user could define in a simple and intuitive way, i.e. by creating his own evolution scenario (WP4.1).
- The model must be understandable, transparent and open (open source and open data), coded in a language commonly used in science and capable of linking to accessible databases. The architecture must allow the addition of modules in an iterative way, especially economic and industrial sectors, without having to recode the core.
- The model must be backed up and linked to a database that is also transparent, referenced, remotely searchable in the form of adapted queries and controlled access rights (WP4.2).

Input/Output (WP2 et WP 3.1)

Flows at national boundaries will be estimated from I/O trade matrices, such as Exiobase. These matrices can be completed by adding specific flow data (MFA) for underground uses. Wherever possible, French regional flows will be compiled.

Aggregated Life Cycle Analyses and environmental impacts (WP1.3)

It is important to be able to follow the evolution of environmental impacts according to the chosen development scenarios in order to limit them. Environmental impacts will be quantified by coupling the biophysical model to LCA data (link with Eco-invent and complemented by PC6 for specific technologies and specific types of use addressed in SousSol). We will develop approaches to adapt the fineness of industrial processes to the less detailed granularity of the model. We will also develop approaches to include technological improvement of industrial processes (dynamic LCA) and regionalization. Finally, the environmental impacts can also be estimated from the Exiobase matrices, which allow regionalization of the impacts. A first test has been successfully conducted with MATER, which should be extended.

Energy intensity (WP1.3 et WP2)

The long-term price (value) of mineral and hydrocarbon resources is a function of the evolution of the quality of the exploited resources (ore grade and EROI), which decreases with exploitation (Vidal et al., 2022 and in review). This evolution is a function of the exploitation speed imposed by the country scenarios and resources at the global level. This is why the French model must be coupled with a global model. As for the resources, the embodied energies of goods and infrastructures will be estimated from the prices. This will allow to complete the LCA approaches and to make an empirical link between cost-price and energy.

Agent based modelling (WP3)

In addition to the approaches listed above, we propose the creation of an Agent Based Model (ABM) branch. This is a promising work because it will allow to explore a wider variety of scenarios, including components related to human and social sciences. It will also allow us to adapt the current models to serious games to make them more accessible and to integrate decision mechanisms during the simulations.

2.2. Scientific and technical description of the project

2.2.1 WP1 : Estimation of demand in subsurface resources and scenarios of energy

The development of energy infrastructure, transportation, building and underground uses for the urbanized part, geothermal energy and underground storage will be estimated by bottom-up approach, with two evolution drivers:

- the evolution of GDP/capita, which gives an assessment of the evolution of major energy consuming sectors (buildings, transport and industry). Knowing the infrastructure in place, the energy to be produced can be calculated for different assumptions of consumption that depend on the electrification of uses, intensity of use, progress in energy efficiency, and change in consumption patterns. The infrastructure of energy production can then be calculated
- an allocation of technologies by minimizing costs or by minimizing environmental impacts (WP1.3). Other material and energy consumption by chemicals, agriculture, pharmaceuticals, packaging or domestic appliances will be estimated by a top-down (aggregated) approach. The infrastructure will be transformed into material needs by using the material intensities and the anticipated technological progress. Recycling potentials will be estimated for imposed product lifetimes, scrap collection and recycling rates.

The study will focus on France, but the models will integrate other world regions and countries. The approach will allow us to estimate the global footprint of France in Subsoil use and to evaluate the import-export of materials, energy and environmental impacts for scenarios of delocalization or relocation of its activities. We will use the Exiobase input/output matrices that describe bilateral exchanges between countries for 200 consumption and production sectors. A preliminary study conducted at Isterre shows that the approach is possible but it needs further development. These approaches should ultimately allow us to discuss the vulnerability of France to imports in a global context.

Different coupling and benchmarking of available models will be done, to better identify their complementarities, types of input and output data, and underlying assumptions. A general objective of the coupling is to be able to generate scenarios of technology deployment calculated with TIMES or POLES approaches that can be read by MATER to evaluate the needs (and possibly prices) of raw materials.

WP1.1 : Soft coupling of TIMES and MATER models (Isterre-IFPEN): Post-doc PD1

While issues related to geothermal energy and gas storage can be addressed at the local level, the situation is different for mineral resources. These resources, as well as the associated value chains, are indeed unevenly distributed across the globe. In order to address the issue of supply and demand of mineral resources on a local scale, it is necessary to consider the entire value chain on a global scale.

The MATER model developed by Isterre can be used to model a local scale. It integrates the interdependencies between the different sectors modeled (for example, steel production will evolve with the demand for new vehicles). However, it requires input of deployment curves for each of the technologies modeled. Symmetrically, the TIMES model developed by IFPEN does not integrate a dynamic loop between supply and demand. For example, the demand for steel is an input to the model, and does not depend on the deployment trajectories of the different technologies. On the other hand, the TIMES models propose an optimization of the energy system, and thus of the deployment of technologies. By their very design, the two tools MATER and TIMES present strong synergies since the input data of one is the output of the other. In addition to these conceptual synergies, there are spatial scale synergies. The IFPEN tools represent the global (TIAM-IFPEN) and European (MIRET-EU) scales. MATER, on the other hand, has the global scale, but can go down to the local scale in a simpler way than the TIMES models. The coupling of the two tools can allow to go from the global to the local scale. Finally, complementarities are also to be expected on the side of the modeled value chains. In particular, MATER proposes a recycling value chain that is much more detailed than that modeled in the TIAM-IFPEN or MIRET-EU models. The objective is therefore to use TIAM-IFPEN and/or MIRET-EU to generate technology deployment trajectories, in particular by using the new objective function developed in subtask WP1.3. These scenarios will serve as input data for MATER. It will then be possible to loop back using the outputs of MATER (industrial demand for example) as input to TIAM-IFPEN/MIRET-EU.

The work will consist of adapting the levels of technological and spatial aggregation of the different models, the rates of technological improvement based on historical evolutions, as well as the evolution of the price of technologies and resources according to the learning curves and energy intensity approaches (see 2.1.4).

WP1.2 : Strong coupling of POLES and MATER models (GAEL-Isterre): Post-doc PD2

As in the case of the TIMES-MATER coupling, the POLES-MATER coupling will allow the endogenization of the allocation dynamics of energy consumption in the different sectors with an economic minimization constraint. Unlike TIMES, the code of POLES is available and we propose a strong coupling between the POLES and MATER models. The work will consist in translating POLES from Vensim to Python language, and in integrating the cost minimization into the structure of MATER. The coupling will make possible to estimate the dynamics of price, including the raw material long-term prices according to their cumulative consumption with the approach described in 2.1.1.4 and/or by using the results of the PC3 ("economic foresight"). The final modeling structure will allow for the estimation of the national need for primary and secondary material. The project will

also allow the modeling of renewable energy production and gas storage technologies as well as evaluation of the net CO2 emission trajectories.
The work will be done by a post-doctoral fellow familiar with both models.

WP1.3 : Environmental impacts and optimization of an energy system on environmental criteria (all PC2 partners, link with PC6) PD3

- Isterre is developing an empirical method for estimating embodied energy from price (Andrieu et al., 2022; Vidal et al., 2022 and submitted). The approach is based on the analysis of the relationship between these quantities (in MJ/euros), for a variety of products in different countries. For mineral commodities, the production energy is calculated as a function of the ore grade of mineral deposits. This approach reproduces both the long-term energy and prices observed from 1900 until today for 15 metals and mineral commodities. For semi-finished and finished products, the embodied energy/price ratio constrained by the Exiobase data is remarkably similar for about 100 consumer sectors. The variation of the ratio over time can be estimated from the historical evolution for ten world regions according to their GDP/capita evolution. Eventually, we hope to be able to estimate embodied energies of goods as a function of prices and GDP/capita. For a given energy mix, it would then be possible to estimate GHG footprints as well as other environmental indicators by producing and consuming sectors and countries.
  This approach is less accurate but complementary to the LCAs developed in PC6 to which they will have to be compared. In order to integrate the LCAs in the dynamic models, the different industrial stages of production will be aggregated in 3 stages of production of raw materials, semi-finished products and finished products. These stages will be specified for the particular technologies used for the exploitation of the subsoil.
  IFPEN's models optimize the total cost of the energy system under greenhouse gas emission constraints. However, there are several ways to achieve carbon neutrality and the economic criterion is not necessarily the most relevant to discriminate between them. The total consumption of resources (energy, subsoil, materials and other resources) can advantageously replace the economic evaluation. This implies collecting data on resource consumption for all the technologies modeled. It is also necessary to modify the objective function of the models and thus modify the core of the optimization. This will allow us to propose energy transition scenarios optimizing the consumption of one or more resources.
  The work will be conducted by PD3.
- A similar approach will be developed in the POLES model. The objective function will minimize the cost of the global energy system each year under constraints of greenhouse gas emissions reduction implemented by a carbon shadow price. The cost of environmental externalities will be included in the objective function based on the POLES/MATER coupling established in WP1.2 and the environmental constrains (pollution, water...) estimated for the considered trajectories. This approach will allow for the analysis of the combination of public policies. *The work will be conducted by PD3.*

2.2.2 WP2 : Estimation of local production capacities

WP 2.1. Regionalization (Isterre-BRGM-IRIT) PhD 1 + PhD 2’

In contrast to the demand in raw material and energy than can be satisfied by inter-regional flows, the production capacities depend on local parameters. The national demand scenarios (WP1) will have to be compared to local potentials (solar, wind, mineral resources, water, geothermal, type of subsoil and storage, possibility of urban extension, etc). This comparison requires the regionalization of models and the estimation of exchange flows of mineral resources and energy between regions, whether within one nation or between global regions.

The regionalization of models is a real challenge because it must take into account the local specificities such as renewable energy potentials, relief, availability and type of subsoil, socio-economic characteristics (industrial potential, transport and communication routes, current energy production, urban planning, population density, employment basin, etc.) as well as other cultural, regulatory and investment capacity dimensions. Two major difficulties are identified:

1) For the demand side and thus evolution of infrastructures, it is not certain that the GDP/capita-infrastructure-energy relationships used in MATER and validated at the level of nations or large world regions are directly usable at the sub-national level. In addition to the already used variables (population density & urbanization) that control the saturation levels of the infrastructures/cap versus GDP/cap logistic functions, other variables are possibly necessary to reproduce the historical trends observed at the regional scale. Such variables could be the average and extreme temperatures that control the type of construction and degree of isolation, the landform that controls the development of cities and exchange routes, or other parameters that have to be identified.
2) A method must be developed to estimate the future potentials of inter-regional flows. This method must be able to reproduce the magnitude and evolution of historical flows of commodities in ore and in exchanged goods reported in Exiobase for the period 1995-2015. A possible approach would be to describe these flows with Fick's laws, where the gradient is controlled by the difference between local demand and available resources of the exchanging regions, and the diffusion coefficient could be proportional to the transport cost, itself a function of the existing or to be built transport infrastructure, of the distance between production and consumption locations, etc. *The work will be conducted by PhD1*

To address the two points mentioned above, a great deal of work is needed to collect data and their historical evolution over time. These data are crucial to constrain the regional logistic evolutions and saturation levels (point 1), but also to estimate potentials, production and exchange capacities (point 2). At the subnational level, at least two regions will be studied, including Occitanie, in collaboration with PC13. This region is identified because some researchers from PC13 at GET laboratory in Toulouse are planning to get involved in data collection. A financial support for a PhD (2') has been demanded for this task by the GET laboratory to the region Occitanie. Another region will be considered, the Paris basin or the Rein Graben being probable targets, to be confirmed according to the available data. If time permits, other sites will be considered.
The ultimate objective of the regionalization work is to eventually couple the dynamics of demand with Geographic Information Systems including transportation infrastructures (material, energy), urban infrastructures, local availability of resources and renewable energy, and subsoil access potentials This work will be coupled with the one carried out in WP3.1, by another PhD (4') student financed outside of the PEPR.

WP2.2. Raw materials supply (BRGM) PhD 3

For the specific question of raw materials supply at the global scale, an effort will be dedicated to taking into account exploration investments and the life cycle dynamics of local extractive industry projects. This would allow us to consider the possible future unavailability of certain materials due to economic constrains and to create feedback loops to study substitution mechanisms and the transfer of demand to other available materials. These mechanisms are important for establishing development scenarios and trajectories, and for assessing the criticality of mineral feedstocks in a forward-looking approach. A financial support for PhD working on this task will be demanded by the BRGM and CEA through the call to projects organized by the PEPR at the end of 2023 and later.

2.2.3 WP3 Implementation and use of actors' decision models via role-playing, serious and playful game (BRGM-Isterre-Chaire science et jeu vidéo)

The aim is to create a decision component model, driven by the following 5 objectives: (a) to identify the list and respective role and stake of actors influencing – or influenced by - the system (legislator, companies, citizens ...), (b) to represent their features (structural level), (c) to represent the decisions that these respective roles have to take (behavioral level), via two inputs: (d) the interactions between these different roles and (e) the influence of the decisions taken by these roles on, for example, the energy transition and the physical flows that underlie it: flows of goods, of raw materials, of energy, of built-up area estimated in WP2. The first four objectives are fed by PC1 *"Building scenarios for the use of the French subsoil"*. The five one could be addressed by the coupling of the decision component with the tools and approaches developed in PC2.

WP3.1. Coupling of existing models with an Agent Based Model (Isterre-BRGM) PhD 4'

The existing models (MATER, TIMES and POLES) do not have the appropriate structure to be used in gaming mode, because gaming requires model able to simulate the actions and interactions of autonomous agents (individual or collective entities). These decisional entities can be individuals or organizations, or even, in some applications, technological units (e.g. cars or a trains, buildings, etc). In order to understand the behavior of a system and what governs its outcomes, agent-based models must be developed with two objectives: 1) integration of the geography and local resources of the regions of interest. This will allow a more precise evaluation of the possible flows of matter and energy between regions, 2) integration of components which are able to make decision.
The expected model developments will open the possibility to go down to the regional scale and offer tools for political and social decision making that are currently missing. The ABM model will also make it possible to explore different energy transition scenarios, taking into account the behavior of the various stakeholders and local environmental constraints. The work will be conducted in close collaboration with WP2 and WP3.2. The creation of an ABM is a central but risky objective of PC2 requiring specific skills and background in modeling and computer coding. We have identified a PhD candidate with the required profile and network: physicist by training, currently a research engineer at the Institut de Recherche en Informatique de Toulouse (IRIT).

WP3.2 Creation of a role-playing game based on the ABM model (BRGM - Isterre) - PhD 5

The objective is to allow actors to explore and analyze the consequences of the decisions they make during the simulation, which may lead to a deviation of the actual trajectory from the initial scenario trajectory. The game would also make the resulting coupled models of the project accessible to different audiences, including policy makers, scientists, and citizens. The connection between the game and the model (via ABM) will be as follows: (i) each human agent (a player) who wishes to play a given role will choose one of the computer agents that plays that role, and thus will be its representative in the model; this computer agent will be the bi-directional bridge between a player, who will manipulate aggregated indicators, and the model, which can also manipulate complex variables. A detailed reflection will be necessary to define specific indicators intelligible to decision makers and citizens, such as local emissions and consumption of resources and energy, water, land use, visual impact, investments, employment, etc. This requires a detailed study of the positions of the different actors, and a strong link with the PC1. The indicators will be the information the players will use to make their decision to modify the long-term trajectory initially foreseen in the "what if" scenario. The consequence of the decisions will be governed by the model's couplings, so that it will possibly have effects contrary to what was the player was expecting. It will then be possible (at the end of the game) to analyze the mechanics involved and the couplings that were not anticipated by the players. The goal is not to provide an expert and infallible decision support tool, but to make the players/decision-makers perceive the complexity of the couplings and the short-term decisions on the long-term evolution.
The PhD student recruited for this WP will work in close collaboration with PhD 4' and 2'. A candidate has been identified (physicist by training, familiar of sociological issues, currently doing a research internship at Isterre).

WP3.3. Creation of a multiplayer video game based on the dynamic model (Chaire science et jeu vidéo) Research engineer at Polytechnique

The aim here is to turn the scientific model, tested in the form of serious games, into a game accessible to all without any external intervention. The interest is to valorize the scientific work by democratizing the access to the model in a playful way. The creation of an open access version will be entrusted to professionals if they see the interest, but an upstream preparation is necessary. This task will be entrusted to the "science and video game" chair (Ecole Polytechnique-ubisoft) and partly financed in the form of an AAP (internal call to projects of the PEPR “Sous-sol bien commun”). The work will consist in

1) establishing the objectives of the game(s) according to the target(s) (Benchmark of comparable games, choice of the target(s), of the scope of the expected learning or awareness topics, of the game model, first estimation of the dimensioning),

2) establishing the specifications and the distribution to studios capable of producing the game (Formatting of the specifications, distribution and contribution to the recruitment). This step will require dedicated funding, which will be requested in response to the AAP.

3) supervising the work (support in the implementation of the methodology for the realization of the game, monitoring of the realization according to pre-established milestones, participation in intermediate user tests).

4) evaluating the results (participation in the final user tests and the diffusion).

2.2.4 WP4 Accessibility to data and models (all partners) - Research engineer at Isterre

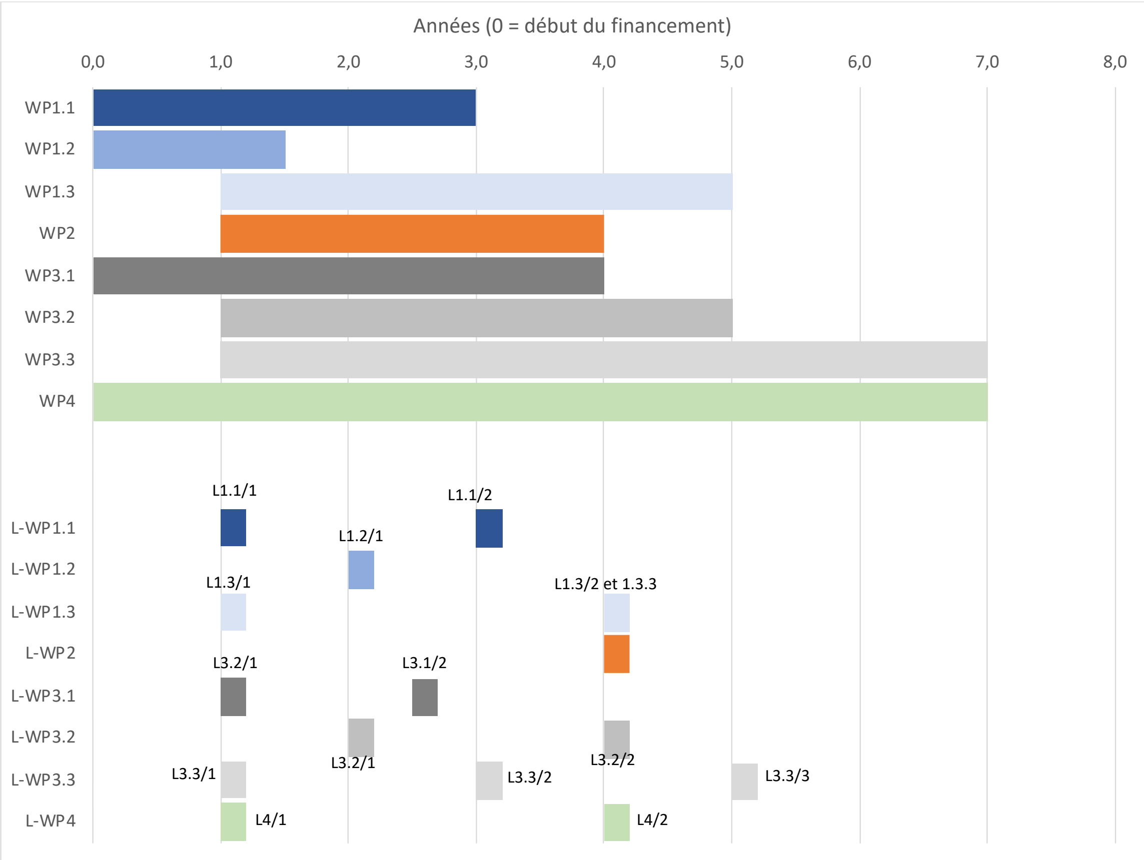
WP4.1. Graphical interfacing

One of the ambitions of PC2 is to develop dynamic models with a robust scientific basis, accessible not only to specialist researchers but also to an audience unfamiliar with modeling. This requires building graphical interfaces to run the models, modify assumptions and scenarios, access input data and results, and visualize them without having to enter lines of code. We will build these graphical interfaces for the DyMEMDS-Mater models and the model coupled with POLES using Vensim & Python tools. This work is not in the realm of research per se, but is absolutely necessary to democratize the use of the models by a non-specialist audience. In addition to the models, we will develop tools to help interpret the results. This could be in the form of automatically generated documents and/or figures, which will highlight the important results. This involves selecting the final results while hiding intermediate results. This is the classic approach of agency’s summary documents (such as the IEA) where the reader only has access to some of aggregated results. However, intermediate results are important for understanding the assumptions of the models. Models generate thousands of values and the question arises of how to visualize them. One solution is to organize all the results in a tree structure corresponding to the calculation logic, and to identify the links between the variables used. Another approach is to develop specific visualization tools, such as Sankey diagrams for exchanges between regions (Andrieu et al., in review). An effort to represent and call up the results is therefore necessary, which must be included in a graphic interface that is as intuitive as possible.

WP4.2. Production of a remotely searchable SQL database

A lot of data will be needed for the modeling work. The data will be fed into a database already existing within the framework of an Isterre-Carbone4 collaboration, which currently includes about a hundred technologies, fifty socio-economic indicators and thirty environmental indicators for the years 1930-2020, 15 world regions and different countries like France, the US, Japan and Germany. This database will be completed during the project and connected to other commercial (Exiobase) or environmental (Ecoinvent) databases. It is important to ensure the durability and accessibility of the database in accordance with the best standards. Eventually, we will propose an architecture and a user interface allowing access and sharing of data. Confidentiality and data ownership aspects will of course be handled in a transparent way. The PEPR “*SousSol, bien commun”* would be an opportunity to build a broader base with the contribution of geologists, economists, sociologists and industrial ecologists. Experience shows that data sharing is often a hard point, for various reasons including the potential for financial value of the data and sometimes its confidentiality, or interoperability. These points will be discussed according to the progress of the work and the openness of our collaborators and partners. The PC2 will initially remain on an independent database that can be integrated at any time in a larger framework, including the database developed in the PC4 "digital Earth Platform".

2.3. Planning, KPI and milestones



- Deliverable L1.1/1 (Isterre): Publication of the MATER model and its documentation - Scientific article in an international journal of rank A. *Risk: low*
- Deliverable L1.1/2 (IFPEN, collab IFPEN): Successful example of model coupling - description and illustration. The results will be communicated in the form of a scientific publication. *Risk : weak*
- Deliverable L1.2 (GAEL): Python code (open source) and description of the model coupling procedure. *Risk: medium, the main difficulty is the relatively short time allotted.*
- Deliverable L1.3/1 (Isterre, collab PC3): Description of the approach used to constrain the evolution of mineral resource prices as a function of deposit quality. *Risk: low*

- Deliverable L1.3/2 (Isterre, collab. PC6): Embodied energy-price relationships for manufactured products (energy intensity approach and from Exiobase input/output matrices): methodology, limitations and comparison with LCA. *Risk: medium, the main difficulties are 1) the conceptualization and coding of the approach and 2) the realization of the LCAs produced by the PC6*
- Deliverable L1.3/3 (IFPEN, collab PC6): Description of the optimization procedure of an energy system on environmental criteria + example of optimization for France in Europe with the MIRET-EU model. Scientific publication. See if the work is also done with POLES. *Risk: High: Lack of data necessary to evaluate the objective function; problem of convergence of the optimization with the new objective function.*
- Deliverable L2 (Isterre, Collab. PC8) : Dynamic modeling for a region, in priority Occitania. The type of modeling (ABM or not), the type of subsurface resources considered (at least some mineral resources) and the sectors studied will be specified according to the progress of WP2 and WP3.1. *Risk: High. Lack of accessible regional data, problem of integration of GIS in the models, inability to complete WP3.1 in time. Success cannot be assured as this is novel research. Depending on these successes/failures, WP2 may revise its ambitions downwards. If the preliminary results are promising, a specific request for financial support by AAP will be made.*
- Deliverable L3.1/1 (Responsable : Isterre, Collab BRGM) : Preliminary study and modeling strategy. The deliverable of WP 3.1 is given as an indication, as this WP is funded outside the PC2. *Risk: High: Difficulty to take into account physical geography parameters, difficulty to access data. Coupling GIS with the dynamic model may be difficult and the time required to do so is difficult to assess. This requires the recruitment of a PhD specialist in ABM. We have a candidate with this profile.*
- Deliverable L3.2/1 (BRGM, collab. Isterre) : Preliminary and conceptual study of the game
- Deliverable L3.2/2 (Person in charge: BRGM): Example of gaming session
- Deliverable L3.3/1 (Chaire X) : Preliminary and conceptual study of the game
Risk: High, necessary simplification of the model to make it playful while keeping the scientific rigor, difficulty of code and environment.
- Deliverable L3.3/1 (Chaire X) : Specifications and distribution to studios capable of producing the game (by AAP) / to profiles likely to produce the game. *Risk: High: Lack of interest from game designers but subcontracting necessary.*
- Deliverable L3.3/3 (Chaire X) : Game prototype (if APA funding obtained)
- *Risk: High: requires additional funding (AAP)*
- Deliverable L4.2./1 (Isterre-carbone4) : First database and proposal of architecture, interfacing and access rights. *Risk: weak*
- Deliverable L4.2./2 (Isterre-carbone4) : Final database operational, searchable via internet with a graphical interface. *Risk: Low*

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

3.1. Project manager / Responsable du projet

VIDAL Olivier
Reasearch director CNRS classe exceptionnelle. Author of about 250 publications including a book on the energy-raw materials link. 8000 citations, h index = 48.

- 2021-2022 : Co-director of PEPR « Sous-sol bien commun », coordinator of the preparation and co-writing of the project document to the PIA4 call for proposals
- 2021- Membre of the scientific comittee of BRGM

- 2020-2021 : Member of the Steering Committee of the "low-carbon transition mineral resources programming plan" (Ministry of Ecological and Solidarity Transition)
- 2021-2024 : Member of Total's PIE (Parcours Innovation & Expertise) committee as an expert in low-carbon energy, energy transition, rare metals and thermodynamic phenomena
- 2016-2020 : Project leader of the OROGEN project (5 million euros) for CNRS/INSU (CNRS-Total-BRGM)
- 2015-2019 : Member of the Geoenergy Scientific Council (CNRS/INSU-BRGM)
- 2015-2019 : Member of the CNRS energy group
- 2016 : Member of the Scientific Council of ANR Défi 1 for the Ancre alliance
- 2015-2017 : Scientific expert of the European project INTRAW
- 2014 – 2015 : Member of the inter-ministerial committee on strategic metals (COMES)
- 2014-2015 : Member of the Scientific Council of Needs (CNRS)
- 2013-2018 : Co-coordinator of the GP2 of the Anchor Alliance for Energy
- 2014 – 2018 : President of the Scientific Council of Labex Voltaire
- 2012-2015 : Member of the advisory board of the European project I2mine.
- 2012-2014 : Member of the working group of the European Innovation Partnership (CE) on raw materials.
- 2011-2014 : Coordinator of the European project 'Era-Min' (2 Meuros, 10 countries) led by CNRS/Insu. Coordinator of the drafting of the roadmap 'Raw materials for the industry' which served as a support to the raw materials initiative of the EU in 2014
- 2010-2012: Responsible for the Environment, Planet, Universe, Space at the General Direction for Research and Innovation, Ministry of Higher Education and Research.
- 2009 : Member of the "Energies and Georesources" commission - StratOM of the Ministry of Higher Education and Research.
- 2007-2010 : Member of the GNR "Forpro II" scientific committee
- 2006-2008 : Coordinator of the 3F program at INSU.
- 2007-2011 : Head of the Alpine Range Geodynamics Laboratory (CNRS, UGA, USMB)

3.2. Organization of the partnership

The proposed consortium involves the main institutes working on resource and energy modeling in France (CNRS and universities, BRGM, IFPEN). The entities involved are complementary, with different specialties in economics (GAEL, IFPEN), earth sciences (BRGM, Isterre), energy (IFPEN), serious games and SHS aspects (BRGM), science and video games (Science and video game chair - Ecole polytechnique-Ubisoft), agent-based models and informatic (IRIT). The consortium brings together researchers with proven experience in issues related to resources and energy, and who are active in numerous national bodies (Ancre, Geodenergy, mineral resources programming plan for the low-carbon transition, CNRS energy unit, etc.).

3.2.1 Isterre : Skills in dynamic modeling and the link between resources and energy

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- Andrieu, B., Marrauld, L., Chevance, G., Vidal, O., Egnell, M, Boyer, L. & Fond, G. Associations between regional energy footprint and the occurrence of diseases. *Under review at JAMA Network Open.*

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- Delannoy, L., Auzanneau, M., Andrieu, B., Vidal, O., et al. (2023). Emerging consensus on net energy paves the way for improved integrated assessment modeling. *Energy and Environmental Science*. Available at SSRN: https://ssrn.com/abstract=4500020 or http://dx.doi.org/10.2139/ssrn.4500020
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- Delannoy, L., Palle, A., Rebi`ere, N. & Andrieu, B. (2023). Transdisciplinarit´e 'forte' en Anthropoc`ene : retour d'exp´erience d'un dialogue crois´e entre sciences sociales et mod´elisation ('Strong' transdisciplinarity in the Anthropocene: lessons from a cross dialogue between social and modeling sciences). H´erodote. La D´ecouverte. doi.org/10.3917/her.188.0041
- L Riondet, D Suchet, O Vidal, J Halloy (2023) Applicability of Hubbert model to global mining industry: Interpretations and insights. Plos One, PLOS Sustainability and Transformation 2 (4), e0000047
- Le Boulzec, H., Delannoy, L., Andrieu, B., Verzier, F., Vidal, O., Mathy, S. (2022). Dynamic modeling of global fossil fuel infrastructure and materials needs: overcoming a lack of available data. *Applied Energy. Applied Energy 326, 119871*
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- O Vidal, H Le Boulzec, B Andrieu, F Verzier (2022) Modelling the Demand and Access of Mineral Resources in a Changing World. *Sustainability 14 (1), 11*
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- PJ Valayer, O Vidal, N Wouters, MCM van Loosdrecht (2020) The full energy cost of avoiding CO2: A clean-energy booking provision for a vigorous energy transition. *Journal of Cleaner Production 237, 117820*
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- O Vidal (2018) Ressources minérales, progrès technologique et croissance. Temporalités. Revue de sciences sociales et humainesO. Vidal (2018) : Matières premières et énergie : les enjeux de demain (115 pages), éditions ISTE, 115 pages.
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3.2.2 BRGM : Expertise in dynamic modeling, game, territorial prospective, dynamic modeling via ABM

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- Mottis, T., Dumat, C., Baills, A., Andriamasinoro, F., Bellenfant, G., Berry, S., Lebot, B., Busca, D., 2022, « Écologisation de la gestion des sites post-mines : co-construction des connaissances et usages », Pour : Enquêtes et Témoignages, 244, 3, p. 111-122, https://doi.org/10.3917/pour.244.0111.
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research project », International Journal of Sustainable Development, 22, 3/4, p. 123-157, https://dx.doi.org/10.1504/IJSD.2019.105321.

3.2.3 IFPEN : Expertise in prospective modeling of energy systems, specialization on the evaluation of the criticality of materials.

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3.2.4 GAEL : Expertise in prospective energy modeling under carbon constraints, international energy markets and access to energy resources, economic analysis of climate and energy policies, dynamics of technological progress of low carbon technologies

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Key positions

Isterre/CNRS : Olivier Vidal, CNRS researcher, coordinator of PC2 and co-coordinator of PEPR SousSol (CV in 3.1). Role and responsibilities: co-supervision of PhD students where Isterre is a partner, organization of discussions, research directions and cooperation of PhD students, active participation (30% of time) in the research of WP2, 1.1, 3.1 and 4.1.
GAELCNRS : Sandrine Mathy. CNRS researcher in economy, leader of WP1.2.
IFPEN :

- Louis Marie Malbec : Economist engineer. Scientific co-leader of WP1.1 and WP1.3

BRGM :

- Antoine Boubaut. Research engineer, co-coordinator of PC2, co-supervision of PhD students and postdocs on modelling raw materials supply
- Feninstoa Andriamasinoro, Socio-economist working on the links between Geosciences and Human and Social Sciences (SHS) fields, co-supervision of PhD students involved in the implementation of the decisional (Agent-Based and serious-game) models and their links to the other models in PC2, contribution to the co-construction of models' scenarios with stakeholders (link with PC1), leader of WP3.2

Chaire Science et jeux vidéo, Polytechnique-Ubisoft : Catherine Rolland, Professor, leader of WP3.3.

3.3. Management framework

3.3.1 Organization between partners and project management methods

The budget for PC2 and the number of stakeholders and partners is relatively limited. The objective of PC2 is to produce different models and to test different approaches to modeling the demand for subsoil resources and the exploitation capacity. The different work packages have been built to be relatively independent (the results of one work package do not depend on the results of the other), which limits the risks. Moreover, the majority of the PhD students and post-doc envisaged will be co-supervised by the different partners, which remains the best way to share information and the progress of the tasks. For these reasons, we do not foresee a very elaborate organization.

- Monthly meetings of all the partners will be planned and specific sessions will be organized as the project progresses in case of identified problems or difficulties in following the planned deadlines (deliverables). Particular attention will be paid to accompanying and monitoring doctoral students and avoiding isolation. They will be invited to spend time in each laboratory of their co-supervisors and to participate in all planned meetings, with a rotating presentation of the progress of their work.
- Discussion with other PCs will also be done in a flexible manner.

3.3.2 Intellectual Property Rights

The intellectual property is classical: The researchers/laboratories/institutions have the IP of the models 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 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. The question of IP could arise for the development of the model into a game, if commercialization is envisaged. The legal services of the concerned institutes will be contacted to study the question if necessary.

3.3.3 Access to shared resources

Les chercheurs et institutions s'engagent à partager leurs données propres et modèles pour un usage interne au PC2. La diffusion des données et modèles en dehors du PC2 devra être demandée et validée par écrit par le partenaire mettant les données et modèles à disposition. Cela est également vrai pour la base de données SQL avant de la rendre publique.

3.3.4 Link with PEPR steering

This link should be relatively easy as O. Vidal is both coordinator of PC2 and co-coordinator of PEPR.

3.4. Institutional strategy

CNRS: The questions addressed by FP2 and more broadly the PEPR Sous-Sol bien commun are part of three of the six societal challenges of the 2019-2023 Contract of Objectives and Performance between the State and CNRS: Climate Change, Territories of the Future and Energy Transition. As stated in the introduction, part of the objectives of this COP "presupposes means and room for maneuver that CNRS does not have today." FP2 will provide some of these means and foresight tools for resource and energy issues. In this COP, axis 2.4 is dedicated to "Planet and Universe" with an item focused on the resource cycle for sustainable societies. The subsoil is naturally part of these resources, either because it contains particular resources (heat, mineral resources, water), or because it hosts urban infrastructures, and is a storage site (energy, CO2). Finally, the CNRS aims to promote interactions between technical and technological research on energy systems on the one hand, and research on the impact of these technologies on society, lifestyles, behavior, etc. FP2 was built with this philosophy in mind: it integrates the earth sciences, social sciences, economics and engineering. It is resolutely oriented towards research, but also towards citizen involvement and discussion with the industrial world and decision-makers.

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 in times of climate crisis. An important objective of FP2 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.

IFPEN : The Contract of Objectives and Performance (COP) binding IFPEN to the State for the period 2021-2023 is structured around 4 Strategic Axes, the first of which is to put R&I at the service of the ecological and energy transition. Within this framework, IPFEN devotes each year about 1/3 of its R&I budget to fundamental research (TRL 1 to 3), itself articulated around 9 Scientific Challenges. Participation in the PEPRs is therefore a structuring element of IFPEN's fundamental research policy. IFPEN is co-pilot of 3 PEPRs (Decarbonization of Industry; Biobased Products and Sustainable Fuels; and Digitization and Decarbonization of Mobilities) and is participating in the construction of the Hydrogen and Recyclability PEPRs. More specifically, participation in the PEPR Sous-Sol bien commun FP2 fits perfectly with Objective 1 of the COP's Strategic Axis 1: "Focusing fundamental research on the ecological transition", and with Scientific Challenge 9 "Economic and Environmental Impacts of Energy Transition Innovations". The latter aims to develop a socio-technical-economic modeling of energy systems, which is also the objective of FP2.

4. Expected outcomes of the project

The production of energy transition scenarios has accelerated rapidly over the last few decades, both at the national and global levels, particularly within the Intergovernmental Panel on Climate Change (IPCC). These scenarios make it possible to analyze the constraints and the coherence with the climate objective of technological trajectories, and are mainly produced by integrated assessment models. However, these models do not allow, or only partially, to quantify the need for primary and secondary raw materials for the transition. They ignore the possible geological limits, the environmental impacts of production and the associated social aspects. The modeling proposed in PC2 will allow this to be done.
Discussing the energy, economic, social and environmental future requires aggregating various approaches and today's strategic choices impact us in the long term. The goal of FP2 is to build a reference modeling tool, transparent and usable by all, to enlighten these choices by integrating all the complexity of the interactions between technology, economy, society and environment. Such a model does not exist today.
Any prediction contains many uncertainties related to the assumptions, but also to the chosen or forgotten couplings, to the data, etc... It is very important to identify not only the exogenous and endogenous variables, but also the sensitivity of the results to the assumptions and uncertainties on the data. Each model for each scenario will be accompanied at least by a sensitivity analysis so that the user understands the uncertainties associated with the results. The understanding of the couplings and the long-term projection of the decisions will be explained by the post-run analysis and the debriefing of the interactive models (game)

There is no specific dissemination strategy for public authorities and the general public, but the project is designed to make the models developed in PC2 open, accessible and participatory, especially through Work Packages 3 and 4. The PC2 partners all have contacts with industry and policy makers who may be interested in the tools developed and results. These will be shared with different think-tanks and business advisory structures (e.g. shift project, carbon4) which will be a strong relay for dissemination.

PC2 will be in close contact with PC1 for the issues of scenario and ABM game, PC3 for the economic dimensions (value of resources and recycling of raw materials) and for the evaluation of the material intensities of the different subsoil technologies, PC6 for the environmental aspects and the LCA, PC13 for the regionalization of the models. PC2 will develop approaches and models that have potential applications in other PEPRs like TASE, IRIMA and OneWater. This positions PC2 at a crossroads of the National Acceleration Strategy.

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