ALLEGATO B

PE00000021
"PNRR MUR - M4C2 – NEST - Extended Partnership Network 4 Energy Sustainable Transition"

SPOKE N. 4

CUP D33C22001330002

Research proposal

Topic addressed by the project (with reference to Allegato 2)

i. **Innovation for green hydrogen production from biomass**

Acronym - Project Title

AB2H - **A**dvanced **B**iomass **to H**ydrogen: Pathways for Eco-Efficient Energy Conversion

- Name of the PIs' host institution for the project: **University of Calabria (Italy)**
- Name of the Principal Investigators (PIs):
  - ***Prof. Petronilla Fragiacomo***
  - ***Prof. Vincenza Calabrò***
- Proposal duration in months: **12 months**

- Name and qualification of the Principal Investigator (PI)
- Name and qualification of the co- Principal Investigator (PI)
- Name and qualification of the components the research team

ROLE IN THE PROJECT	*NAME*	*SURNAME*	*INSTITUTION/ DEPARTMENT*	*QUALIFICATION*	*YOUNG (under 40 al 31.12.2023)*	*F/M*
Principal Investigator	*Petronilla*	*Fragiacomo*	*University of Calabria – Department of Mechanical, Energy and Management Engineering*	*Full Professor in Power and Energy Systems*	*No*	*F*
co-Principal Investigator (PI)	*Vincenza*	*Calabrò*	*University of Calabria – Department of Computer Engineering, Modeling, Electronics and Systems (DIMES)*	*Full Professor of Transport Phenomena*	*No*	*F*

ABSTRACT

The current research proposal focuses on advancing hydrogen production from various sources, including organic biomass, synthesis gas, and wastewater. It aims to investigate and improve three main processes: bio-fermentation and dark fermentation, advanced Water Gas Shift (WGS), and advanced Microbial Electrolysis Cells (MECs). In addition to achieving efficient green hydrogen generation, the proposal aims to contribute to waste-to-energy initiatives by converting waste materials into valuable energy resources. Dark fermentation shows promise for hydrogen production from diverse biomass sources, such as agricultural waste to algae, without requiring external energy input, potentially leading to cost savings and enhanced efficiency compared to traditional methods. Innovative WGS systems and catalysts aim to enhance green hydrogen generation from syngas, thereby increasing the total hydrogen output and improving the conversion efficiency of CO to hydrogen. MECs offer a novel approach by combining microbial biocatalysis with electrolysis to directly convert organic substrates into hydrogen, potentially reducing energy consumption and environmental impact. Additionally, the possibility of directly converting wastewater into hydrogen is a noteworthy aspect of the proposal. A specialized research team has been assembled, with expertise in efficient hydrogen generation methods, particularly in fuel cell-based systems, and in bio-chemical processes typical of process engineering, such as those involving bio-fermenters. The project will involve both theoretical and experimental studies to explore avenues for process improvement through the introduction of innovative materials. Efforts will be made to optimize the processes and integrate the system, ensuring a proper Balance of Plant is accounted for, proposing real-world integration and/or modifications. The results are expected to demonstrate significant improvements compared to the State of the Art through proper KPIs.

RESEARCH PROPOSAL
Sections (a) and (b) should not exceed 4 pages. References do not count towards the page limits.

Section a. State-of-the-art and objectives

The biomass-to-hydrogen production landscape is currently varied, using a range of thermochemical and biochemical processes [1–7]. Conventional techniques for producing hydrogen, including pyrolysis, gasification, and steam reforming, have been well studied [8,9]. These technologies do, however, have a number of drawbacks, such as their poor efficiency, excessive energy consumption, and substantial environmental effects. There are usually differences in the efficiency of converting biomass to hydrogen, which leads to a reduced output of hydrogen relative to the potential of the biomass feedstock. Furthermore, the high energy input costs and the intricate process infrastructure further impede the wider use of these technologies.

The limits of conventional biomass-to-hydrogen conversion techniques have given rise to innovative strategies including fermentation and dark fermentation as viable alternatives. Through the anaerobic conversion of biomass into hydrogen by microorganisms, these technologies provide a more efficient and sustainable route for the generation of green hydrogen:

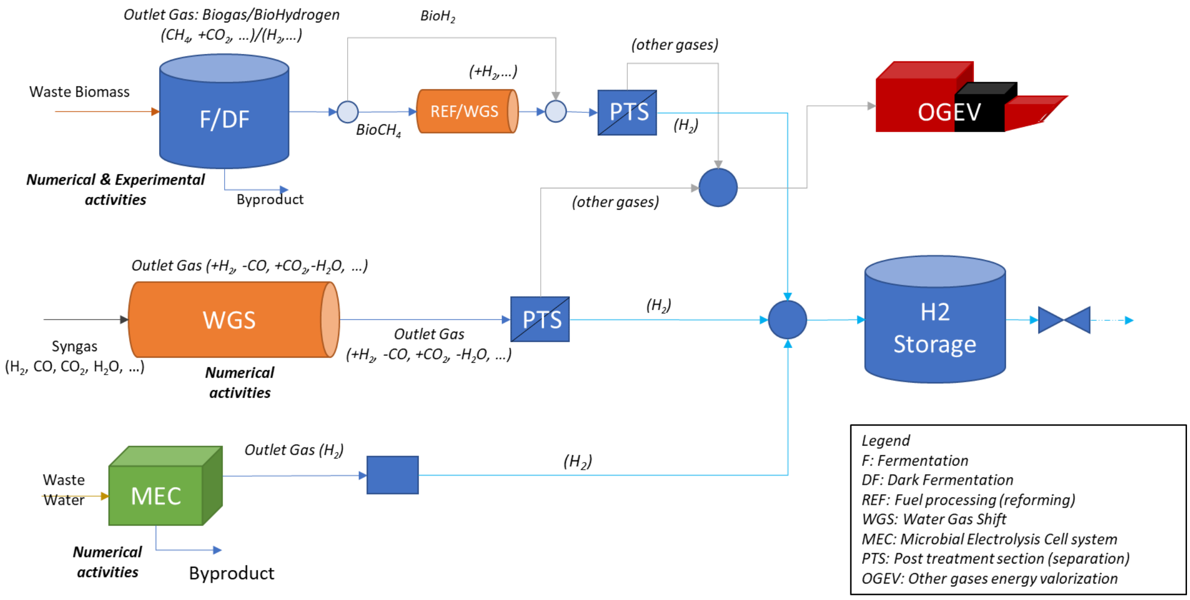
- Fermentation and Dark Fermentation Processes [10–19]: These novel techniques make use of the organic matter's natural breakdown by certain bacteria when there is no light present (dark fermentation) or just a small amount of light exposure (fermentation). The capacity of dark fermentation to create hydrogen from a variety of biomass sources, including agricultural waste, without requiring external energy input makes it especially noteworthy. Comparing this strategy to traditional ways might result in cheaper costs and improved efficiency.
- Innovative Water-Gas-Shift (WGS) System Development [20–22]: The plan calls for the development of innovative WGS systems and catalysts to improve the generation of green hydrogen from syngas. These cutting-edge systems seek to increase the total output of hydrogen from syngas obtained from biomass by improving the conversion efficiency of CO to hydrogen via catalyst design and reaction condition optimization.
- Utilizing Microbial Electrolysis Cells (MECs) to Produce Hydrogen [23–25]: The creation of methods for producing hydrogen effectively using microbial electrolysis cells (MECs) is another field of innovation. By combining microbial biocatalysis with electrolysis to directly transform organic substrates into hydrogen, MECs provide a novel method that may reduce the energy used and the environmental impact of hydrogen generation.

In addition to addressing the technical elements of producing green hydrogen, the main objective of the present proposal "***Advanced Biomass to Hydrogen (AB2H): Pathways for Eco-Efficient Energy Conversion***" is to guarantee that these breakthroughs make a substantial contribution to the field of renewable energy, economic growth, and environmental sustainability. The following objectives are the main goals that the proposal ***AB2H*** aims to achieve for an innovative and efficient H_2 production:

1. Improve the Efficiency of Hydrogen Production:
   - In-depth research and development on dark fermentation and fermentation methods to determine the ideal circumstances for achieving the highest possible output of hydrogen. This includes choosing appropriate biomass types, refining process parameters including pH, temperature, and nutrient delivery, optimizing microbial consortia, and process engineering including enhancement on pre and post-treatment. The valorization of waste biomasses, including invasive macroalgae affecting marine ecosystems' integrity and unbalancing native communities, allows to turn a threat into a major opportunity. This goal will be achieved via both numerical and experimental activities.
   - By concentrating on system integration, analysis of the innovation in the design and operating parameters of Water-Gas-Shift (WGS) systems to increase the efficiency of hydrogen generation

from syngas. This goal will be achieved via numerical simulation. A broad range of operating conditions will be explored, incorporating techniques such as stream recycling and stepwise adjustments in temperature and pressure. These investigations will leverage the latest catalyst advancements, with their parameters integrated into the models. The simulation runs will identify the optimal operating parameters, thereby preventing potentially harmful operating conditions that could damage reactors and diminish performance.

- Performance analysis and scale-up process of microbial electrolysis cells (MECs). This goal will be achieved via numerical simulation. Studies will be directed mainly towards: (1) Process Optimization, by developing advanced control strategies and optimization algorithms to maximize hydrogen production rates, minimize energy consumption, and improve overall process efficiency, (2) Scale-Up Strategies to enable large-scale hydrogen production for industrial applications; (3) Exploring the integration of MECs into biorefinery processes for simultaneous wastewater treatment and hydrogen production, thereby enhancing overall process sustainability and economic viability.



2. Create Economically Viable and Scalable Processes:
   - To create scaled models of the suggested methods for producing hydrogen that are feasible from an economic standpoint for use in large-scale manufacturing.
   - To investigate the viability of incorporating these systems for producing hydrogen into already-existing biomass processing plants in order to take advantage of synergies and save installation costs.

Other parallel goals are: 3. Minimize the Effect on the Environment and Encourage Sustainability, 4. Promote the Sector of Renewable Energy; 5. Boost Diversification and Energy Security.

Through the accomplishment of these goals, the present proposal aims to elevate fermentation and dark fermentation methods to the forefront of green hydrogen generation, demonstrating their potential to transform the energy industry and promote environmental sustainability, as well as investigating via numerical activities the system integration of WGS systems to increase the efficiency of hydrogen generation from syngas and providing in-depth performance analysis and scale-up process of MECs.

Section b. Methodology

The following points will be considered for the methodology that the proposal ***Advanced Biomass to Hydrogen (AB2H): Pathways for Eco-Efficient Energy Conversion*** intends to adopt*:*

Design Experiments: The purpose of the experimental design is to assess the effectiveness and optimize the circumstances of the dark fermentation and fermentation processes used in the production of green hydrogen and, therefore estimate KPIs. The following essential elements are included in the design:

a. Choosing the Types of Biomass:

- Examination of a range of biomass sources, such as energy crops, municipal organic waste, slaughterhouse waste, and agricultural wastes (such as husk and straw). The primary selection criteria will centre on accessibility, eco-friendliness, carbon and water (and land) footprint, and possible hydrogen production. A combination of biomass sources will improve the yield and efficiency of the process.

b. Conditions of Process:

- Fermentation: Setting up of a controlled batch and continuous fermentation studies to analyze how several factors affect the amount of hydrogen produced, including pH (5–9), temperature (20–85°C, into the mesophilic and thermophilic ranges), substrate concentration, and nutrient availability. The biohydrogen production will be performed after choosing proper bacterial strains in a suitable bioreactor configuration (the continuous stirred tank reactor, CSTR, was widely used for continuous fermentative hydrogen production) and under optimized operating conditions, organic loading rate (OLR), in order to achieve desirable H_2 yield and production rate. The effect of nitrogen, phosphate and substrate contaminants on the production will be addressed. Yield and productivity as well as energy consumption and sustainability will represent the goal of the process optimization based on an accurate choice of best combination of operating conditions.
- Dark Fermentation: Execution of comparable studies in anaerobic environments, paying special attention to microbial consortiums, pH, and temperature (30–55°C) to optimize hydrogen output from various biomass sources. The effect of substrate concentration, pH, temperature, and residence time on hydrogen yield and productivity will be studied and the optimum operating conditions to obtain the desired hydrogen production will be selected.
- Gas-Water-Shift (WGS) Reaction Optimization: Efforts to enhance the efficiency of hydrogen synthesis from syngas derived from biomass will involve exploring various pathways for process and system optimization. Initially, a broad range of potential catalysts will be scrutinized through an in-depth review of the literature, with a focus on recent trends. Subsequently, process enhancements will be examined using sensitivity analysis methodology, involving adjustments to all operating parameters, including inert gas concentrations, to identify the Pareto energy frontiers. Finally, attention will shift to the system level, with investigations into the potential recirculation of off-gases and the implementation of successive series-steps reactors.
- Microbial Electrolysis Cells (MECs): Research into waste-water processing will involve a comprehensive review of recent literature findings, which will then be incorporated into appropriate modeling frameworks. Furthermore, efforts will be directed towards process and system optimization in this domain as well.

2. *Strategies for Performance Analysis under various circumstances*:
    - Analysis of the ideal circumstances for maximal hydrogen production, and use of the Design of Experiments (DOE) to methodically examine the relationships between process factors.

Use adaptive control techniques in ongoing operations to keep conditions at their best even as the biomass composition or external circumstances change. The method for analyzing data consists of:

1. Hydrogen Yield and Process Efficiency:

- Adoption of statistical analytic methods, quantification of the hydrogen yield (volume of hydrogen generated per unit of biomass) with its comparison across various biomass kinds and process conditions.
- Assessment of the process's energy efficiency by measuring the energy input-output ratio and comparing it with conventional hydrogen generation techniques.

2. Advantages for the Environment:
    - Determination of the carbon footprint, water footprint, and overall environmental effect of the hydrogen production process, from biomass procurement to hydrogen generation.
    - Estimation of greenhouse gas emissions reduction and other environmental advantages, and comparison of the environmental performance of fermentation and dark fermentation procedures with traditional fossil fuel-based hydrogen generation techniques.
3. Identification and estimation of KPIs, considering the entire engineered plant and its related Balance of Plant (BoP):
    a. Energy KPIs – (electrical) kWh_{el}/kg_{H2}, (thermal) kWh_{th}/kg_{H2}, (heat recovery by energizing waste outlet gases) $kWh_{th,rec}/kg_{H2}$;
    b. Flow KPIs – (hydrogen yield) $kg_{H2}/kg_{biomass}$; (catalyst in WGS) kg_{cat}/kg_{H2};
    c. Footprints - (water usage) l_{water}/kg_{H2}, (land usage,) m^2_{land}/kg_{H2}, (carbon footprint 'GHG') $kg_{CO2,eq}/kg_{H2}$, (outlet ratio other gases other than H_2) $kg_{al,gases}/kg_{H2}$;
    d. Space KPI – $m^3_{reactor}/kg_{H2}$;

An energy valorization analysis will be also performed, as it relates to the generation of green hydrogen via fermentation and dark fermentation processes, and it is the deliberate conversion of biomass into high-value hydrogen energy, with a focus on optimizing the process's sustainability and efficiency. The following methodology will be used for assessing the energy valorization:

- Calculating Energy Yield: Calculate the energy yield of the generated hydrogen, and compare it with its energy content by the energy input needed for fermentation, biomass processing, and any other post-treatment procedures that may be required.
- Integration and Optimization of Processes:
    - Assess potential avenues for integrating processes to enhance energy efficiency. This involves the integration of heat and power systems, which lowers the total amount of energy required for energy input by using waste heat from one process step to power another.
    - Optimize process variables (such as temperature, pH, microbial consortiums, materials to improve H_2 yields, inhibiting side reactions) to increase biomass conversion efficiency to hydrogen, to produce more energy from a given amount of energy.
    - Process engineering, through the study of pre and post-treatment techniques in addition to the search for the best process parameters;
    - System engineering, through the study of flow recirculation, reactor splitting, and subsequent biomass additions.
- Utilizing Sustainable Energy Sources to reduce the carbon footprint, such as solar or wind energy, in the production process.
- Co-product Valorization: Co-products, such as organic acids, alcohols, and biomass leftovers may be used or sold to recoup production expenses and increase the process's total energy value. Digestate can be used as a fertilizer.
- Analysis of Life Cycle Energy (LCEA): To evaluate the whole energy balance of the production process, from biomass feeding to hydrogen generation. This analysis aids in identifying phases that need a lot of energy and provides chances for more optimization.

Technical-economic evaluation (TEA): To assess the energy valorization and economic viability of the suggested hydrogen generation method. This entails figuring out how much producing hydrogen costs per unit of energy and comparing that figure with traditional hydrogen production techniques.

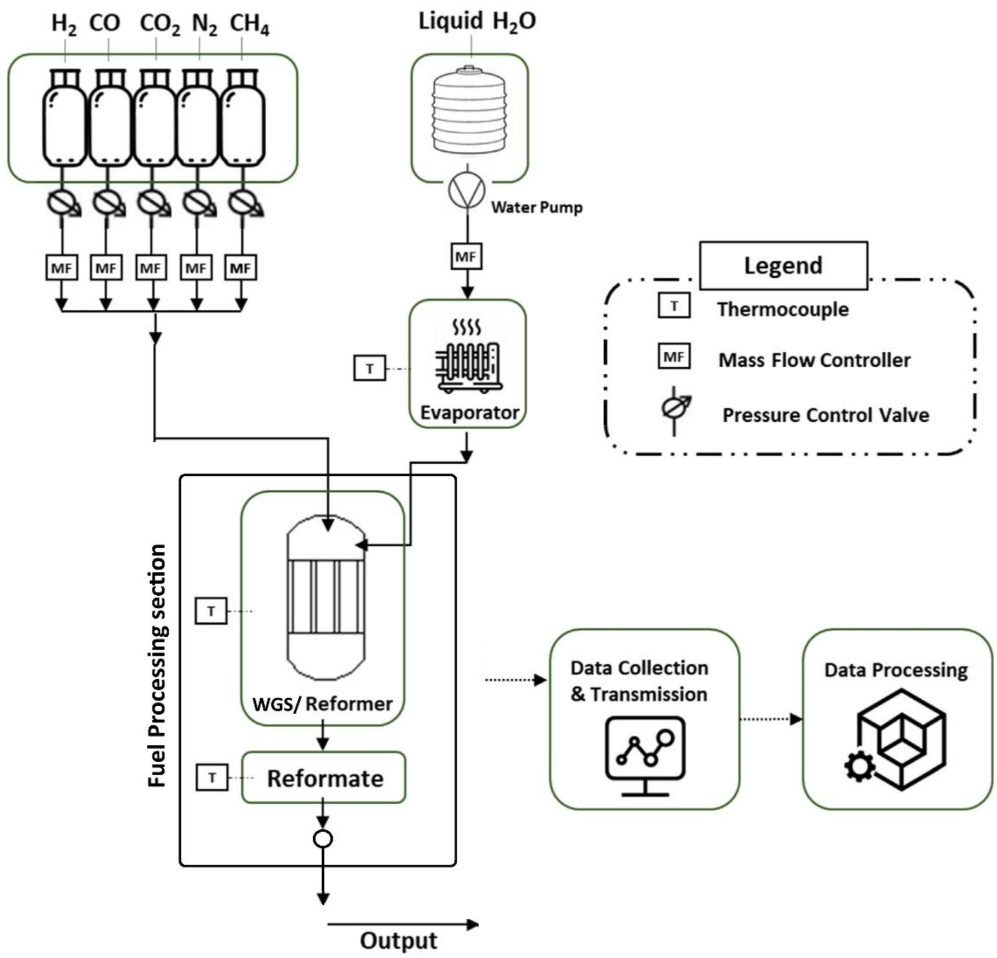
Section c. Available instrumentations and resources

UNICAL has established a group of engineers, chemists, and physicists with diverse expertise, operating in several labs. The proposing research team has significant expertise in the area related to the tender, both in the chain of hydrogen generation, accumulation, and energy usage and in the field of bio-chemical processes regarding bio-fermentation devoted to biogas and biohydrogen from organic matrices.

The research team covers the required skills and experience needed for the activities of the present proposal, according to two well-established working sub-groups.

Fuel cell and Hydrogen Laboratory For this purpose, the "fuel cell and hydrogen team" led by Prof. Fragiacomo makes its expertise available in the field of the study of integrated fuel cell systems for traction vehicles, as well as for stationary power engineering. Research has shifted towards creative energy systems that are environmentally friendly and highly efficient in the last fifteen years, covering both renewable and fossil sources. The whole hydrogen supply chain plays a crucial role. Various fuel cell and electrolyzer types are under investigation using numerical and experimental modeling to produce novel materials. In this, a significant attention is covered by the fuel processing section, which, in its turn, plays a pivotal role when powering fuel cells with gas streams different from pure hydrogen. Fuel processing is operated by a WGS/reforming reactor that is able to convert respectively, CO rich gases and hydrocarbon rich gases. The objective behind research is virtualizing the waste to energy chain, contributing a ring of the chain which is given by the energy usage of the output resulted from a typical biomass and waste biomass (cold and hot) gasification. **Syngas as CO rich gas, deriving from waste biomass gasifier, is approached and simulated by means of the typical gas mixture of CO, H_2, H_2O, CO_2, N_2, and even CH_4 in traces, by changing and organizing opportunely the concentrations. Analogously, biogas, deriving from waste biomass anaerobic digestion, is approached and simulated by means of the typical gas mixture of CH_4 and CO_2.**

For the purpose of the present proposal, the "Fuel Cell & Hydrogen" (FCH2) Lab is dedicated to researching the hydrogen supply chain, specifically focusing on hydrogen production technologies, fuel cells, and sustainable hydrogen transportation. The associated laboratory is furnished with cutting-edge equipment for researching and analyzing hydrogen and fuel cell systems. The primary research activities involve conducting electrical characterization of solid oxide fuel cells to create voltage-current maps.



Additionally, electrical characterization of solid oxide electrolytic cells is done during electrolysis and co-electrolysis using combined steam and steam-carbon dioxide flows to generate voltage-current maps. Investigation in fuel processing covers a central role too, especially when operating with carbon-rich gases. The laboratory is complemented with a round trip-low temperature power station (polymer membrane-based) devoted to hydrogen production, accumulation, and energy usage.

The laboratory's gas supply system is a pivotal component meticulously designed with specialized and advanced equipment to ensure uninterrupted and safe gas provision. Specifically tailored to handle gas streams generated from waste biomass processing, the system accommodates gases such as H_2, CO, CO_2, CH_4, and N_2, which are stored in dedicated storage units and controlled through a specialized management system. Steam generation is facilitated through the evaporation of deionized water. Additionally, the fuel processing section plays a crucial role in transforming gases into hydrogen-enriched streams, thereby facilitating processes like the Water Gas Shift (WGS) or Reforming. Equipped with dedicated catalytic reactors, this section serves as either a WGS or reformer unit depending on operational requirements. Furthermore, alongside managing gas composition and flow rates using precision mass flow controllers, the fuel processing section allows for temperature adjustments to optimize performance.

The following activities are carried out in the FCH2 Lab:

- Analyze the thermo-electrochemical processes of the "Fuel Cell System" experimentally with varying operating settings.
- Numerical modeling of thermo-electrochemical and fluid dynamic processes in Fuel Cell/Electrolyzer systems developed at different degrees of detail.
- System combining a hybrid/integrated polymer electrolyte fuel cell with a low-temperature PEM electrolyzer.
- Hybrid system (battery and PEM fuel cell, fuel cells and turbines, coupling gasification-fuel cells).
- Numerical simulation of green hydrogen generation systems for Electrochemical Storage and Power-to-X Applications.
- Researching the feasibility, analysis, and development of hydrogen valleys.
- Designing innovative hydrogen infrastructures for production, distribution, and operating strategies.
- Tools for analyzing performance and co-designing hybrid fuel cell powertrains for sustainable transportation in various modes such as road, rail, and marine.
- Managing energy in PEM fuel cell stacks for combined electricity and thermal energy production.
- Optimizing power and energy distribution in hybrid fuel cell vehicles.
- Managing PEM stacks in Vehicle-to-Grid applications.

Numerical modeling approaches are used to provide efficient and dependable computational tools for designing and managing fuel cell systems. The tools enable users to choose the most advantageous system configuration based on the kind of user it interacts with, improving the energy process by determining the optimal operating circumstances:

- Green hydrogen generating systems for power storage and conversion applications in electrochemical devices.
- Waste-to-energy supply chain: converting biomass into energy.
- Utilizing high-temperature fuel cells in integrated power plants.

Regarding the subject matter of the tender, Prof. Fragiacomo possesses a wealth of consolidated experience in energy conversion, conservation and rationalization as well as environmental protection. In actuality, various fuel cell and electrolyser types are studied using experimental and numerical modeling. Regarding low-temperature technology, fuel cells and polymer membrane electrolysers are extensively studied, as supported by research published in international journals in the field.

She is also CEO of the University SpinOff ENERVA H2. The ENERVA H2 mission is focused on the "green and clean energy ”with particular vocation to the“ waste to energy chain ”, with a view to process efficiency and energy maximization according to the objectives of efficiency and environmental sustainability. The systems underlying the company vision use the Fuel Cell technology. These systems are used in the production of cogenerative energy and in the chain of production, storage and distribution of hydrogen. The company is the depositary of an application for an engineering patentability solution, for which the undersigned is among the inventors - Patent application for invention n. 102021000023411 filed on 10 September 2021, Country: Italy, Ref.: Anaerobic Digester Energy System _ Solid Oxide Fuel Cell

Prof. Fragiacomo along her long-run research activity has established several international and national collaborations, with university, research centers and industries operating in the hydrogen supply chain. Zooming into the context of activities showcased in this proposal is has to be highlighted that a collaborative effort have been established with the company **Waste to Methane (W2M)**, which designs and manages biomethane production plants and **Calabra Maceri & Servizi.** W2M is a pioneering entrepreneurial venture situated in Rende—Cosenza, Italy, which originated from the concept of transforming organic waste sorted by Calabra Maceri & Servizi into valuable and environmentally friendly biomethane. The Calabra Maceri & Servizi enterprise deals with the management of municipal solid waste, encompassing a range of facilities, including material recovery plants dedicated to recycling and reusing, a landfill, an eco-district, and a composting facility.

As presented in the attached CV, Prof. Fragiacomo is the author of over 140 publications. It is important to emphasize that cutting-edge, environmentally friendly, and clean energy systems—particularly hydrogen—have a significant role in her scholarly and scientific endeavors. Prof. Fragiacomo has an extensive and long-run experience and expertise in the field of biomass conversion and valorization, with a specific emphasis on the waste biomass, as described in the CV and in her scientific publications, with more of 20 scientific items on this topic. In this context, several scientific articles are focused on the engineering design of integrated systems of biodigester and biomass valorization systems, as well as gasification, with conventional and innovative technologies, such as fuel cells.

Transport Phenomena and Biotechnology laboratory

The research team of Transport Phenomena and Biotechnology, led by Prof. Calabrò, is instead involved in the study, investigations, and experimentations of phenomena typical of process engineering as those occurring in the biochemical process of fermentation for energy gases.

Transport Phenomena and Biotechnology (LabFTB) - The Transport Phenomena and Biotechnology research team has been carrying out intense research activity for around thirty years in the field of chemical and process engineering. The main lines of research concern the production of biofuels from wastewater and "competitive non-foodstuff" sources, the study of transport phenomena in separation/purification systems (membrane technologies); mathematical modeling and engineering of products and/or transformation processes, as well as a whole series of activities typical of process engineering.

A central activity concerns modeling, investigation and testing of transport phenomena in bioreactors, fermenters and anaerobic digesters. In the field of biofuels, the processes of: fermentation of dairy waste for the production of bioethanol, enzymatic trans-esterification with lipase for the production of biodiesel from vegetable and waste oils and anaerobic fermentation for the production of biogas and upgrading to biomethane are investigated. The kinetic and thermodynamic aspects in biocatalyzed reactions are explored through theoretical and experimental analysis of specific bioconversions. A significant aspect is also inherent to energy storage for which activities are carried out on the characterization of phase change materials, stability analysis using TURBISCAN, biodiesel in smart city field, green metrics and circular economy. The laboratory is equipped with advanced equipment and systems for the characterization of biomaterials and process analysis. In particular, among the numerous pieces of equipment it is worthy mentioning:

- an APPLIKON laboratory fermenter, which can also be used as a bioreactor in CSTR or STR configuration, complete with all control units (capacity 1 liter and 2 liters);
- STEROGLASS laboratory fermenter, which can also be used as a bioreactor in CSTR or STR configuration, complete with all control units (capacity 500ml);
- Pilot scale plant for biogas production, used for mixed matrix testing;
- AMPTS system consisting of 15 anaerobic digesters for the determination of the methanogenic power of organic matrices;
- Dry incubator to study photocatalyzed processes and algal growth;

- Refrigerator-thermostat for BOD determination for wastewater analysis and characterization of the thermal properties of phase change materials.

Prof. Calabrò is Full Professor of Transport Phenomena since 2017 at the University of Calabria, Department of Informatics, Modeling, Electronics and Systems Engineering - DIMES. She is responsible and co-responsible for several research projects, International, funded by the European Community, and Nation, funded by Government and Industrial Houses such as the Ministry of Economy or University and from local and national companies, in the field of Biotechnology, Agro-food, Separation, Environment and Biofuels.

Over the course of ten-year activities, she organized a research team deeply expert in process engineering, particularly competent in the biochemical processes of degradation of organic substances into energetic gases. Its research activities, in the field of chemical engineering, are perfectly suited to the energy transition chain, particularly in the circular economy ring which concerns the recovery and energy transformation of waste.

The research team avails of several collaborations with national and international research centers with shares and updates research results.

Aside the university professors presented in the proposal, and whose CVs are attached, the project will include the involvement of other researchers/external collaborators of our Departments.

Section d. GANTT diagram

According to the activities exposed in the previous sections, this paragraph showcases how the latter are intended to be carried out over 12 months. Following, the activities and sub-activities of the Gantt are reported.

The proposed activities are organized to include three development phases, as follows:

- PHASE 1: A phase of analysis of the reference process and the technological challenge faced, of its complexity and state of the art of the technologies/approaches currently existing to identify the level of innovation of the proposed solution.
- PHASE 2: An innovation development phase.
- PHASE 3: A prototyping/validation and testing phase of the proposed processes/solutions

Therefore, the conduct of activities follows the set framework.

The activities are classified into 4 main groups (A1- Fermentation 2 H_2; A2 - Advanced WGS; A3 - Advanced MECs; A4 – Tool and KPIs delivery). Generally, the first three activities are centered on the study and enhancement of fermentation, WGS, and MEC processes, while the fourth regards the tool tuning devoted to the presentation of KPIs that will be gained.

In particular, activity A1 is expected to reach a TRL4 level "Technology validated in the laboratory", starting from a TRL3 level "Experimental proof of concept". The research team, following the implementation of the proposed innovation, is confident in taking the TRL to the next level.

The processes will be studied and investigated firstly numerically, by updating the models with proper parameters fitting the novel material used. Therefore, a first numerical update is considered, before playing numerical runs. After that, an accurate activity of process optimization and system integration (to account for the proper Balance of Plant) will be carried out to propose real-world integration/modification. Results will show gains compared to the State of Art.

Experimentally, the fermentation and dark-fermentation of organic matrices devoted to biogas/biomethane and biohydrogen generation will be carried out, taking care of gaining significant energy advancement in the field and moving TRL to 4. In this regard, specific equipment will be purchased for laboratory activities.

		Month											
Nr.	Activity	1	2	3	4	5	6	7	8	9	10	11	12
A1	***Fermentation 2 H_2***												
A1.1	Numerical updates												
A1.2	Numerical runs												
A1.3	Process optimization and system integration												
A1.4	experimental tuning												
A2	***Advanced WGS***												
A2.1	Numerical updates												
A2.2	Numerical runs												
A2.3	Process optimization and system integration												
A3	***Advanced MECs***												
A3.1	Numerical updates												
A3.2	Numerical runs												
A3.3	Process optimization and system integration												
A4	***Tool and KPIs delivery***												

Section e. Milestones, Deliverables and KPI

Milestones

- M1 - Completion of Literature Review: Comprehensive understanding of the state-of-the-art and identification of innovation opportunities.
- M2 - Experimental Setup Completed: All experimental systems are operational, and initial tests have been conducted to ensure readiness for data collection.
- M3 - Initial Data Collection Completed: First set of data on hydrogen production from biomass using fermentation and dark fermentation processes has been collected.
- M4 - Optimization Milestones: Key process parameters have been optimized to enhance hydrogen yield and process efficiency.

		Month											
	Milestone	1	2	3	4	5	6	7	8	9	10	11	12
	M1			■									
	M2							■					
	M3					■							
	M4											■	

Deliverables

- **3** Comprehensive Reports on Process Efficiency: A detailed report including methodology, data analysis, findings, and recommendations for the fermentation and dark fermentation processes, as well as efficient WGS and MECs.
- **1** Report presenting the tool tuning and KPIs obtained.
- Publications: At least two publications in peer-reviewed journals, presenting the findings and innovations developed during the project.
- Prototype Model: A working prototype demonstrating the optimized process for green hydrogen production at a scaled-up level.

KPIs

- Hydrogen Production Rate: The volume of hydrogen produced per unit of biomass (l/kg) and per day (l/day) as a measure of process productivity.
- Process Energy Efficiency: The ratio of energy contained in the produced hydrogen to the total energy input required for the process, aiming for a positive net energy balance.
- Energy KPIs – (electrical involvement) kWh_{el}/kg_{H2}, (thermal involvement) kWh_{th}/kg_{H2}, (heat recovery by energizing waste outlet gases) $kWh_{th,rec}/kg_{H2}$;
- Flow KPIs – (hydrogen yield) $kg_{H2}/kg_{biomass}$; (catalyst in WGS) kg_{cat}/kg_{H2};
- Footprints - (water usage) l_{water}/kg_{H2}, (land usage,) m^2_{land}/kg_{H2}, (carbon footprint 'GHG') $kg_{CO2,eq}/kg_{H2}$, (outlet ratio other gases other than H_2) $kg_{al,gases}/kg_{H2}$,
- Space KPI – $m^3_{reactor}/kg_{H2}$,
- Reduction in Carbon Footprint: Quantified reduction in CO_2 emissions compared to conventional hydrogen production methods, aiming for a significant decrease to demonstrate environmental benefits.

Annexes: Curriculum vitae research team

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Curriculum vitae PI (max. 5 pages)

PERSONAL INFORMATION

Family name, First name: **FRAGIACOMO, Petronilla**

Researcher unique identifier(s) (such as ORCID, Research ID, etc. ...):

- **ORCID: 0000-0003-0720-5490**
- **LINK IRIS: https://iris.unical.it/cris/rp/rp35409**
- **Link Scopus: https://www.scopus.com/authid/detail.uri?authorId=6506689818**

Date of birth:

Nationality:

URL for web site: **https://www.unical.it/storage/teachers/gAAAAABjExFBy_RpR-yv4iTmC6H5aacFzJBXjA4MfRKx0jJ6DL7hUznK22MnQE_XoU_ShBBuD5tau2h_nP8aks1P675FIOhTxg==/?lang=en**

Scientific production: M**ore than 140 papers published in journals of international and national relevance**

- **CURRENT POSITION(S)**

2022	Full Professor Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy
1990	Scientific Director of the Fuel Cell and Hydrogen Lab Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy
2018	CEO of ENERVA H2 S.r.l., Academic Spin off

- **PREVIOUS POSITIONS**

2005 – 2022	Associate Professor Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy
1992 – 2005	Researcher Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy

- **FELLOWSHIPS AND AWARDS**

2023	Energies MDPI, Best Paper Award 2021, 3rd Prize, V. Cigolotti, M. Genovese, P. Fragiacomo, "Comprehensive review on fuel cell technology for stationary applications as sustainable and efficient poly-generation energy systems". Energies, 14(16), 4963; DOI:

	https://doi.org/10.3390/en14164963 https://www.mdpi.com/journal/energies/awards/1844
2022	Paper Editor Choice – Energies V. Cigolotti, M. Genovese, P. Fragiacomo, Comprehensive review on fuel cell technology for stationary applications as sustainable and efficient poly-generation energy systems. Energies, 14(16), 4963; DOI: https://doi.org/10.3390/en14164963

- **SUPERVISION OF GRADUATE STUDENTS AND POSTDOCTORAL FELLOWS**

1992 – 2024	Number of Postdocs: 5 Number of PhD: 9 Master Students: more than 100 Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy

- **ORGANISATION OF SCIENTIFIC MEETINGS (if applicable)**

2020	Session Organizer of the sustainable mobility section at the “75° Congresso Nazionale ATI 2020” Roma, Italy.
2016	Member of the organization Committee of the “Giornata della Ricerca del DIMEG”, which included the attendance of numerous companies.
2011	Member of the organization Committee of the “66° Congresso Nazionale ATI”, University of Calabria, Italy.
1989	Member of the organization Committee of the “44° Congresso Nazionale ATI”, University of Calabria, Italy.

- **INSTITUTIONAL RESPONSIBILITIES**

2022– 2024	Chair of the Master degree session Committee of Energy Engineering, Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy
2017– 2020	Chair of the Bachelor degree session Committee of Mechanical Engineering, Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy
2020 – 2024	Vice Coordinator of the Master Course in Energy Engineering Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy
2012 – 2024	Member of the Department Committee, Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy
2012 – 2024	Member of the PhD Course Committee, Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy
1999– 2024	Member of numerous Committees for the selection of Researcher, Post-doc Fellow, Scholarship and PhD positions.

- **REVIEWING ACTIVITIES (if applicable)**

2022 – 2024 Guest Editor of the Special Issue "Hydrogen-Based Energy Systems for Sustainable Transportation" - Energies - IF: 3.252; Citescore: 5.0.
1990 – 2024 Reviewer of numerous international journal, among them: Energy Conversion and Management, Applied Energy, Energy, Renewable Energy, International Journal of Hydrogen Energy, Journal of Rail Transport Planning & Management.
2024 Reviewer of scientific books

- **MEMBERSHIPS OF SCIENTIFIC SOCIETIES (if applicable)**

1989 – now Associated Member ATI (Associazione Termotecnica Italiana)
2018 – now Representative Member of UNICAL in AIMSEA(Associazione Italiana di Macchine e Sistemi per l'Energia e l'Ambiente)
2018 – now Representative Member of ATI in AIMSEA
2018 – now Representative Member of AIMSEA in the DICI (Dottorato in Ingegneria Civile ed Industriale) PhD course (UNICAL)
2021 – now Member of the ATI Calabria board
2018 Member of the Scientific committee for the working group management in the collaboration between Trenitalia and other partners (Università della Calabria, Università Sapienza, Università Mediterranea, Comitato Nazionale Italiano per la Manutenzione)

- **MAJOR COLLABORATIONS (if applicable)**

Dr. David Blekhman, Hydrogen refueling infrastructure, Cal State University Los Angeles, Hydrogen Research and Fueling Facility in Los Angeles (USA)

Prof. Nicola Paltrinieri, Liquid hydrogen, Norwegian University of Science and Technology (NTNU), in Trondheim (Norway)

Dr. Suk-Woo Nam, Reversible Molten Carbonate Fuel Cell, Hydrogen Fuel Cell Research Center of the Korea Institute of Science and Technology (KIST), in Seoul, (Republic of Korea)

Prof. Panagiotis Tsiakaras, Low temperature fuel cells, University of Thessaly, in Volos (Greece)

Prof. Jack Brouwer, Solid oxide fuel cells, University of Irvine, California (USA)

Prof. Jarosław Milewski, High temperature fuel cells, Warsaw University of Technology, in Warsaw (Poland)

Prof. Walter Theodor Czarnetzki, Anionic exchange membrane fuel cells, University of Applied Sciences, in Esslingen (Germany)

Prof. Stuart Hillmansen, Fuel cell hybrid vehicles, Birmingham Centre for Railway Research and Education, University of Birmingham, in Birmingham (Great Britain)

Prof. Elio Jannelli, Hydrogen refueling stations and hybrid vehicles, ATENA Future Technologies Scarl, Napoli

Dr. Viviana Cigolotti, Hydrogen refueling stations, ENEA, Roma

Dr. Vincenzo Antonucci and Dr. Laura Andaloro, Hydrogen and fuel cells, CNR-ITAE, Messina

Other collaborations with Italian universities: Università di Trento, Università Mediterranea di Reggio Calabria, Università di Genova, Università di Messina, Università La Sapienza, Università Partenope (Napoli), Università di Palermo, Università della Basilicata, Università di Udine.

Dr. Massimo Bertoldi, Solid oxide fuel cells and electrolyzers, SolydEra Spa, Italy

Dr. Jann Martin, Hydrogen and e-fuels , E.ON SE, Germany

Dr. Lorenzo Flaccomio Nardi Dei, Fuel cell-based rail vehicles, Trenitalia Spa, Italy

Dr. Alessandro Fiorucci, Green hydrogen production, De Nora, Italy

Dr. Alberto Litta Modignani, Low temperature electrolyzer, NextChem, Italy

Dr. Francesco Massari, Low temperature electrolyzer, F2N, Italy

Dr. Ernesto Ferraro, Hydrogen refueling infrastructures, Ferrovie della Calabria, Italy

Dr. Daniele Severi, Hydrogen-based system modelling, AVL, Italy

Eng. Francesco D'Amico, Biomass, biogas and bio-methane, Waste-to-Methane, Italy

Dr. Crescenzo Pellegrino, Biogas Waste valorization and biodigestor, Calabra Maceri, Italy

Dr. Alessio Capanni, Hydrogen compressors, Baker Huges, Italy

Appendix: All current grants and on-going and submitted grant applications of the PI and Co PI (Funding ID)

Mandatory information (does not count towards page limits)

Current grants (Please indicate "No funding" when applicable):

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current proposal*
SaFE H2D (Safe, Fast and Efficient Hydrogen refuelling for Heavy-Duty Vehicles)	PRIN 2022 PNRR	239˙312,00 €	11/2023 - 10/2025	Principal Investigator	Same field: Hydrogen and fuel cells
Joint project on hydrogen and its derivates with the focus on Germany and Italy	EON company	40˙000,00 €	12/2023 - 05/2024	Scientific coordinator	Same field: Hydrogen and fuel cells
Sviluppo di modelli di ottimizzazione dell'esercizio dei principali componenti costituenti di stazioni di rifornimento a idrogeno (HRS)	PNRR	60˙000,00 €	10/2023 - 12/2025	Scientific coordinator	Same field: Hydrogen and fuel cells
Studio e ottimizzazione tecnico-economica del dimensionamento e dell'esercizio dei principali componenti di stazioni di rifornimento a idrogeno	PNRR	60˙000,00 €	04/2023 - 10/2025	Scientific coordinator	Same field: Hydrogen and fuel cells

Tech4You (Tecnologia per ridurre il consumo energetico e salvare la biodiversità)	PNRR	250˙000,00 €	01/2023 - 12/2025	Sub-action coordinator	Same field: Hydrogen and fuel cells

Appendice dell'Allegato B

Curriculum vitae CO-PI (max. 5 pages)

PERSONAL INFORMATION

Family name, First name: Calabrò Vincenza
Researcher unique identifier: ORCID 0000-0002-0381-7169
Date of birth:
Nationality:
URL for web site: https://www.researchgate.net/profile/Vincenza-Calabro

- **EDUCATION**

1989	PhD "Chemical Sciences and Technologies" University of Calabria, Country PhD Supervisor: Enrico Drioli
1985	Master "Chemical Engineering" Faculty of Engineering, University of Calabria, Italy

- **CURRENT POSITIONS**

2017 –	Full Professor of Transport Phenomena (ING-IND/24) Department of Informatics, Modeling, Electronics and Systems Engineering – DIMES, University of Calabria, Italy
2022 –	Coordinator of the degree course in Chemical Engineering University of Calabria, Italy
2019 –	Scientific Responsible and Coordinator of the activities of Technnological Hall for the mitigation of Pollution -HTI, project PONa3_00341 "PON INFRASTRUTTURE S.I.L.A." University of Calabria, Italy
2019 –	Member of the Technical-Scientific Committee of BATS - Technical and Scientific Library University of Calabria, Italy
2015 –	Member of the Committee of PhD School "Life Science and Technologies" University of Calabria, Italy
2020 –	Responsible of the Laboratory "Transport Phenomena and Biotechnologies" Department of Informatics, Modeling, Electronics and Systems Engineering – DIMES, University of Calabria, Italy

- **PREVIOUS POSITIONS**

2019 – 2021	Coordinator of the degree course in Food Engineering University of Calabria, Italy
2001 – 2017	Associate Professor Faculty of Engineering, University of Calabria, Italy
1992 – 2001	Researcher of Chemical Engineering

	Faculty of Engineering, University of Calabria, Italy
1990 – 1992	Researcher CNR-IRMERC, University of Calabria, Italy
1989 – 1990	Researcher ENIRICERCHE, Italy

- **FELLOWSHIPS AND AWARDS**

2001	Awars "Best paper", XVIII Summer Membrane School "Using Membranes to Assist in Cleaner Processes", European Membrane Society (EMS), Poland
1988	Award "Silver Medal for the Technological Research", Società Chimica Italiana (SCI), Italy
1985 – 1986	Fellowship, ENI P.F.E., CNR/ENEA, Italy

- **SUPERVISION OF GRADUATE STUDENTS AND POSTDOCTORAL FELLOWS**

Several Postdocs (Chemical Engineering), PhD students (Tecnologie chimiche e dei nuovi materiali, VIII-XI cycles; Ingegneria chimica e dei materiali, XV cycle; Ambiente, salute e processi eco-sostenibili, XXI-XXVI cicles), Master students (more than 150, mostly in Chemical Engineering, but also in Science and Engineering of innovative and functional materials, Energy Engineering, Biology, Chemistry, Pharmaceutical Chemistry and Technologies)
University of Calabria, Italy

- **ORGANISATION OF SCIENTIFIC MEETINGS**

2023	Organization of the Conclusive Workshop "IR SILA, tra obiettivi realizzati e prospettive future", University of Calabria, Italy
2023	Organization and Chair of the 5th International Euro-Mediterranean Conference for Environmental Integration (EMCEI 2023), University of Calabria, Italy
2016	Organization of the Workshop "Prìncipi e princìpi dell'Ingegneria Chimica, Cetraro, Italy
2015	Organization and direction of the Conclusive Event of the Master PON SEI, University of Calabria, Italy
2015	Organization of the Conclusive Event of the PON Infrastrutture S.I.L.A., University of Calabria, Italy
2015	Organization and Direction of the Workshop "Un laboratorio multidisciplinare per l'Ambiente: La Hall Tecnologica Integrata (HTI) del PON SILA", University of Calabria, Italy
2015	Organization and Direction of "Ciclo di Seminari TIA. Tecnologie Innovative per l'Ambiente: caratterizzazione, trattamento e valorizzazione di inquinanti, reflui e rifiuti", University of Calabria, Italy
2010	Organization of COST Action 543 Second Training School on "Sustainable Hydrogen and Energy Production from Renewable Sources. Catalytic and Bio-catalytic Membrane reactors. Fuel Cells", University of Calabria, Italy
2008	Organization of Conference GRICU 2008, Le Castella, Italy
1994	Organization of Italy-United Kingdom Workshop on Membrane Bioreactors, University of Calabria, Italy

- **PROJECTS RESPONSIBILITIES**

2021 – 2023 Responsible, Project "Sistema Integrato di Laboratori per l'Ambiente SILA 4.0", University of Calabria, Italy

2019 – 2023 Responsible, Project "Sistema Integrato di Laboratori per l'Ambiente SILA 2.0", University of Calabria, Italy

2017 – 2021 Scientific Responsible, Project "INNOVAZIONE NEL MONDO DEL CAFFÈ MONOPORZIONATO (COFFEE PADS)", University of Calabria, Italy

2018 – 2023 Scientific Responsible, OR Project "ComESto - Community Energy Storage: Gestione Aggregata di Sistemi d'Accumulo dell'Energia in PowerCloud", University of Calabria, Italy

2010 – 2015 Scientific Responsible, WP5 Project POR APQ "My Darling Clementine", University of Calabria, Italy

2012 – 2015 Scientific Responsible of Laboratory "Hall Tecnologica per la Mitigazione dell'Inquinamento" (HTI), Project PONa3_00341 "PON Infrastrutture S.I.L.A.", University of Calabria, Italy

2011 – 2015 Scientific Responsible, OR Project PON01_02061 "Progetto di un sistema energetico avanzato completo, basato sulla coltura massiva di microalghe in fotobioreattori trasparenti per la produzione, in condizione di competitività ed ecosostenibilità, di energia da fonte rinnovabile e di altri prodotti", University of Calabria, Italy

2011 – 2015 Scientific Responsible, OR Project PON01_01366 "Nuovo processo a basso impatto ambientale ed a ridotto rischio operativo per il recupero ed il riciclo dei materiali costituenti le batterie al piombo", University of Calabria, Italy

2011 – 2015 Scientific Responsible, OR Project PON04a2_E "RES NOVAE - Reti, Edifici, Strade – Nuovi Obiettivi Virtuosi per l'Ambiente e l'Energia", University of Calabria, Italy

2011 – 2015 Scientific Responsible, OR Project PON01_01840 "microPERLA Programma di Energie Rinnovabili e Micro-Cogenerazione per l'Agroindustria", University of Calabria, Italy

2007 – 2008 Responsible and coordinator of the research project PIA "Dispositivo di Filtrazione a membrana per Depuratori ad Alta produttività", ECOTEC-UNICAL, Italy

1998 – 2009 Responsible and coordinator of PRIN 1998, 2000, 2002, 2004 and 2009, University of Calabria, Italy

- **REVIEWING ACTIVITIES**

Peer reviewer of several scientific international journals
Evaluator, Albo Revisori MIUR, Italy

- **MEMBERSHIPS OF SCIENTIFIC SOCIETIES**

Member of GRICU (Group of Chemical Engineering Researchers), AIDIC (Italian Association of Chemical Engineering), AIBB (Italian Association of Bioctalysis and Biotechnologies), ESMST (European Society of Membrane Science and Technology), SIR (Italian Society of Rheology).

- **MAJOR COLLABORATIONS**

University of Valencia, Economic Structure Department, Spain.
ICATALIST Service provider, Spain.
Teriva environment Service provider, France.

Institut Européen des Membranes – University of Montpellier, France.
Laboratory of hydrology and geochemistry of Strasbourg, CNRS/UNISTRA ITES LHYGES, France.
University of Sfax - Faculty of Science of Sfax, Tunisia.
University of Carthage (INAT), Tunisia.
Department of Chemical Engineering, Ege Üniversity, Turkey.
Van Yüzüncü Yıl University, Turkey.
Geological Engineering Department, Dokuz Eylül University, Turkey.
Laboratory of civil Engineering and Hydraulics, University of Guelma, Algeria.
Sartorius Stedim Biotech, Gottingen, Germany.
Department of Chemical Engineering, University of Leuven, KU Leuven, Belgium.
Department of Chemical and Biochemical Engineering, Technical University of Denmark (DTU), Lyngby, Denmark.
Department of Process and Environmental Engineering. Mass and Heat Transfer Process Laboratory, University of Oulu, Finland.
University of Lund, Sweden.
Institute of Arid Lands, Medenine, Tunisia.

ITALY:
Università di Genova, Dipartimento di Ingegneria civile, chimica e ambientale (DICCA).
Università di Padova, Dipartimento di Ingegneria Industriale.
Università di Salerno, Dipartimento di Farmacia/DIFARMA.
ENEA Centro Ricerche ENEA Trisaia - Policoro (MT): Laboratorio Biotecnologie (UTTRI-BIOTEC; Renewable Energy Division.
ENEA, C.R. ENEA Casaccia (Roma).
ENEA, Unità Tecnica Fusione, C.R. ENEA Frascati.
CNR - ITM (Istituto Tecnologie a Membrana ex-IRMEC), Università della Calabria (Rende).

Appendix: All current grants and on-going and submitted grant applications of the PI and Co PI (Funding ID)

Mandatory information (does not count towards page limits)

Current grants (Please indicate "No funding" when applicable):

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current proposal*
Management of industrial Treated wastewater ReUse as mitigation measures to water Scarcity in climaTe change	PRIMA Foundation (Call 2020 Section 1 Water IA)	1.985.000	2021-2024	Coordinator	Environmental protection

context in two Mediterranean regions (TRUST)					
Tech4You - Technologies for climate change adaptation and quality of life improvement (SPOKE 2 GOAL 2.2 PP 1)	MUR	2.737.206	2023-2025	Scientific Responsible	Environmental protection
Development of NEw MEmbranes as Smart devices to limit Infections – NEMESI (PRIN 2022)	MUR	197.413	2023-2025	Coordinator	Process modelling