Towards an
ET EMR INSTRUMENT & UNDERGROUND STUDIES R&D AGENDA

Table of contents

Towards an 1

ET EMR INSTRUMENT R&D AGENDA 1

1. Introduction 1

2. Nikhef 2

3. R&D linked to main EMR facilities 3

3.1. R&D linked to ETpathfinder 3

3.2. R&D linked to ET-CRISTAL 4

4. R&D related to local research facilities 7

5. Underground exploration 14

6. Valorisation and impact on technological industry 17

1. Introduction

In 2021, the Einstein Telescope (ET) was included in the ESFRI Roadmap 2021 as a third-generation gravitational wave (GW) observatory to be built in a suitable location in one of the European Union's Member States. Currently, two sites are being explored as potential hosts of the ET, one located in the Euregio Meuse-Rhine (EMR) - in an area that spans across the Netherlands, Belgium and Germany - and one in Sardinia, the second largest island in Italy. The bids for the respective proposals for the ET are expected to be submitted and evaluated over the coming years.

The instrument R&D agenda that underlies the design, establishment and exploitation of the ET is a scientific and technological endeavor of the highest complexity. The effort that was undertaken in the EMR region is groundbreaking and carries unprecedented opportunities for the research, innovation and business ecosystems of the involved regions and countries. To succeed, close collaboration between all stakeholders and long-term structural investments are needed to optimally enable R&D at all TRLs and at every stage of the ET project. **The goal of this document is hence to further connect the scientific community with industrial partners, governments and funding agencies to enable a successful implementation of this ET EMR Instrument R&D agenda.**

Despite being of vital importance for the exploitation of the ET outputs and sustainability, several domains that are currently under study are not addressed in this document. They include topics such as sustainability, design of new wind turbines, studies of ultimate physics ET potential, calculations of GW waveforms, exascale computing, urbanization, power distribution, and more. Although they are not in the scope of this document, we want to

emphasize that, for them too, support and coordination at all levels is and will be needed for the entire duration of the ET project.

This document has been drafted by the team composed by the ET EMR R&D Coordinators (Prof Giacomo Bruno UCLouvain, Jurgen van Gorp Flemish Universities, Prof. Achim Stahl RWTH Aachen, Prof. Stefan Hild UM) and aims at providing a strong basis for the definition and operationalisation of a comprehensive **R&D agenda for all ET instrumentation**. Hence, in the following sections we exclusively focus on research and technology areas that are essential for the design, construction and reliable operation of the ET.
In the next sections, we discuss the objective, status and (future) priorities for several infrastructures and projects that have been established by universities and research institutes operating within the involved regions in the Netherlands, Belgium and Germany. The relevant facilities and projects span the entire Technology Readiness Level (TRL) scale, which makes the ET EMR R&D agenda highly relevant to all players of the knowledge and innovation chain.

2. Nikhef

Nikhef is the Dutch national institute for subatomic particles, a collaboration of an NWO-I Institute and 6 Dutch Universities: University of Amsterdam, Vrije Universiteit Amsterdam, Utrecht, Radboud, Groningen and Maastricht. Having acted as nucleus for gravitational wave research in the EMR region for the last 15 years, Nikhef is nowadays providing a unique vertical integration from excellent and powerful technical workshops and engineering teams, over leading scientific innovation and exploitation, up to driving the political strategies and agendas in unison with funding agencies and governments, which is unique and essential for a strong EMR bid.

The Nikhef partnership (which includes also leading roles in other R&D stars of this document, e.g. ETpathfinder in the next section), and in particular the Nikhef institute in Amsterdam has a variety of specialised R&D laboratories and conducts R&D in strategically important areas:

- Seismic Isolation and Suspension
- Optical Design
- Sensing and Control
- Simulations and Modeling
- Vacuum and Cryogenics
- Optical materials and coatings
- Quantum Noise reduction techniques
- Newtonian noise and other environmental noise

Nikhef has been instrumental for allowing several research institutions in the EMR region to start up GW related research by providing strong, capable, reliable support and guidance.

3. R&D linked to main EMR facilities

Towards the final development of the ET, a broad variety of technologies is required, some of which are completely new. For many other technological areas, progress needs to go beyond the current state-of-the-art that characterizes the existing instrumentation. The partners of the ET EMR collaboration are bringing together their competences and capabilities to jointly address these complex scientific and technological challenges. In this context, two main facilities are currently being developed in the EMR region at Maastricht University with ETpathfinder and Liège University with ET-CRISTAL. These two facilities act as complete testing environment for technologies which are developed in local facilities.

3.1. R&D linked to ETpathfinder

Objective

The ETpathfinder[1] will be one of the most capable and hence the most important research infrastructures for the ET, and hence for GW research and technologies. Nearly all of the key technologies of the ET are included in the ETpathfinder, which serves as a unique test-bed to qualify ET related technologies in a full interferometer configuration and at a sensitivity level similar to what is required for ET (of the order 1e-18m/sqrt(Hz) at 10Hz). Moreover, the full interplay and interdependencies between different subsystems can be explored in ETpathfinder, ultimately derisking the ET and helping to avoid delays during its commissioning. Finally, aspects related to long-term operation and maintenance can be tested, and strategies contributing to maximizing the duty cycle of the ET will be developed.

The ETpathfinder is a collaboration of about 20 research institutes and Universities from 7 European countries, with particularly strong contributions from the Netherlands, Belgium and Germany.

The scientific relevance and importance of the ETpathfinder is independent of the specific final configuration and location of the ET. However, the ETpathfinder also represents a unique asset for the ET EMR bid. This applies also to the ET-CRISTAL facility, discussed in the next section.

Status of infrastructure development and valorisation

The construction of the ETpathfinder started in 2020 in Maastricht and in 2023 the initial project phase was completed. Currently, a specialized cleanroom of 800 square meters is hosting a 190 cubic meter ultra-high vacuum system consisting of 6 towers of which 4 can be cooled to cryogenic temperatures. Dedicated passive and active seismic isolation systems will provide the required isolation from ground vibrations for the optical components and main silicon mirrors. Laser and photonics systems are being developed, tested and integrated at 1550nm and 2090nm.

A variety of valorisation activities linked to ETpathfinder (and ET-CRISTAL) have been carried out or actively ongoing on via projects like ET2SMEs, ET-Technologies and ET for business.

[1] See www.pathfinder.eu for more information. Moreover, an overview peer-reviewed article on the ETpathfinder can be downloaded here: https://iopscience.iop.org/article/10.1088/1361-6382/ac8fdb.

Future R&D Roadmap

Since ETpathfinder constitutes a full interferometer configuration, R&D efforts attain all relevant subfields, including (but not limited to):

- Cleanroom technology, low noise ventilation, cleanliness, particle deposition;
- Vacuum aspects, including water and ice reduction, vacuum sensors, optical interfaces, long-term operation and maintenance, vacuum controls;
- Low vibration cryogenic coolers, cryogenic heat links and switches, cryogenic controls, vacuum and cryogenic integrated modeling;
- Active and passive seismic isolation systems, low noise inertial sensors, advanced control of opto-mechanical systems;
- Near infrared photonics (1550nm and 2090nm), including low noise stabilized laser sources, electro-optic components, high quantum efficiency photodetectors, segmented photodiodes;
- Interferometry concepts beyond the standard quantum limit, including e.g. squeezed light, quantum speedmeters, etc;
- Control systems, signal processing tools, control strategies, digital twins, calibration strategies;
- System engineering, health and safety, component life-cycle management.

Although the ETpathfinder infrastructure is hosted in Maastricht, this R&D line includes also activities related to ETpathfinder but carried out elsewhere (like for instance the cryogenic test facility in Twente; various test setups for inertial sensing, seismic isolation, interferometry and controls at Nikhef; the laser and optics laboratories at UGent and UCLouvain; mirror coating labs in KULeuven and UGent; seismic measurements and control at UAntwerpen, quantum sensing and squeezed vacuum at UHasselt). See also section 4 on local facilities for more details.

3.2. R&D linked to ET-CRISTAL

Objective

ET-CRISTAL is a facility hosting a large-size (100kg) prototype mirror suspension system in a vacuum chamber equipped with optical instruments, together with a seismic network and dedicated noise sources, and working at very low cryogenic temperature (<20K) (as opposed to 120 K foreseen for ETpathfinder in its initial phase). The objective of the ET- CRISTAL instrumentation program is to develop a facility for validating the low-frequency seismic isolation technology and radiative cryogenic cooling techniques that will be employed in ET-LF.

Knowledge institutes and companies can use results obtained at the ET-CRISTAL facility to develop and test new products or gain new insights/knowledge, with ET-CRISTAL acting as a Living Lab.

Thanks to their complementarity, both ETpathfinder and ET-CRISTAL work in synergy to generate outputs that will be merged and implemented in the ET.

Together with the ETpathfinder, ET-CRISTAL will provide the EMR region a substantial competitive edge in the R&D areas that are crucial for the establishment of the ET.

Status of the facility

The ET prototype suspension system was one of the two pillars of the Interreg Euregio Meuse-Rhine V-A project “E-TEST” that started in 2020. The project included 10 partners from the EMR region and was coordinated by the University of Liège. The other pillar of the E-TEST project focused on underground exploration of the EMR site.
In the context of the E-TEST project, the ET prototype suspension system was designed, constructed, tested and validated at the Liège Space Centre (CSL).
At the end of this initial 4-year project, the suspension prototype consisted of a 100kg mirror, an excellent suspension system for isolating the mirror from seismic motion, and a cooling strategy that is compatible with the isolation system. The suspension system is based on active isolation that was combined with a radiative cooling system on the suspended payload. The latter was based on an innovative compact cryogenics radiative heat exchanger. This cooling system was designed and implemented at the CSL to benefit from its know-how in cryogenic qualification for space instruments.

In December 2023, a test campaign was conducted at the CSL . After less than 18 days, the dummy mirror reached a temperature of 22 K with an estimated heat load around 200mW.

Future R&D Roadmap

At the time of writing, the suspension system prototype has just been moved outside the CSL because the vacuum chamber in which it was installed had been scheduled to be used for other purposes.

The new temporary location will remain available until the end of 2025. It will then be essential to install the suspension system prototype in a permanent laboratory after the end of 2025. This new laboratory, called ET-CRISTAL (funded by the SPW Win4project program and the Uliège Lidge initiative), is being built at the CSL. This solution has several advantages: (1) benefit from expertise in the field of cryogenics and (2) pool the costs linked to the use of vacuum and cryogenics.
The deployment of the ET-CRISTAL laboratory requires the implementation of an adequate space to accommodate a dedicated vacuum tank of 3m in diameter and a system to connect this tank to the cryogenic installations of the CSL.
In practice, it will be necessary to first of all install a clean room in one of the new CSL building. This cleanroom will be completely dedicated to the research on the ET prototype and manipulation. The second step will consist of making modifications to the cryogenic fluid distribution system in order to provide the new facility with cryogenic capabilities. The third step will be the installation of the 3m vacuum chamber dedicated to host the E-TEST prototype.

During this transient phase, thanks to projects funded at the regional level, the R&D is still on-going:

- Experimental validation of advanced control strategies for low-frequency seismic isolation.

- Improvement of the cryogenic cooler is investigated thanks to a revised exchanger structure and improved surface treatments.
- Development of a large (100kg, 45 cm diameter) mono-cristalline silicon mirror
- Development of low noise and cryogenic electronics
- Development of high resolution cryogenic inertial sensors
- Improvement of the thermo-mechanical behavior of the heat exchanger, in particular regarding the potential thermal noise induced by the radiating surface.
- Improvement of thermo-optical properties measurements at cryogenic temperature
- Cryogenic proximity sensors to potentially monitor the relative displacement between the fins of the radiative heat exchanger
- Innovative high thermal conduction, high quality factor silicon suspension
- Installation of a seismic network surrounding the facility and artificial controlled seismic noise sources
- Development and experimental validation of Newtonian Noise modelling and subtraction techniques

The ET-CRISTAL facility is expected to be ready by the end of 2025. The R&D roadmap includes a new validation campaign based on the improved cryo cooler and suspension with a realistic 45 cm diameter Si mirror (polished by AMOS).

Later, the ET-CRISTAL facility will be managed as a *living lab* dedicated to host EMR researchers and hi-tech companies for tests of instrumentation and experiments.

4. R&D related to local research facilities

Objective

The facilities described in the previous section, namely ETpathfinder and ET-CRISTAL, are critical landmarks, but substantial work is and will continue to be carried out at several other research facilities within the ET EMR collaboration (and beyond) beyond both ETpathfinder and ET-CRISTAL. Many researchers drive critical research at different locations and within their own laboratories, making use of the infrastructures available locally. Knowledge is exchanged between the partners through the scientific networks and access to local facilities is possible for the partners based on bilateral agreements.

In this section we refer to these additional facilities as to *local facilities*. Research and development conducted at local facilities are expected to be carried out in coordination with either or both of ETpathfinder or/and ET-CRISTAL. Local facilities allow for the initial phase of development of new instrumentation that not qualified to be deployed in a complete testing environment. When this instrumentation or solution have reached a sufficient level of readiness and performance, the following stage of their development will (very often) take place at the ETpathfinder or ET-CRISTAL facilities that offer a more complete testing environment closer to the one expected at ET.

Status and Roadmap

In this section, we briefly discuss the existing local facilities in the EMR region. The latter are in principle open to the whole ET community and their exploitation by scientists, science and technology institutions, and companies is encouraged. *The list below is not intended to be exhaustive, as the whole document is a first concept and is open to input. Further, facilities and projects are listed in the alphabetical order of the cities where hosting institutes/institutions are located.*

<u>Mirror-related facilities</u>

- A cryostat for testing instrumentation of the cryogenic mirrors is available at the RWTH Aachen University. It was initially funded through the E-TEST project. Operation is now continued by RWTH. The cryostat offers a volume of about 1 liter at temperatures of 10 Kelvin and a pressure of 10^{-10} mbar with a fast turn-around time. Opening and Closing takes 1 to 2 hours. It is used to test sensors, actuators and other equipment in a realistic environment.

- B-PHOT (Free University of Brussels) has acquired the equipment for polishing mirrors and started the first tests. B-PHOT has been asked to create the first series of mirrors for ETpathfinder.
  B-PHOT is also using their already existing laboratories and equipment for the design of the Input Mode Cleaners for 2090 nm lasers.
  The initial measurements at B-PHOT show that improvement is necessary to overcome defects in the mirror surface during polishing. The research will continue to

bring the polishing quality up to the target levels required for the ET.

- Ghent University has started research on amorphous coatings. The results are still at a lower TRL and it is expected that the monocrystalline coatings from KU Leuven will be used for the first version of the mirrors for ETpathfinder. The Ghent University uses its already existing equipment in their local laboratories, which are already used for other research projects.
  Ghent University will continue its efforts on investigating amorphous coatings on larger sizes of mirrors. Though this is a parallel track to the work done at KU Leuven, amorphe coatings are being investigated on a lower TRL level. The decision on the coatings can only be taken later. The target configuration for ETpathfinder and ET-CRISTAL can only be decided after final coating research and may even change for future upgrades of the ET.

- A new laboratory has been installed at KU Leuven, which will become a dedicated cleanroom for monocrystalline mirror coating. The local research facility will host multiple bespoke machines required in the production process. Machine orders are ongoing for the monocrystalline coating of mirrors up to 300 mm in diameter which can be used in ETpathfinder.
  In a first phase the monocrystalline coating is to be completed for the 300 mm mirrors at KU Leuven and used for the mirrors of ETpathfinder and ET-CRISTAL. Depending on the measurements results - e.g. mechanical noise - a decision needs to be taken on the mirrors for the ET, e.g. scaling up to 500 mm diameter mirrors.

- The Centre Spatial de Liege (University of Liège)

  CSL has started investigating amorphous multilayered coatings for ET mirrors using ion beam technologies not only for their application but also for alternance fine layer correction during the deposition process; for this purpose, CSL relies on its decades-long expertise:

  - in engineering space qualified optical coatings operating under vacuum and at cryogenic temperature, as well as

  - on surface processing and characterization (optical and topological) capabilities. In parallel, CSL is developing a new interferometer capable of real time 3D scanning of the mirror surface at cryogenic temperatures, eliminating the need for movable components: the device monitors mirror deformations that result from cryogenic temperature fluctuations.

  In a first phase, laboratory tests have confirmed the instrument innovative principle through a proof of concept. In a second phase, the measurement technique and the real time mirror surface reconstruction will be optimized.

- The University of Namur, Belgium is active in coating technology:
  Prof. Julien Colaux – Physics – NISM Institute: Elemental depth profiling of coating synthesized by vacuum plasma technologies.

ICS – Innovative Coating Solutions – Company thin film deposition: Available as subcontractor (Thin-film deposition by vacuum method (PVD)).

Laser-related facilities

- The Fraunhofer Institute of Laser Technology (located in Aachen) has extensive laboratories for the development of lasers and related technologies. Several of these labs are in use for ET. For example, there is a lab for the development of a Holmium-based fiber laser at a wavelength around 2 micrometers for ETpathfinder and ET.

- Ghent University has set up a test lab for 1550 nm and 2090 nm laser tests. The local research facility is used for research on the new lasers and photonic amplifiers, and for design of the Output Mode Cleaner for ETpathfinder.

- The University of Louvain (UCLouvain) Lasers and Optics (LAS&O) technological platform has been hosting research on instrumentation for the optical system of the Virgo GW detector. So far, research activities have focused on the attenuation of higher-order resonant modes of the laser beams using the phase cameras installed in Virgo.
  The UCLouvain GW group (Prof. Giacomo Bruno) has submitted an important funding request for equipping a new extension of this technological platform in order to conduct research for ET too. The outcome of this funding application is expected in the coming months. In addition, the UCLouvain GW group has access to an electronics lab and a large mechanical workshop (more than 500 m^2) with a design office, where mechanical pieces for ETpathfinder, ET-CRISTAL and other facilities, including eventually ET, can be designed and fabricated.

Seismic measurements and attenuation facilities

- The University of Antwerp has a lab for seismic measurements and control. Amongst their efforts, there is also the testing of Newtonian Noise at the LSBB mines in France. The research results for active control are already being implemented in E-TEST, and will continue to be used in ET-CRISTAL and ETpathfinder. The seismic control components being developed at the University of Antwerp will continue to be installed in ET-CRISTAL and are planned to be employed also in ETpathfinder.

- The University of Liège (Prof Christophe Collette, Precision Mechatronics Laboratory (PML)) is developing high precision inertial sensors and active control strategies for gravitational wave detectors since 13 years. In the E-TEST project, PML was mainly in charge of the mechanical design of the prototype, and the development of interferometric sensors and control strategies for low-frequency seismic isolation. Besides E-TEST, this work is funded by several projects, including the ERC consolidator SILENT project.

- The University of Liège (Lidge Research group within BELGRAV-WAL RU : Precision Mechatronics Laboratory -PML-, Applied Geophysics - AP GEO-, Centre Spatial de Liège -CSL- and Gravitational Waves -GW-) has facilities to measure the seismic

ambient noise and to model Newtonian noise both for the ET-CRISTAL facility and in-situ in the EMR region and has facilities to measure spatially variable density and seismic velocities and attenuation distribution in the field.

Vacuum facilities

- A laboratory on the development of ultra-high vacuum technologies will be constructed at the RWTH Aachen University. Funding is anticipated from the FIS.NRW (EFRE) program. A few projects with industrial partners are already ongoing on coatings, materials and production technologies for the pipes, pumps, and other equipment.

- Researchers at the University of Antwerp and the University of Ghent are investigating new structures and materials for the vacuum tubes. Lab research on welding takes place at the workplaces in Werkhuizen Hengelhoef and SBE Piping Maschinen- und Apparatebau in Eijsden (NL).
  Based on the results generated by the University of Antwerp and the University of Gent, decisions need to be made on the materials and configurations used for the vacuum tubes. Moreover, as the topic is also being investigated at CERN, close collaboration between all relevant groups will be maintained. While the work is on the engineering level - and already higher TRL - the decisions will have a high impact on ET as a whole. Hence, further research on the impact of the design decisions will need to be carried at the ETpathfinder.

- The Interreg project IMR6-00052 under the cross-border cooperation Programme Interreg Meuse-Rhine VI-A (NL-BE-DE), and on the fully automated, continuous production of vacuum pipes in the tunnel has been approved. A prototype robot will be built, which can make vacuum pipes of approx. 0.5 m diameter and several hundred metres of length. It will use innovative welding techniques and new technologies to add flanges and T-sections will be added.

Cryogenics

- The KU Leuven has a lab for cryogenic chips and is currently investigating the PDK library for simulating ICs at lower temperatures. The research is still at very low TRL and results are expected only later in the development of ETpathfinder and ET-CRISTAL.

- The University of Liège (Prof Serge Habraken, CSL) has cryogenic facilities and is working to improve the innovative cryogenic concept developed in the frame of E-TEST (see section 3). Following the first positive results, several enhancements are planned to increase overall efficiency while reducing complexity. These include radiative exchanger architecture, super black coating, emissivity characterization, interfaces with sensors and actuators…). Later, the project will benefit from a building extension to house a clean room surrounding the ET-CRISTAL vacuum chamber with full cryogenic capabilities (LHe and LN2).

- The University of Liège (Prof Christophe Collette, PML) has facilities to develop sensors operating in cryogenic conditions; PML is developing high resolution cryogenic

inertial sensors, dedicated to low-frequency vertical and horizontal motion. These sensors measure the motion close to the mirror and are used to demonstrate experimentally that the radiative cooling strategy is not inducing vibrations.

Quantum Technologies

- The University of Hasselt has dedicated photonics labs for quantum sensing of environmental parameters and for the optics in the ETpathfinder.
  The UHasselt research on quantum sensors is at a higher TRL level. The sensors can be tested in ETpathfinder and ET-CRISTAL and decisions taken on use and configuration at a later stage.

- The University of Hasselt photonics labs also houses equipment for research on squeezed vacuum, next to similar labs at B-PHOT in Brussels.
  The research is being aligned with work done for LIGO, and is expected to be used in the ETpathfinder and later also in the ET.

- *UNamur is investigating in optics and photonics linked to ET.*
  Prof. Yves Caudano – Physics – NAXYS and NISM Institute: involved in quantum optics and all optical aspects related to Einstein telescope.
  Prof. Alexandre Mayer – Physics – NAXYS Institute: Modeling and optimization in nanophotonics with advanced algorithms, HPC and deep learning.
  Prof. Benoit Champagne – Chemistry – NISM Institute: Nonlinear optics and photonics and numerical modelling.
  Prof. Michaël Lobet – Physics – NISM Institute: Optics and photonics of multi-materials, simulations, and optimization of perfect electromagnetic absorbers/reflectors.

GW modelling, AI, deep learning

- UNamur has developed expertise:
  Prof. André Fuzfa – General relativity and cosmology – NAXYS Institute: Modeling of incoming GW signals, astrophysical sources and cosmological implications and Electromagnetic detections.
  Prof. Benoit Frenay – Artificial intelligence – NADI Institute: AI, machine learning, deep learning for complex data analysis Prof. Bruno Dumas – Computer Science – NADI Institute: Augmented reality - Mixed reality

- The University of Liège brings over a decade of experience in gravitational wave research through OGrav and Prof. Maxime Fays. Specialising in non-modeled transient sources, their work focuses on distinguishing between gravitational waves and instrumental transient noise, a key challenge in current detector technologies. This expertise is crucial for developing strategies for noise characterization and subtraction, enhancing the accuracy of the Einstein Telescope.
  OGrav's proficiency extends to constructing several end-to-end pipelines, showcasing their capability in handling complex data. Their experience is not only technical but also collaborative. Prof. Maxime Fays serves as a vital link between the Data Analysis platform and the Transient Gravitational Wave sources division within the Einstein Telescope consortium. Additionally, his roles as the Belgian representative of G2net and Chair of the Machine Learning Algorithms group in the LIGO Virgo Kagra collaboration highlight the team's leadership in integrating gravitational wave research

with advanced machine learning techniques. This blend of theoretical knowledge and practical application positions OGrav uniquely in the Einstein Telescope project. Their ability to navigate and interpret the nuances of gravitational wave signals makes them a key contributor to the project's goal of groundbreaking discoveries in astrophysics.

5. Underground studies

Objective

The EMR area, like other sites, requires a feasibility study to make informed decisions when optimizing the location and structure of the ET underground and estimating the overall engineering costs. Underground studies constitutes an essential step for the assessment of the feasibility of the ET establishment in the EMR region and is closely linked to ET R&D activities including Newtonian noise estimates and the estimation of in-situ ET sensitivity but also to more specific R&D such as the development of multi-scale models to estimate groundwater inflow or the resolution of inverse problems in geophysics to obtain more reliable models and realistic uncertainty quantification. Such studies are also key in terms of general public information and the overall project acceptance.

A subsurface model populated with quantitative engineering parameters will help guiding decisions on corner points, tunnels, caverns, exit types (shaft/ramps) and be leading towards the infrastructure geometry. Options like vertical shafts or longer slopes to the surface will be evaluated, considering underground (stability, water inflow…) and surface factors (population, environmental, land use, road access, facilities…).

At this stage, the feasibility study gathers new data on top of the extensive existing geological database in the three countries: 1) indirect geophysical data to map with a large coverage the physical parameters variations, interpreted in terms of geology, 2) direct observation through boreholes and coring, providing detailed but local information along the infrastructures and more particularly at the corner points, 3) monitor relevant noise such as seismic noise (for Newtonian noise estimates), and magnetic noise (for interference with the mirrors locks); together with the identification of the sources (windmills) to develop noise mitigation strategies; and develops several models in order to make informed decisions: 1) geotechnical models to design civil engineering and define realistic infrastructure planning, 2) hydrogeological models to understand the water inflow for civil engineering and to quantify the environmental impact and design adequate mitigation strategies, 3) seismic noise model to understand the seismic field behaviour and correlation and to estimate the ET sensitivity in-situ.
The overall amount of data collected at the EMR site provides the region with a unique large scale multiphysics underground laboratory.

Status

The Interreg project E-TEST (Underground Study partners: ULiège UEE, RWTH Aachen, KNMI, Nikhef, UniBonn) has led to the first substantial set of activities and is being continued through the PO EMR in collaboration with different institutions, including the University of Liège (ETGEO, Prof. Fred Nguyen), the RWTH Aachen, The Belgian Geological Survey, TNO, the consortium E=MC2, Nikhef, KNMI, KU Leuven. Studies are currently ongoing.

Geophysical mapping, imaging and noise monitoring are ongoing in the region with a new seismic reflection campaign, deep electrical resistivity tomography, confirming a strong impedance contrast below the cretaceous cover (attenuating layers), but could lead to a loss of information at depth due to the little penetration of seismic energy below it. Deep electrical resistivity tomography highlights strong variations underneath this cover, potentially related to

folds and faults, and narrows the position of the Booze-Val Dieu block that need to be interpreted together with borehole date and a structural model of the geology.

A first regional hydrogeological model of the area has been consolidated (submitted for publication) based on E-TEST, and will serve as basis for improvements given the additional data and the requirements to model the caverns at a different, more local scale, and to integrate local heterogeneities.

An environmental impact study has also started including first documents on all relevant aspects and legal and permitting studies have been established and will continued to be updated.

A total of 14 boreholes have been completed and are being analyzed in terms of interpretation, and geotechnical description. Core workshops are being held on a regular basis with the different countries led geologists to strengthen the interpretation of the samples in addition to their description in terms of engineering geology. Some of which have been equipped with seismometers to complete the surface noise monitoring with depth monitoring (including skylines towards potential noise source such as bridges, windmills, quarries…), others with piezometers to gain more information on deep hydrogeological parameters, and to perform hydraulic tests. Data are being processed and will be integrated.

Future Roadmap

A new series of boreholes will enable the PO EMR to refine the 3D underground models and to improve our knowledge of the seismic noise field in the EMR region, since only one borehole (Terziet) is currently being used as a reference.

A database of all data is being assembled and will be integrated in a common framework (such as a leapfrog model able to handle 3D information).

The geological team will follow a 12-phase identification model to minimize model risks, pinpoint areas needing detailed analysis, and produce a well-documented proposal for the ET end points and caverns with a continued evaluation of the feasibility study.

A comprehensive GIS model is being developed, covering not only the results of the test boreholes, but also geographic information, legal and environmental limitations, surface aspects, etc. The GIS model will provide a representation of the region, supporting decisions on the configuration and location of the ET.

Based on decisions on the end points for the ET, additional horizontal boreholes ??are planned by 2025. The information gained from these boreholes will support the validity of the decisions taken, and will help the tunnel boring teams to plan their work.

Persistent geological measurements in the area, facilitated by seismometers and geological instruments, will not only contribute to ongoing research but also provide valuable support during the operational phase of the ET, allowing continuous environmental monitoring, not only for the ET but also for other geological studies in the area.

The non exhaustive roadmap includes different future developments such as:

- Potential exploitation of geothermal resources highlighted by the current studies (ULiège AP GEO)
- Sustainability in underground construction with limited water use and reuse of excavated materials to limit ground transportation. Circular construction of the underground infrastructure. (ULiège UEE Building Materials, UEE GeMMe, UEE AP GEO, PEPs, PsyNCog together with industrial partners)
- KULeuven has built a consortium with industrial partners focusing on circular construction and re-use of excavated materials
- Impact of deep groundwater on infrastructures and their potential uses (ULiege)
- Innovative logistical solution based on existing infrastructures (boat and train transport)
- Seismic hazard impact studies on ET detection
- Development of multiscale models to compute water inflow along tunnel and in caverns in the different phases of the projects and to assess the potential impacts ot the ET infrastructures on groundwater, surface water and related ecosystems (ULiege Hydrogeology /VUB)
- Societal and psychological studies on public acceptance of disruptive projects (ULiège PsyNCog)
- Structural health monitoring of underground structures
- Mitigation of geological risks and conflicting use of the subsurface
- Numerical modeling of Newtonian noise based on high resolution cavern details and tunnels (*Lidge Research group within BELGRAV-WAL Research Unit)*
- Development of high-order numerical schemes based on spectral finite element to model seismic noise in the area (Prof. C. Geuzaine, ACE ULiège)

- UNamur has an expertise in:
  Prof. Johan Yans – Geology – ILEE Institute: Valorization within the cement industry of excavated rocks.
  Prof. Max Collinet – Geology – ILEE Institute: planetology

6. Valorisation and impact on technological industry

Objective

The construction of the ET entails a significant investment and is expected to bring substantial returns in terms of scientific knowledge, economic growth, public image, and social impact.

Besides the considerable scientific return for universities, knowledge centers and companies within the region, the project will lead to the emergence of new technologies that can be integrated into relevant industries and foster the creation of spin-offs. Moreover, the presence of the ET in the EMR region will inspire young people and contribute to strengthening STEM education and training in the EMR region. In turn, this will benefit the scientific and innovation ecosystems of the organizing countries, with (indirect) positive repercussions also on their economies. Also from a general public perspective, the ET will contribute to increasing the attractiveness of the border region which will benefit tourism overall.

In the light of the considerations above, in this section the focus of the valorization effort is discussed for these three dimensions: scientific, economic, and social.

Status of Valorisation & Impact agenda development

In order to optimally coordinate the valorisation work, a team of experts has been put in place which includes representatives from FWO (Flanders BE), LIOF (Netherlands), EZK (Netherlands), the Walloon Region (Wallonia BE) and NRW/MWIKE (DE) as observer.

The Valorisation & Impact experts will also work closely with the R&D Coordinators who lead the definition and implementation of the instrumentation R&D agenda, which is the objective of this document.

Initial studies on valorisation potential are complete, with more ongoing. Currently, the team is engaging with industry stakeholders and forming consortia for research, supported by national/regional subsidy budgets. The Valorisation & Impact team is identifying additional technology areas where the industry can contribute to initial research for the ET.

To maintain effective communication with the Taskforce, the team has defined a Terms of Reference (ToR) for an Expert Committee on Valorisation & Impact, pending Taskforce approval. The Expert Committee members are meeting on monthly basis since September 2024.

Roadmap

The Expert Committee on V&I will coordinate valorisation areas across regions and streamline efforts for the development of the ET. Their focus will be on forming consortia around the telescope's technical needs and optimizing subsidies and resource allocation.

Regular updates and coordination with the R&D Coordinators team are planned to identify new opportunities and align with the ET-CRISTAL and ETpathfinder roadmaps. Collaboration is anticipated among the regions, involving multiple universities and companies whose expertise and technologies are needed to develop the ET in the Euregio Meuse-Rhine.

The collaboration between regional partners aims at generating a maximal return on the money invested in the ET, not limited to the EMR region but for all European partners.

Overall, the Valorisation & Impact team is on a structured path towards maximizing its scientific, economic, and social benefits, with a clear focus on collaboration and efficient resource use.