17th International Conference on Greenhouse Gas Control Technologies, GHGT-17

20th - 24th October 2024 Calgary, Canada

HERCCULES project: overview, objectives and early progress

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Abstract

HERCCULES is an Innovation Action under the Horizon Europe research programme aimed at demonstrating, for the first time, the feasibility of the entire CCUS chain in southern Europe at TRL 7-8. The project focuses mainly on decarbonizing two strategic clusters in northern Italy and Greece, specifically targeting two hard-to-abate sectors: cement production and energy from waste. To achieve this goal, significant effort is being directed towards piloting and demonstration activities. Three CO_2 capture pilots are

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currently in the design phase; two will be installed in two cement plants and one in an EfW plant; three CO_2 utilization pilots will be set up to test the mineralization of a portion of the captured CO_2, and finally, the two most advanced CO_2 storage sites in southern Europe, Ravenna (Italy) and Prinos (Greece), will be employed to conduct storage activities. Currently, the movable solvent-based Post-Combustion Capture pilot plant design and procurement has been completed, the construction phase is underway in a cement plant in Italy, and the plant is expected to be commissioned in the coming months. On the other hand, the development of the oxyfuel calcination pilot plant, which is important for demonstrating the novel hybrid process, is still under development. Furthermore, the design and detailed engineering of the integrated CaL+CPU pilot plant to be installed in an EfW plant in Italy have been completed, and the procurement phase is currently underway. Finally, to support the demonstration of technologies for CO_2 mineralization and CaO-CaL by-product re-utilization, several natural and synthetic zeolite materials have been evaluated to support the design of the zeolite-based mineralization pilot. The mineralization plant's construction is underway, with its commissioning expected to be completed in the coming months.

Keywords: HERCCULES; CCUS; CO_2 capture; Pilot plant; Cement; Energy-from-Waste; Partial oxyfuel; Calcium looping; Process simulation; Circular economy

1. Introduction

In Europe, cement and Energy from Waste (EfW) emit around 120 Mt_{CO2}/y and 96 Mt_{CO2}/y, respectively, but unlike other industrial sectors, which could expand their reliance on renewable sources or bio-based intermediates, their process-related CO_2 emissions can be fully abated only by CCUS [1,2]. Therefore, attaining Europe's carbon neutrality by 2050 calls for urgent actions to apply CCUS in these sectors [3]. For that reason, several projects from cement and EfW have also started in recent years to develop and bring to industrial scale the most promising technologies in the field of CCUS [4].

In 2022, the global cement sector was responsible for direct emissions of 2'356 Mt_{CO2}, which represented 6.2% of global energy-related CO_2 emissions [5]. The cement industry is classified as a hard-to-abate sector due to two primary characteristics: (i) approximately 60% of the CO_2 emissions come from the calcination of raw materials, primarily limestone ($CaCO_3$), known as process emissions, and (ii) the calcination process requires high-temperature heat, which is challenging to produce without burning fossil fuels. In the short term, improving energy efficiency, reducing the clinker-to-cement ratio, electrification, and utilizing low-emission fuels are essential but insufficient for achieving the targets set for Net Zero Emissions scenario [3]. Significant reductions in emissions necessitate additional innovative technologies, including the use of alternative raw materials for cement production and Carbon Capture Utilization and Storage (CCUS) [3].

To meet the emissions targets established for 2030, the International Energy Agency (IEA) states that 12% of the total heat needed for the clinker production process must be generated using carbon capture technologies, with this requirement increasing to 50% by 2050 [3]. Therefore, accelerating the development of these processes is critically important. Partial oxyfuel is one of the most promising options due to its relatively straightforward integration into conventional cement plants [6–9]. It minimizes retrofitting complexity by implementing oxy-combustion only in the pre-calciner while keeping the core of the clinker production process, represented by the rotary kiln and clinker cooler, largely unchanged. However, partial oxyfuel can achieve CO_2 capture rates of about 70-80% and should be combined with other CO_2 capture systems, such as an amine-based solvent plant, to reach higher levels of decarbonization by also capturing the CO_2 generated in the rotary kiln.

The EfW sector is another hard-to-abate sector of particular interest in recent years, especially following the decision of the European Parliament to include these plants in the CO_2 European Trading Systems (ETS), likely starting from 2026-2028 [3]. The combustion of unsorted municipal solid waste in grate-fired boilers is a key component of the waste management chain. Flue gases released from the stack of an EfW plant on average contain about 50% biogenic CO_2. Therefore, applying carbon capture technologies to EfW plants could allow these facilities to achieve negative CO_2 emissions [10,11]. Calcium-Looping (CaL) is among the most promising CCS solutions for this sector. CaL application has been studied across various industries [12] and has shown high CO_2 capture efficiency alongside competitive energy and economic costs [12–17]. This technology is particularly relevant for WtE plants because of its flexibility in fuel use; both Municipal Solid Waste (MSW) and Refuse-Derived Fuel (RDF) can serve as the heat source for the regeneration of the calcium-based sorbent (via calcination) used in the CO_2 capture process [18].

At the heart of both partial oxyfuel and CaL processes is oxy-calcination, which produces a gas stream with a CO_2 concentration of 70 – 90 $\%_{vol,dry}$, depending on the specific process conditions. The raw CO_2 gas stream requires further purification to meet the purity standards necessary for CO_2 transport and storage, which are project-specific. Generally, a minimum CO_2 concentration of $95\%_{vol,dry}$ is needed, but even more stringent purities have been reported by some ongoing full-scale CCS projects [19,20]. The Compression and Purification Unit (CPU), which processes the CO_2-rich gas from the calciner, allows producing very high purity (>$99.99\%_{vol,dry}$) liquid CO_2; by contrast, the CPU, after purification, still leaves a fraction of the captured CO_2 together with the non-condensables in the vent gas (due to its finite selectivity and recovery, especially when very high CO_2 purities are required). For example, the CPU vent gases from a 1 Mt_{clk}/y cement plant operating in partial oxyfuel configuration and a 500 kt/y WtE plant using CaL could still contain up to 50-100 kt_{CO2}/y, [21]. Therefore, optimizing the integration of the CPU with the whole capture process is essential to achieve significant emission reductions in both sectors utilizing oxyfuel-based CO_2 capture technologies.

Within this framework, the HERCCULES project, started in January 2023 and projected to last for 5 years [22], aims to accelerate the application of the CCUS in Southern Europe, demonstrating the techno-economic feasibility of two full-scale CCUS chains, each serving an industrial cluster with a capture potential of up to 10 Mt_{CO2}/y by 2030: (i) in Greece, driven by the cement sector; (ii) in Northern Italy, driven by the synergic integration of cement and EfW industries. The project will leverage the two most advanced geological CO_2 storage sites in southern Europe, Prinos in Greece and Ravenna in Italy, involving the main industrial actors of the CCUS field, which will implement three capture pilots and three CO_2 mineralization pilots at a Technology Readiness Level (TRL) 7-8.

The purpose of the following work is to present an overview of the project and the progress of the first year and a half of HERCCULES activities.

Nomenclature

CaL	Calcium-Looping
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture Utilization and Storage
CFB	Circulating Fluidized Bed
CFD	Computational Fluid Dynamics
CPU	Compression and Purification Unit
EfW	Energy-from-Waste
ETS	European Trading Systems
FEED	Front End Engineering Design
ICP	Inductively Coupled Plasma
IEA	International Energy Agency
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
MEA	MonoEthanolAmine
MSW	Municipal Solid Waste
PCC	Post-Combustion Capture
RDF	Refuse-Derived Fuel
SCM	Supplementary Cementitious Material
SRF	Solid Recovered Fuel
TRL	Technology Readiness Level
WP	Work Package
XRD	X-Ray Diffraction

2. HERCCULES structure and activities

HERCCULES is an innovation action under the Horizon Europe research programme, aimed at demonstrating, for the first time, the feasibility of the entire CCUS chain in southern Europe. The project focuses particularly on the decarbonization of two strategic clusters located in northern Italy and Greece, specifically targeting two hard-to-abate sectors: cement production and energy from waste. The consists both of research organizations and industrial partners, including leading European universities, research centers, major players in energy production, waste management, and cement production, as well as several technology providers in the field of CO_2 capture technologies. Fig. 1 (left) shows the various partners and the location within Europe.

Significant effort is being directed towards piloting and demonstration activities to achieve ambitious targets. Three CO_2 capture plants are currently in the design phase; two will be installed at a cement plant and one at an EfW plant. Additionally, three CO_2 utilization pilots will be set up to test the mineralization of a portion of the captured CO_2. Finally, the two most advanced CO_2 storage sites in southern Europe, Ravenna and Prinos, will be utilized to conduct storage activities. The test facilities will be operated for over 10'000 hours, capturing and storing more than 3'500 tonnes and 1'000 tonnes of CO_2, respectively, while also producing over 8'000 tonnes of low-carbon concrete.

Fig. 1 (right) illustrates the structure of the project, emphasizing the interactions among the various Work Packages (WPs). WPs 1 and 10 are transversal, focusing on project management, communication, and dissemination. The remaining WPs are organized into three blocks. The first block concentrates on designing, optimizing and demonstrating CO_2 capture technologies in cement plants (WP2) and EfW plants (WP3), as well as CO_2 utilization (WP4) and CO_2 transportation and storage (WP5). The second block addresses the exploitation activities related to the design and optimization of the CCUS chain integration at full-scale in the future (WP6); this block also includes the exploitation of results through delivering pre-FEED studies of the tested technologies at full-scale (WP7). The final block focuses on socio-economic strategies, evaluating both social and regulatory aspects (WP8) and business and financial factors (WP9) concerning the CCUS chain. The overall budget for the project is approximately 40 million Euros (of which, nearly 30 million Euros funded by the EU), and the project is set to last for 5 years.

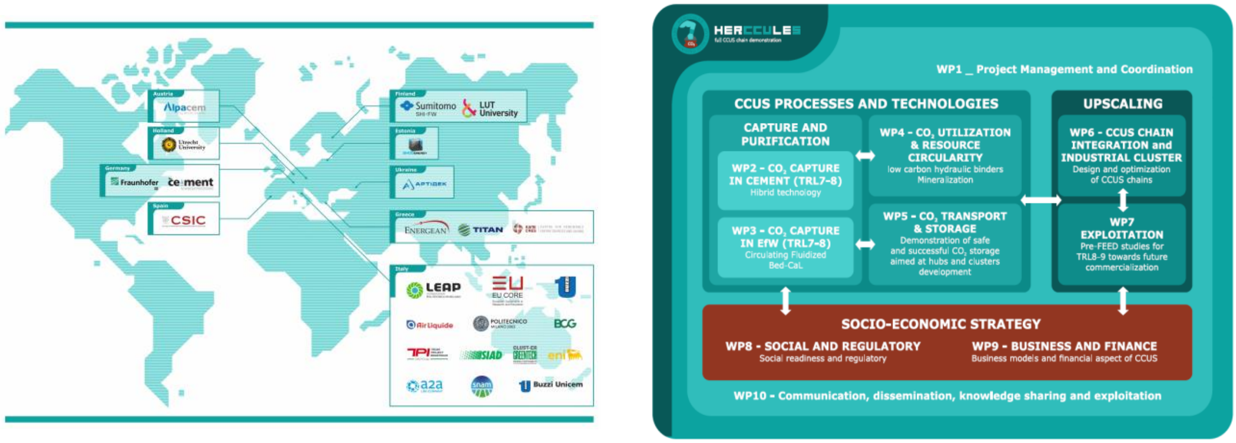

Fig. 1. Partner list and location (left) and work package structure (right) of the HERCCULES project.

Currently, we are in the project's first phase, which is dedicated to modeling and designing the CO_2 capture and utilization plants. The test facilities for both cement and EfW plants are in the advanced engineering phase. The next demonstration activity will involve operating an advanced amine-based post-combustion capture system, which is under installation at the Vernasca cement plant operated by Buzzi Unicem. In a subsequent phase of the project, the hybrid capture technology will be demonstrated at the Greek cement plant operated by Titan, while the post-combustion calcium looping process will be tested at an EfW plant located in Milan, operated by A2A. These technologies will be demonstrated at TRL 7-8, meaning they are not full-scale applications but are of significant size and will be conducted in relevant industrial operational environments. All results will contribute to future capture technology upscaling as well as to designing and optimizing the transportation networks in the northern Italy and Greece clusters.

Regarding the CO_2 capture technologies to be demonstrated at the cement plant, three configurations will be tested: two stand-alone processes (i.e., post-combustion capture with solvents and oxy-fuel) in addition to their combination, known as the hybrid configuration [23]. The first technology is the partial oxyfuel process, which captures the CO_2 generated by the calcination of the raw meal, the main source of emissions, and the oxidation of the fuel fed into the calciner. Once dried, the flue gas produced through oxy-combustion is rich in CO_2 and can be purified using a cryogenic unit to meet transportation specifications. This approach can achieve an overall reduction of 70-80% in emissions from the cement plant, even if the rotary kiln flue gas is not fully decarbonized. The second technology is a post-combustion capture system, specifically a new-generation amine-based solution featuring innovative process configurations (intercooling, rich solvent split, multiple solvent injection points, a membrane contactor and lean vapor recompression can be tested). This system can decarbonize both the calciner and kiln flue gases depending on the stream to which PCC is applied. The hybrid configuration utilizes the oxyfuel technology for the calciner while applying the post-combustion solution for the kiln flue and purification unit vent gases. This configuration can capture CO_2 mixed with incondensable gases, resulting in a high purity of the captured CO_2. With this approach, it is possible to achieve high CO_2 purity (greater than $99.9\%_{vol}$) and capture rate of up to 98%.

The calcium looping system will be demonstrated at the EfW plant operated by A2A in Italy. A slipstream of flue gas from the full-scale plant will be directed to a carbonator reactor containing calcium oxide sorbent, which will react with CO_2 to capture it and produce calcium carbonate. This calcium carbonate will then be sent to the calciner for the regeneration process. The fuel for the endothermic calcination reaction will be Solid Recovered Fuel (SRF). The CO_2 released from both the regeneration of the sorbent and the oxidation of the fuel will be sent to an advanced purification unit based on low temperature distillation and liquefaction, aiming for a target capture rate of 95% and high purity of the captured CO_2. Sumitomo SHI-FW is currently conducting the basic engineering and detailed design of the calcium looping system and its associated components.

The calcium looping system requires a continuous makeup and purge of sorbent to maintain high reactivity, and this purge can be utilized to produce construction materials, as it is still rich in calcium oxide, the main constituent of clinker. Therefore, the project aims to demonstrate potential synergies between the CO_2 capture system in the EfW sector and the cement sector, particularly in producing decarbonized clinker. Several mineralization processes will be tested, including a zeolite-based material at a low TRL and a commercial mineralization skid integrated with a partial oxyfuel demonstration plant in Greece, which represents an alternative solution for capturing the CO_2 released in the vent gas from the CPU.

The two most advanced storage sites in southern Europe, Ravenna and Prinos, operated by ENI and Energean respectively, with estimated total capacities of 500 million tonnes [24] and 100 million tonnes [25], will be used to store the captured CO_2. Models and monitoring strategies for the reservoirs will be developed, along with guidelines to facilitate the permitting and authorization processes for these sites.

Finally, the results obtained from the various work packages will be utilized to optimize the CCUS chain. This includes the development of multi-criteria optimization methods for designing the CO_2 transport network. The project will also deliver multiple pre-FEED studies, exploitation materials, business plans, and guidelines for all the technologies demonstrated for CO_2 capture and utilization. Case studies will be conducted for selected industrial partners' plants to facilitate the full-scale implementation of the CCUS network in the Italian and Greek clusters. Additionally, various business models, Life Cycle Assessment (LCA), and cost-benefit analyses will be produced. For instance, a potential pathway for implementing the hybrid capture system in a cement plant is illustrated in Fig. 2.

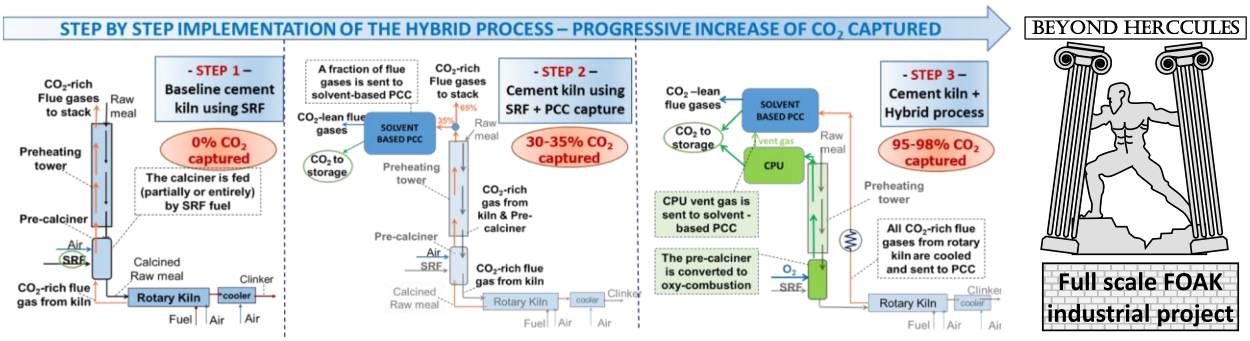

Fig. 2. Possible pathway to implement the hybrid capture system in a cement plant.

3. Objectives

The first objective of the HERCCULES project is to demonstrate flexible and optimized high-purity CO_2 capture technologies in cement plants, reaching TRL 7-8. The project will advance a novel hybrid CO_2 capture technology by integrating: (i) oxyfuel calcination combined with a CO_2 compression and purification unit; and (ii) next-generation solvent-based Post-Combustion Capture (PCC). First the PCC will be tested at the Vernasca cement plant for 2'000 hours to optimize solvent composition and plant configuration in a real industrial environment and to evaluate solvent degradation, then the hybrid oxyfuel/PCC configuration will be tested at a Titan cement plant, with over 2'000 hours of operation planned. The project aims to produce 7-8 tonnes per day of ultra-high purity (>99.9%) liquid CO_2 while achieving an impressive CO_2 removal efficiency of 98%. Additionally, when co-firing biomass in the calciner, the process intends to generate negative emissions. The system is designed to have reduced energy penalties for CO_2 capture, decreasing by more than 50% compared to MonoEthanolAmine (MEA) SPECCA benchmarks. The project will also demonstrate the system's flexibility, ability to be retrofitted, and gradual implementation across two cement plants through specific tests conducted in subsequent phases.

The second objective is to optimize CO_2 capture in EfW plants by designing, building, and demonstrating a novel high-purity CO_2 capture system using Circulating Fluidized Bed (CFB) CaL technology at the A2A “Silla2” EfW plant in Milan. This innovative pilot system, approximately 1 MW_{th} in size, will be installed in one of the three lines of the Silla2 plant, which efficiently treats waste and provides electricity and district heating services to the city. The demonstrator is expected to achieve up to 95% capture efficiency, while reducing the energy penalty associated with CO_2 capture by 30% compared to the MEA benchmark. Additionally, the system will be integrated with a CPU designed to treat and liquefy 15 tonnes of 99.9% pure CO_2 per day captured by the CaL facility. This demonstration aims to verify several key aspects: (i) the synergies with the existing flue gas treatment system, particularly regarding the co-removal of acid gases; (ii) potential reductions in pollutant emissions from EfW facilities; and (iii) the possible recovery of materials such as phosphorus and ashes.

The third goal of the HERCCULES project is to demonstrate circularity and optimal resource usage through by-products and CO_2 utilization. The initiative aims to create synergies between the cement and EfW sectors by reducing the carbon footprint of cement and concrete through experimental studies at TRL 7-8. The complete CCU chain will be demonstrated by advancing two mineralization processes. Additionally, resource circularity will be tested by recycling CaL by-product material (CaO) in two full-scale concrete casting and cement making plants. Promising mineralization technologies that utilize zeolites and demolished concrete will be installed within the Buzzi and Titan cement plants. These will be integrated with the capture demonstration plants, producing more than 8'000 tonnes of low-carbon concrete. The mineralization technologies will showcase both the direct sequestration of CO_2 and the enhanced quality of the carbonated concrete, which allows for a reduced cement-to-concrete ratio. This also results in additional CO_2 avoidance using Supplementary Cementitious Materials (SCMs) and low-CO_2 binders. The exhaust CaO-based sorbent, purged from the CaL-EfW pilot plant in Milan, will be recycled as decarbonized raw meal for two applications: (i) producing an alternative hydraulic binder using the TRL 8 Celitement pilot plant and (ii) creating low-carbon clinker in an operational Buzzi cement plant, where the CaL purge will replace the conventional raw meal.

The fourth objective is to expedite the implementation of CO_2 storage in strategic areas of the Mediterranean basin. More than 1'000 tonnes of captured CO_2 will be stored at Southern Europe's most advanced CO_2 storage sites: Prinos in Greece (Energean) and Ravenna in Italy (ENI). These sites are notable for their high-capacity and cost-effective potential for CO_2 storage, their strong connections to potential clusters of emitters, and the ability to repurpose existing infrastructure for CO_2 transport and storage. Assessing permitting, CO_2 transport and logistics, safety, injection, and monitoring plans at these two sites will be crucial for enabling pioneering industrial projects that encompass the entire CCUS chain in Southern Europe.

The final goal of the HERCCULES project is to promote CCUS in Southern Europe by establishing a foundation for societal acceptance, creating effective business models, and generating regulatory experience and political awareness. Significant attention is being focused on several key areas: (i) raising CCUS awareness among societal stakeholders and assessing their readiness to engage in decarbonization initiatives with dedicated activities at regional scale; (ii) facilitating the development of an efficient policy and regulatory framework; and (iii) integrating technical and societal requirements into a comprehensive CCUS management framework. The project consortium is taking a multidisciplinary approach to evaluate the upscaling of the entire CCUS chain. This includes examining business models, CO_2 logistics, safety measures, permitting processes, regulatory elements, and financial mechanisms aimed at reducing perceived financial risks, with the final goal of identify and eliminate the barriers that limit CCUS deployment in Northern Italy and Greece.

4. Activity progress

In WP2, the design of the movable skid-mounted PCC pilot plant has been completed, and the procurement and construction phases are currently underway. The plant is expected to be commissioned in the coming months. Through collaboration among TPI, SIAD, PoliMi, and Buzzi the engineering of this new generation, fully instrumented PCC pilot plant has been achieved, integrating it with a CO_2 liquefaction unit. This setup will demonstrate enhancements in the post-combustion capture process, including a novel membrane contactor, absorber intercooling, mechanical vapor recompression applied to the regenerated lean solvent, and solvent regenerator with solvent split. The plant will utilize MEA and advanced solvents to evaluate their effectiveness in treating real exhaust emissions from two cement plants. The PCC plant will operate in a stand-alone configuration in Vernasca (Buzzi) and will be integrated with the oxyfuel calcination pilot plant in Thessaloniki (Titan) to showcase the hybrid process. This PCC plant is fully instrumented and incorporates all the necessary features to achieve the ambitious targets of the HERCCULES project, aiming to produce 2.5-3 tonnes of high-purity CO_2 per day.

On the other hand, the design and construction of the oxyfuel calcination pilot plant, which is relevant for demonstrating both partial oxyfuel and the novel hybrid process, is under development. LUT, LEAP, and PoliMi have implemented simulation tools, using various approaches, such as 0D process modelling and CFD routines, for reactor simulation. These tools helped assess the mass and energy balances of the oxyfuel calcination process (LEAP, PoliMi), provide preliminary designs for the 1.5 MW_{th} calciner according to the specifications, and estimate the pilot's performance under different operating conditions. The preliminary results will be refined in the project’s next phase through collaboration with the pilot plant designers, aiming to produce the final version for the upcoming procurement and construction stages.

In WP3, the design and detailed engineering of the integrated CaL+CPU pilot plant have been completed by the joint collaboration of Sumitomo SHI-FW, A2A, TPI, LEAP, and PoliMi, and the procurement phase is currently underway. The project's technology providers have made significant additional efforts to ensure that the pilot plant incorporates all the innovative features necessary to achieve the specified Key Performance Indicators (KPIs). The pilot plant is designed with the flexibility to explore the performance of the integrated CaL+CPU process under various operating conditions, such as different types of fuel, oxygen concentration, and carbonator temperature. It features a unique configuration that includes vent-gas recycling to the carbonator, aimed at enhancing CO_2 capture rates (>95%) and achieving high CO_2 purity levels (>99.9%), surpassing the current state of the art. Experimental activities have been conducted by CSIC to evaluate the physicochemical properties of the Ca-based sorbent to be used in the CaL pilot plant. The properties assessed include sorbent purity, chemical composition, real density, and porosity, which were determined using techniques such as Inductively Coupled Plasma (ICP), X-Ray Diffraction (XRD), helium pycnometry, and mercury porosimetry.

The demonstration of technologies for CO_2 mineralization and CaO-CaL by-product re-utilization is yet to begin, as it is heavily dependent on the operation of CO_2 capture demonstrators in both the cement and EfW plants. However, to support the design of the zeolite-based mineralization pilot, several natural and synthetic zeolite materials have been evaluated by Artidek, Buzzi, and PoliMi. Two of these materials have been further characterized to assess their suitability for upcoming CO_2 adsorption tests at the Vernasca cement plant and the production of cementitious matrices. In addition to reducing the carbon footprint of the cement and concrete industries through direct CO_2 capture, the HERCCULES project aims to demonstrate the carbon-sink potential of construction materials. This will be achieved by integrating innovative methods for CO_2 mineralization and the combined re-utilization of spent CaO-based sorbents and waste demolished concrete to create new low-carbon binders, as well as cement and concrete formulations. The construction of the mineralization plant is currently underway, with its commissioning expected to be completed in the coming months. The selection of the additional mineralization pilot plant, which will be integrated with the partial oxyfuel pilot plant in Thessaloniki, is still in the early stages. This selection process will be finalized once the design of the oxyfuel calciner is complete. In this case, fine demolished concrete will be utilized to capture CO_2 from the vent gas of the oxyfuel and CPU pilot plant, demonstrating a novel combination of CO_2 capture and utilization technologies. Subsequently, the CO_2-loaded material will serve as a recycled feedstock for producing low-carbon, high-quality, and marketable concrete.

Finally, regarding the communication, social and regulatory activities, the in-depth regional community profile of the two regions in Italy and Greece, where CO_2 storage is planned to occur, and the survey results on community acceptance of CO_2 storage pilots have been delivered. On the other hand, the analysis of the international and national CCUS regulations influencing the implementation of CCUS cluster projects is ongoing, and a preliminary outline for HERCCULES citizen engagement plan has been designed. Regional (Kavala and Emilia-Romagna) stakeholder committees have been set up, group meetings are proceeding according to schedule, the local stakeholder and citizen engagement strategy effort is ongoing, and the interdisciplinary dialogue aimed at creating awareness for societal readiness and engagement among the consortium partners is regularly taking place during the consortium meetings.

Acknowledgements

Founded by the European Union. This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101096691.

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

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