3rd International Conference on Sustainable Chemical & Environmental Engineering

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SUST ENG 2024

Proceedings

4th - 8th September 2024
Rethymno, Crete, Greece
hybrid event

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organizers

Design of Environmental Processes Lab

Technical University of Crete
School of Chemical and Environmental Engineering

co - organizers

Cyprus University of Technology

Dear friends and colleagues,

I am pleased to invite you to the 3rd International Conference on Sustainable Chemical and Environmental Engineering (SUSTENG 2024), which will be held in Rethymno, Crete, Greece, between 4th to 8th September 2024.

The conference is organized by the "Design of Environmental Processes Laboratory", of the School of Chemical and Environmental Engineering, Technical University of Crete and the Cyprus University of Technology.

The SUSTENG 2024 Conference will take place both with physical and virtual presence.

The conference aims to encourage the exchange of knowledge between academicians, scientists and engineers on hot issues and current developments in chemical and environmental engineering through sustainable perspective. The participants will have the opportunity to present their recent research findings on an extended spectrum of conference topics and be informed about new challenges, future trends, and technological innovations on sustainable processes following the principles of circular economy.

After the completion of the conference, all abstracts/full papers will be published in the SUSTENG 2024 Conference Proceedings with ISBN number, while selected manuscripts will be published to at least two Special Issues at high IF scientific journals (more information will be released soon).

The conference Chair

Petros Gikas

Professor

Head of the "Design of Environmental Processes Lab"

School of Chemical and Environmental Engineering

Technical University of Crete, Greece

SESSIONS OF SUSTENG 2024

Session 1: Solid waste management

Session 2: Wastewater management (I)

Session 3: Wastewater management (II)

Session 4: Biochemical engineering

Session 5: Materials science

Session 6: Water resources management

Session 7: Soil management

Session 8: Anaerobic digestion

Session 9: Water treatment

Session 10: Environmental management

Scientific committee:

Achille Ephrem Assogbadjo, University of Abomey-Calavi, Benin

Alexandros Katsaounis, University of Patras, Greece

Alexandros Stefanakis, Technical University of Crete, Greece

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Therese Lee Chan, The University of the West Indies, Trinidad and Tobago

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SUST ENG 2024

SUSTENG 2024 - PROGRAMME AT A GLANCE

DAY 1 - Wednesday 4 September | Susteng 2024	
Rethymno Youth Center	
Registration	**19:30 - 20:00**
Welcome reception	**20:00 - 22:00**

DAY 2 - Thursday 5 September | Susteng 2024	
House of Culture	
Registration	**09:30 - 11:00**
Coffee break - Posters viewing	*10:45 - 11:00*
Greetings	**11:00 - 12:30**
PLENARY LECTURE: Prof. P. Gikas **Chair: K. Kuroda, A.E. Assogbadjo**	**12:30 - 13:15**
Lunch break	**13:15 - 14:45**
Session 1: Solid waste management	**14:45 - 16:30**
Session 2: Wastewater management (I)	**16:30 - 17:15**

DAY 3 - Friday 6 September | Susteng 2024	
House of Culture	
Session 3: Wastewater management (II)	**09:30 - 10:45**
Coffee break - Posters viewing	***10:45 - 11:00***
PLENARY LECTURE: Prof. T. Tsoutsos **Chair: P. Gikas, A.E. Assogbadjo**	**11:00 - 11:45**
Session 4: Biochemical engineering	**11:45 - 12:30**
Session 5: Materials science	**12:30 - 13:15**
Lunch break	***13:15 - 14:45***
PLENARY LECTURE: Prof. K. Kuroda **Chair: P. Gikas, T. Tsoutsos**	**14:45 - 15:30**
Session 6: Water resources management	**15:30 - 16:00**
Rethymno	
Field visit at Wastewater Treatment Plant of Rethymno	**18:30 - 19:30**
Gala dinner	**20:00 - 23:00**

DAY 4 - Saturday 7 September | Susteng 2024	
House of Culture	
Session 7: Soil management	**09:30 - 10:45**
Coffee break - Posters viewing	***10:45 - 11:00***
PLENARY LECTURE: Prof. A.E. Assogbadjo **Chair: P. Gikas, K. Kuroda**	**11:00 - 11:45**
Session 8: Anaerobic digestion	**11:45 - 12:30**
Session 9: Water treatment	**12:30 - 13:15**
Lunch break	***13:15 - 14:45***
Session 10: Environmental management	**14:45 - 16:15**
Closing ceremony	**16:15 - 17:00**

DAY 5 - Sunday 8 September | Susteng 2024	
Rethymno	
Conference excursion at the Historical Monastery of Arkadi and the Archeological Museum of Eleftherna (depending on participation)	**10:00 - 16:00**

SUST ENG 2024

SUSTENG 2024 PROGRAMME

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House of Culture	
Registration	**09:30 - 11:00**
Coffee break	*10:45 - 11:00*
Greetings	**11:00 - 12:30**
PLENARY LECTURE: Prof. P. Gikas **Water reclamation and reuse: Opportunities and Challenges** **Chair: K. Kuroda, A.E. Assogbadjo**	**12:30 - 13:15**
Lunch break	13:15 - 14:45
Session 1: Solid waste management **Chair: A. Giannis, L. Afxentiou**	**14:45 - 16:30**
Technoeconomic assessment of pay as you throw system for the city of Chania **L. Afxentiou,** A. Giannis	14:45 - 15:00
The effect of biochar addition on the properties of alkali-activated materials produced from silicate tailings **K. Komnitsas,** V. Karmali, D. Vathi, A Kritikaki	15:00 - 15:15
A Review of EU refineries oily sludge waste production, management options and sustainability assessment of traditional and emerging oily sludges treatment techniques **E. Vaiopoulou,** A. Mianzan , W. Odle, K. Sakkalis	15:15 - 15:30
Biomass burning emissions from varying landuse over equatorial Southeast Asia (ESEA) **J. Sentian,** J.H. Chin, F.F. Adnan	15:30 - 15:45
Optimized location of electric vehicle batteries recycling center in Attica	15:45 - 16:00

A. Giannis, A. Lygizos, E. Kastanaki	
Current Trends, Challenges, and Future Opportunities in Biogas Production from Hospital Food Waste in Europe: Perspectives from the CaringNature Project **I. Vyrides**	16:00 - 16:15
Evaluation of the Physicochemical Properties and Ecotoxicological Impact of Municipal Biosolids for Agricultural Use **I. Giannakis, P.** Ntailiani, C. Emmanouil and A. Kungolos	16:15 -16:30
Session 2: Wastewater management (I) **Chair: E. Vaiopoulou, C. Rodriguez-Rodriguez**	**16:30 - 17:15**
Treatment of pharmaceutical-containing wastewater with a hybrid approach of advanced oxidation with persulphates/UV and biological removal by fungal pellets **C. Rodriguez-Rodriguez,** S. D. Villegas, M. D. Ramírez, G. V. Castro, M. M. Masís, R.C. Rodriguez	16:30 - 16:45
Effect of hydrogen peroxide on colour changes during the degradation of sulfamethoxazole by photo Fenton **U. Duoandicoechea,** A. De Luis, N. Villota	16:45 - 17:00
Domestic wastewater treatment by a high-rate anaerobic MBR system **E. Politou,** K. Azis, A. Makri, S. Ntougias, N. Remma, P. Melidis	17:00 - 17:15

DAY 3 - Friday 6 September | Susteng 2024	
House of Culture	
Session 3: Wastewater management (II) **Chair: G. Panayiotou, D. Gavrilescu**	**09:30 - 10:45**
Effect of iron catalyst on water quality parameters during the oxidation of diclofenac by photo-Fenton treatment **U. Duoandicoechea,** J. M. Lomas, N. Villota	09:30 - 09:45
Nutrient recovery from urine diverting dry toilets via pyrolysis **M. E. Koulouri,** M.R. Templeton, G. D. Fowler	09:45 - 10:00
Limassol District Local Government Organisation: Challenges and opportunities in sewage treatment **G. Panayiotou,** P. Marti	10:00 - 10:15
Advanced primary filtration process for the upgrade of overloaded activated sludge plants **K. Tsamoutsoglou,** P. Gikas	10:15 - 10:30
Preparation of biochar derived from olive mill solid waste in a circular economy approach for enhanced adsorption of trihalomethanes from water **S. Azerrad**, H. Azaizeh, E. Kurzbaum	10:30 - 10:45
Coffee break - Posters viewing	***10:45 - 11:00***
PLENARY LECTURE: Prof. T. Tsoutsos **Unlocking the potential of heritage-based innovation for sustainable development: The HI-EURECA-PRO project** **Chair: P. Gikas, A.E. Assogbadjo**	**11:00 - 11:45**
Session 4: Biochemical engineering **Chair: R. Konstantinou, T. Tsoutsos**	**11:45 - 12:30**

Enhancement of starch hydrolysis using immobilized cells and enzymes of two Aspergillus strains on oxidized carbonaceous materials **R. Konstantinou**	11:45 - 12:00
Bioprocess development for thermoplastic starch polyhydroxybutyrate biodegradation using algal-microbial co-cultures **F. Pyrilli,** E. Syranidou, G. Constantinides, M. Koutinas	12:00 - 12:15
A critical examination of macroalgae biomass utilization: Perspectives from life cycle assessments **C. Nikoloudakis,** A. Pantis, T. Tsoutsos	12:15 - 12:30
Session 5: Materials science **Chair: S. Azerrad, D. P. Gournis**	**12:30 - 13:15**
The green synthesis of irregular gold nanoparticles and their application in nanomedicine **R. Mariychuk,** R. Smolkova, L. Grishchenko, V. Lisnyak	12:30 - 12:45
Innovative bioprocess employing recyclable immobilized enzyme for paraoxon removal in water and effluents: Phosphotriesterase immobilized on Fe_3O_4-SiO_2-NH_2 magnetic nanocomposites **S. Azerrad**	12:45 - 13:00
2D Xenes of Group-14: New synthetic strategies and derivatives for environmental and energy applications **D. P. Gournis**	13:00 - 13:15
Lunch break	***13:15 - 14:45***
PLENARY LECTURE: Prof. K. Kuroda **Emerging contaminants in groundwater: threats in the 21st century** **Chair: P. Gikas, T. Tsoutsos**	**14:45 - 15:30**
Session 6: Water resources management **Chair: K. Tsamoutsoglou, E. Vaiopoulou**	**15:30 - 16:00**
From data to decision: understanding and mitigating uncertainty in watershed water quality models **A. Gorgoglione**	15:30 - 15:45
Water use and efficiencies in fuel refining sites **E. Vaiopoulou,** E. Fiddaman, S. Gibbons, S. Mackay, J. Shaw, L. Leclezio, J. Russel, M. Hjort, L. G. Guerrero	15:45 - 16:00
Rethymno	
Field visit at Wastewater Treatment Plant of Rethymno	**18:30 - 19:30**
Gala dinner	**20:00 - 23:00**

DAY 4 - Saturday 7 September | Susteng 2024	
House of Culture	
Session 7: Soil Management **Chair: F. J. Chadare, A. Stefanatou**	**09:30 - 10:45**
Soil improvement by electro carbonation induced calcite precipitation (ECICP) from the seawater **H. Abdeh Keykha,** M. Mavroulidou, H. Mohamadzadeh Romiani Hadi	09:30 - 9:45

Biocementation via microbial induced struvite precipitation: A mini review on cleaner method of soil stabilization **S. Joshi,** M. Mavroulidou, M. J. Gunn	09:45 - 10:00
PFAS soil treatment processes – a review of operating ranges and constraints **E. Vaiopoulou,** J. Hurst, S. Hale, J. Miles, E. Dall, W. Gevaerts , J. Burdick, M. Hjort	10:00 - 10:15
Effects of fungicides and bactericides on BVOC emissions in cypriot vineyard soils **K. Kaikiti,** S. Savvides, L. Philippot, I. Ioannides, A. Agapiou, M. Omirou	10:15 - 10:30
Use of residues generated from olive cultivation and olive oil production for the enhancement of soil quality **A. Stefanatou**, A. Kalampokidis, T. Maneka, G.E. Dimitriou, M. Pavlidis, M. Veloutsos, A. Galanidis, F. Galliou, T. Manios, D.F. Lekkas, P. Dimitrakopoulos, N. Fyllas, S. Vakalis, M. Fountoulakis	10:30 - 10:45
Coffee break - Posters viewing	***10:45 – 11:00***
PLENARY LECTURE: Prof. A.E. Assogbadjo **Review on ecosystems nature-based restoration initiatives in Africa** **Chair: P. Gikas, K. Kuroda**	**11:00 - 11:45**
Session 8: Anaerobic digestion **Chair: K. Tsamoutsoglou, G. Antonopoulou**	**11:45 - 12:30**
Environmental and energetic analysis of biogas plants supplied with different substrate scenarios **P. Pochwatka**, J. A. Kowalczyk, J. Mazurkiewicz, J. Pulka, K. Kupryaniuk, J. Dach	11:45 - 12:00
Designing sustainable processes for methane and hydrogen production using poplar woody sawdust biomass: The effect of chemical pretreatment **G. Antonopoulou,** I. Apostolopoulos, A. Tekerlekopoulou	12:00 - 12:15
Modelling hollow fibre membrane bioreactors for biogas purification **A. Hatzikioseyian,** J. Das, P. Lens	12:15 - 12:30
Session 9: Water treatment **Chair: A. Papadakis, T. Thodosiadis-Thomaidis**	**12:30 - 13:15**
The use of hyperspectral imaging in aquatic vegetation analysis **J. Kostecki,** S. Myszograj, E. Płuciennik-Koropczuk, I. Krupińska	12:30 - 12:45
Systematic environmental surveillance for legionella detection and treatment in a hospital water distribution system in the region of Crete during covid-19 era **A. Papadakis,** E. Koufakis, K. Tsamoutsoglou, N. Gikas, D. Chochlakis, A. Psaroulaki, P. Gikas	12:45 - 13:00
Unseen processes in freeze desalination: molecular dynamics of nucleation, crystal growth, and ion entrapment – a short review **I. Janajreh,** K. El Kadi	13:00 - 13:15
Lunch break	***13:15 - 14:45***
Session 10: Environmental Management **Chair: S. Lyle, A.E. Assogbadjo**	**14:45 - 16:15**

Pangaea.cubes - IoT low power challenges towards sustainability H/W - S/W design implementations and applications **T. Thodosiadis-Thomaidis,** G. Panagopoulou, V. Vorrias	14:45 - 15:00
Development of sustainable communication systems supported by high-impact environmental energy sources for people on the Move **S. Lyle,** K. Pappas, C. Lyle	15:00 - 15:15
Forest food resources back to the menu for enhancing food sovereignty in a context of high hybridation: case of Adansonia digitata and Irvingia gabonensis **F. J. Chadare,** F.T.K Fassinou, S. Ahouansou Montcho , M. Affonfere, A.E. Assogbadjo	15:15 - 15:30
Early-stage mathematical modeling of solution spray pyrolysis for the fabrication of functional ceramic films **N. Fotiadi,** D. Lazaridis, N. Rigakis, N. Kiratzis	15:30 - 15:45
Life cycle assessment to address key environmental impact elements of ERASE, an innovative in situ remediation technology **G. Beretta,** E. Sezenna, G. Dolci, L. Rigamonti, S. Saponaro, C. Carnabuci, D. Vezzoli	15:45 - 16:00
West african mangroves in the context of climate change: social-ecological dynamics, challenges and perspectives **R. Glèlè Kakaï**	16:00 - 16:15
Closing ceremony **Chair: P. Gikas, K. Kuroda, A.E. Assogbadjo, T. Tsoutsos**	**16:15 - 17:00**

DAY 5 - Sunday 8 September | Susteng 2024	
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Conference excursion at the Historical Monastery of Arkadi and the Archeological Museum of Eleftherna (depending on participation)	**10:00 - 16:00**

Posters
House of Culture-Upper Floor

Biogas potential of distillery stillage and evaluation of digestate as a potential fertilizer
I. Vaskina, R. Vaskin, M. Cieslik, A. Lewicki, L. Demkova, M. Skidanenko, S. Sydorenko

Modelling Methane Emissions Resulting from Municipal Solid Waste Management: Reduction Options and Environmental Impact
D. Petrisor, C. Cirjan , D. Gavrilescu, C. Teodosiu

Modeling of Waste Electrical and Electronic Equipment Generation Rate using Multiple Regression Analysis
M. Gavrilescu, D. Gavrilescu

Model development for a Renewable Energy Sources Thematic Park – RESTPark A synergistic approach to Water Management and Renewable Energy Systems (Bioclimatic architecture, Solar, Wind, Micro-Hydro, Geothermal & Biomass)
A. T. Thomaidis, T. T. Theodosiadis

Evaluation of Biochar from Sewage Sludge for Sustainable Carbon Adsorption
L. D. Tshenyego, P.T. Odirile, A. Giannis, P. Gikas

Unlocking the timeless wisdom of Athens: A journey towards sustainability through design
D. Tzourmakliotou, E. Sourli

Life Cycle Assessment of PLA/MXene Nanocomposite
V. Tzatzadakis, A.Thomos, F. Gojda, F. Krasanakis, K. Chrissopoulou, S. Anastasiadis, E. Patelarou, M. Stylianakis

Decarbonisation of asphalt mix production
A. Woszuk, S. Malinowski, R. Panek

Exploring innovative cathodes based on perovskites in Microbial Fuel Cells
L. Skopas, G. Bampos , I. Apostolopoulos, S. Bebelis, G. Antonopoulou

Hydrocyclone for the treatment of municipal primary wastewater
K. Tsamoutsoglou, A. Kechagias, P. Gikas

The impact of substrate extrusion on the energy and economic efficiency of biogas plant operation
K. Kupryaniuk, K. Witaszek, P. Pochwatka, J. Mazurkiewicz, I. Vaskina, D. Janczak, J. Dach

Quality criteria for water reuse in the Mediteranean basin
E. Gika, V. Tzika, F. Ranieri, A.C. Ranieri, E. Ranieri, P. Gikas

Carbon dioxide capture from actual industrial flue gas using microalgae
G. Makaroglou, D. Mitrogiannis, P. Gikas

Life Cycle Assessment to address key environmental impact elements of ERASE, an innovative in situ remediation technology

Gabriele Beretta[1], Elena Sezenna[1], Giovanni Dolci[1], Lucia Rigamonti[1], Sabrina Saponaro[1], Claudio Carnabuci[2], Daniele Vezzoli[2]

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ABSTRACT

The remediation of contaminated sites supports the goal of sustainable development but may also have environmental impacts at local, regional, and global scales. Life Cycle Assessment (LCA) is increasingly used to support decision-making in site remediation. ElectRode-Aided Soil rEmediation (ERASE) technology, developed from laboratory-scale proof of concept to pilot field tests, as part of Research & Development related to the Polluted Site Decontamination Pre-Commercial Procurement (POSIDON PCP), combines physical, chemical, and biological processes by powering electrodes in a porous medium, such as soil or backfilling materials, contaminated with organic and inorganic substances. Along with operational conditions to increase efficiency, reduce cleanup time, and improve overall cost-effectiveness, the environmental footprint of this technology was evaluated through LCA. Based on the plant equipment installed at a pilot site in Bilbao and the operating conditions, the LCA study compared different field-scale pilot plant solutions, considering key impact elements for the technology, such as electrode material and energy supply. The results highlighted the potential benefits of using renewable energy sources, particularly photovoltaic panels, in reducing the overall environmental impacts. Graphite electrodes showed promising environmental performance, although corrosion remains a concern. This approach led to pinpointing key factors contributing to significant environmental impacts, guiding future efforts in optimizing an efficient and sustainable remediation intervention.

Keywords: *Electrode-aided remediation; soil; LCA; sustainable remediation.*

1. Introduction

Economic and social development has caused impacts on the quality of soil and groundwater. Soil is a non-renewable resource and, together with groundwater, needs to be preserved for the next generations and eventually restored from negative impacts through appropriate remedial measures and interventions.

The main goal of soil and groundwater remediation is to mitigate contamination and effectively reduce/control the associated risks, but attention should be paid to minimize the environmental footprint of remediation activities. Therefore, it is crucial to consider the potential environmental impacts that may arise from remediation activities to maximize the overall benefits of the intervention.

In the framework of the Polluted Site Decontamination Pre-Commercial Procurement (POSIDON PCP), HPC Italia srl and Politecnico di Milano – Civil and Environmental Engineering Department proposed and developed, from the laboratory proof of concept up to field testing, an in situ remediation technique (ERASE - ElectRode-Aided Soil rEmediation). ERASE is based on the integration and simultaneous exploitation of physical, chemical, and biological mechanisms induced by properly powering at least one pair of electrodes installed in a porous medium (heterogeneous soil/backfilling materials, under saturated or unsaturated conditions), contaminated by organic and inorganic pollutants. Direct current (DC) electric fields promote electrokinetic mechanisms (electromigration, electroosmosis, and electrophoresis), driving mass transport towards the electrodes and facilitating the distribution of injected chemical substances (e.g., oxidants, reductants, substrates, nutrients), supporting pollutant degradation and/or recovery. Conversely, alternating current (AC) power induces soil heating through the Joule effect, up to 30° - 40°C, enhancing biological and/or chemical degradation rates of organic pollutants and thermally activating chemical oxidants such as persulfate. Electrochemical reactions also occur near the electrodes, with the production of hydrogen peroxide (H_2O_2) or high-energy free radicals

($O_2^{-\bullet}$ or $^{\bullet}OH$) and water hydrolysis, which modifies the pH and can increase the availability of oxygen or hydrogen, thereby favoring aerobic or anaerobic biodegradation, respectively (Beretta et al., 2019).

Throughout the technology development process, alongside studying the effectiveness of contaminant removal, evaluating site-specific operational conditions, and assessing costs and time required to achieve clean-up goals, a Life Cycle Assessment (LCA) of the proposed solution was performed to evaluate its environmental impacts. The LCA identified key impact factors, highlighting the electrodes life cycle (production, installation, decommissioning, and end-of-life) and electricity consumption as the most relevant environmental burdens (Beretta et al. 2023). This paper analyses in more detail such elements, focusing on the outcomes of pilot testing in Bilbao and comparing through LCA different electrode materials and different electrical energy sources.

2. Overview of pilot test in Bilbao

The ERASE pilot testing in Bilbao (ES) took place in a small portion of the former Zorrotzaurre industrial area, highly contaminated with Total Petroleum Hydrocarbons (TPHs), Polycyclic Aromatic Hydrocarbons (PAHs), and Inorganics (such as As, Pb, and Cd). The site is an artificial island inside the Deusto Canal connecting Bilbao to the sea. Accordingly, the water table at the site is 1.0 - 1.75 m b.g.s, depending on tides, and the unsaturated soil is a coarse-grained filling material (47 - 67% gravel, 16 - 34% sand, <25% fines).

The pilot plant consisted of an electrical unit, a hydraulic unit, and a monitoring unit (Figure 1). The electrical unit included 18 electrode pairs and the power supply system in DC or AC mode. The electrodes were installed in the unsaturated soil (down to 1 m b.g.s.) in boreholes at a distance of 3 m from each other. The hydraulic unit included an injection system (injection wells - IWs, an injection unit for dosing water and chemicals), and an extraction system (extraction wells - EWs, an extraction unit for removing interstitial water). The monitoring unit included devices for monitoring electrical parameter values (current intensity, voltage, power), monitoring points in the unsaturated porous medium (thermocouples, lysimeters, tensiometers, probes for soil gas), and monitoring points in the saturated porous medium (thermocouples, piezometers).

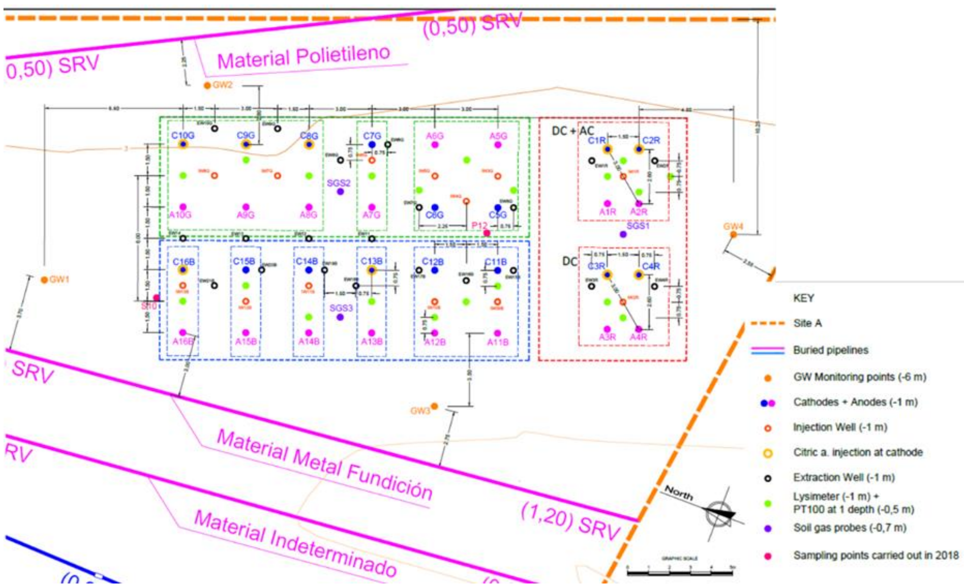

***Figure 1** – Pilot plant layout*

The field strategy was structured according to the following phases: a) installation of the plant, preliminary checks, and tuning; b) DC operation and dosing of persulfate, to promote electrokinetic transport mechanisms of inorganic pollutants and the distribution of the oxidant; c) AC operation to heat the soil to 30° - 40°C and thermally activate the oxidant.

During the test duration, a comprehensive monitoring program was conducted. From test site baseline to the final characterization, many parameters were periodically checked (e.g., soil temperature, interstitial water, soil gas, and groundwater quality).

3. LCA

3.1. Method

The LCA was performed according to the ISO 14044 and 14040 standards (ISO, 2006a; ISO, 2006b).

The selected functional unit (FU) was the overall pilot test including preliminary activities, operational activities, and the decommissioning of the pilot plant.

The Environmental Footprint 3.0 (Fazio et al., 2018) method was selected. It includes 16 impact categories on human health and environment (Climate change - CC; Ozone depletion - OD; Ionizing radiation, human health - IR; Photochemical ozone formation - POF; Particulate matter/respiratory inorganics - RI; Human toxicity, non-cancer effects - HTNC; Human toxicity, cancer effects - HTC; Acidification – A; Eutrophication, aquatic freshwater - EAF; Eutrophication, aquatic marine - EAM; Eutrophication, terrestrial - ET; Ecotoxicity freshwater - EF; Land use - LU; Water use - WU; Resource use, energy carriers - RUE; Resource use, mineral, and metals - RUM). Normalization and weighting stages were not performed.

Based on the pilot test data, performed by using titanium electrodes and the national power grid as the electricity source, the assessment aimed to investigate the effects of the electrode material and the electricity source on the environmental performance of the cleanup system. In particular, three different scenarios were evaluated for each of them: 1) titanium; 2) chromium steel, and 3) graphite, as the electrode material (Table 1 -Stage A); plant powered: a) entirely by the national power grid; b) by the national power grid and on site energy production through photovoltaic panels (PPs) installed in the area under treatment (75 m^2, covering approximately 40% of the plant energy requirements; c) by on site energy production through PPs over about 185 m^2, covering the overall energy requirement of the pilot plant (Table 1 - Stage G). Table 1 summarizes the main inventory data and assumptions for the pilot plant installation and the scenarios evaluated in the LCA. The system was modeled considering the European context (the Spanish context was considered to model the electricity production). The ecoinvent database (version 3.8 allocation, cut-off by classification system model) was used to support the analysis (ecoinvent centre, 2021). The systems were modeled with the SimaPro software (9.3 version).

Table 1 *Inventory data, assumptions, calculations, and ecoinvent processes considered in modelling the pilot test.*

	PRELIMINARY ACTIVITIES Stage – data
A	**Installation of electrodes** • Drilling: number (36), boreholes dimension and depth (Ø 76 mm; 1 m), material for the boreholes filling (70% silica sand and 30% kaolin). Diesel consumption for drilling: 1.63 kg/m^3 soil • Electrodes material: Scenario 1: titanium, as actually used at the field, 1 inch - 25 mm, 1 m long Scenario 2: chromium steel, 1 inch - 25 mm, 1 m long Scenario 3: graphite, 2 inches - 50 mm, 1 m long • Number of electrodes: 36 • Specific weights*: soil: 1970 kg/m^3; silica sand: 1.75 g/cm^3; kaolin: 2.6 g/cm^3; titanium: 4.5 g/cm^3; graphite: 1.7 g/cm^3; chromium steel: 7.86 g/cm^3. • Transportation of extracted soil for 75 km by lorry.
B	**Installation of injection wells (IWs)/extraction wells (EWs)** IWs and EWs: Drilling: number (34), borehole dimension and depth (Ø 178 mm; 1 m), material for the borehole filling (gravel from the borehole bottom up to 30 cm below the ground surface and sealed with bentonite in the last 30 cm). Screened pipes: material (PVC), dimension (4 inches - 100 mm, 1 m long). Specific weights*: silica gravel: 1.5 g/cm^3; bentonite: 2.6 g/cm^3; Weight of PVC pipe - 100 mm: 3.13 kg/m.
C	**Installation of monitoring points of unsaturated soil: lysimeters (LYS)/nesty probes (SGS)** LYS: Drilling: number (20), boreholes dimension and depth (Ø 76 mm; 1 m), drains and filling material: silica sand. Material (PVC), dimension (1 inch - 25 mm, 1 m long). SGS: Drilling: number (3), borehole dimension and depth (Ø 76 mm; 0.7 m), material for the borehole filling (gravel from the borehole bottom up to 30 cm below the ground surface and sealed with bentonite in the last 30 cm). Material (PVC), dimension (0.5 inches - 13 mm, 0.3 m long). Weight of PVC pipe - 25 mm: 0.94 kg/m; Weight of PVC pipe - 13 mm: 0.49 kg/m.

D	**Installation of monitoring points of saturated soil** Drilling: number (6), borehole dimension and depth (Ø 178 mm; 6 m), material for borehole filling (gravel from the borehole bottom up to 30 cm below the ground surface and sealed with bentonite in the last 30 cm). Screened pipes: material (PVC), dimension (4 inches - 100 mm, 6 m long). Weight of PVC pipe - 100 mm: 3.45 kg/m.
E	**Installation of pilot clean-up system** • Transformation and power supply unit including the injection/pumping system control unit and all the installations for energy supply to the electrodes (low voltage distribution panels, transformers, inverter/rectifier units, cables/connections). • Injection unit for water supply and dosage of chemicals: pumping system at the injection/extraction wells, nutrients/reagents dosage system (dedicated pumping system including a tank for dosing and mixing chemicals with water). • Pumping unit for the recovery of interstitial water (e.g. electroosmotic flow). Among the consumable materials, the use of pipes for the connection of the injection/extraction wells is considered. Pipes: material (HDPE), A - dimension (0.5 inches - 13 mm), length (300 m) + B - dimension (9×12), length (500 m) Weight of HDPE pipe A: 0.28 kg/m; Weight of HDPE pipe B: 0.048 kg/m
<u>OPERATIONAL ACTIVITIES</u> <u>Stage – data</u>	
G	Electricity consumption for electrodes, pumps, etc.: overall electricity consumption: 20,700 kWh Scenario a) National grid, as actually used at the field Scenario b) Area covered with photovoltaic panels (PPs): 75 m^2 (i.e., 37 panels; 0.309-0.415 kW/PP; 1300 h/y) → 8,130 kWh/6 months. Remaining consumption: national grid Scenario c) Only PPs: 185 m^2 (i.e., 95 panels; 0.309-0.415 kW/PP; 1300 h/y)
H	Water consumption: amount (1.6 m^3/month), supply (tap water). Total water consumption: 10 m^3
I	Dosage of chemicals: type (sodium persulfate), amount (12.5 kg/m^3 of soil treated). Sodium persulfate consumption: 900 kg
<u>DECOMMISSIONING</u> <u>Stage – data</u>	
L	**Final Soil sampling** Drilling: number (15), borehole dimension and depth (Ø 152 mm, 1 m), material for the borehole filling (bentonite). Mass of soil sent to disposal: 35.7 kg/borehole. Mass of bentonite: 47.2 kg/borehole
A	**Electrodes decommissioning** Mechanical removal of installations and restoration of boreholes with cement mortar. End-of-life treatment of electrodes. Specific weight: cement mortar: 2.1 g/cm^3
B	**Decommissioning of injection wells (IW)/extraction wells (EW)** Injection of cement mortar in each well. Mass of cement mortar (IW + EW): 16.5 + 16.5 kg/borehole.
C	**Decommissioning of monitoring points of unsaturated soil: lysimeters (LYS)/nesty probes (SGS)** LYS and SGS: Installations mechanically removed (drilling as modeled in the installation stage), boreholes restored with cement mortar. End-of-life treatment of lysimeter and nesty probes.
D	**Decommissioning of monitoring points of saturated soil** Injection of cement mortar in each well. -> Mass of cement mortar: 98.9 kg/borehole.
E	**Decommissioning of the clean-up system** End-of-life treatment of pipes used for the connection of the injection/extraction wells. Mass of pipe A sent to disposal: 84.0 kg/300 m. Mass of pipe B sent to disposal: 24.0 kg/500 m.

** Assumed for all the stages*

4. Results: potential environmental impacts

Figure 2 shows the impacts related to the production of one electrode (unit impact) for the different electrode materials considered. When chromium steel is used compared to titanium, impacts decrease in all the impact categories with reductions in the range of 9.8 - 97%. Greater reductions, between 61.5 and 99.8%, are obtained by using graphite. However, graphite is poorly resistant to corrosion during the process, and, despite the use of thicker electrodes, testing would be required especially in the DC phase.

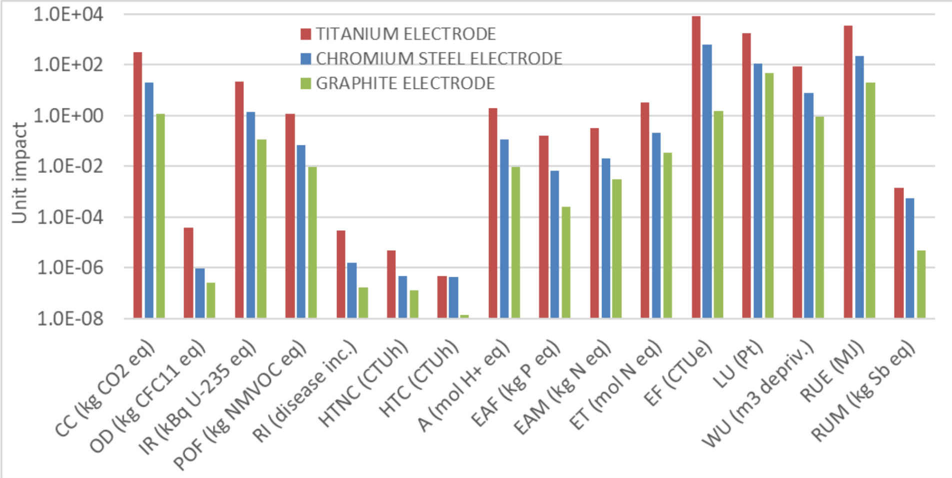

Figure 2 *Impacts of single electrode production (unit impact) as a function of component material. For impact categories acronyms, see Table 2*

Table 2 compares the potential impacts of the overall pilot test using chromium steel electrodes with different electricity sources. The use of photovoltaic energy in scenarios b) and c) allows for the reduction of potential impacts in all the impact categories excluding RUM. RUM impact category is strictly related to the production of PPs and might be mitigated by reusing PPs for other reclamation interventions.

Table 2 *Potential impacts (referred to the FU considered) for scenarios a, b, and c (electricity source). Chromium steel (scenario 2) was considered as the electrode material.*

Impact category	**Unit**	**Scenario**			**Impact variation**	
		a	**b**	**c**	**100 x (b–a)/a**	**100 x (c-a)/a**
Climate change (CC)	kg CO_2 eq	1.03E+04	8.17E+03	4.88E+03	-21%	-53%
Ozone depletion (OD)	kg CFC11 eq	1.16E-03	1.05E-03	8.83E-04	-9.4%	-24%
Ionizing radiation, human health (IR)	kBq U-235 eq	5.32E+03	3.48E+03	6.53E+02	-34%	-88%
Photochemical ozone formation (POF)	kg NMVOC eq	3.69E+01	2.90E+01	1.67E+01	-22%	-55%
Particulate matter/respiratory inorganics (RI)	disease inc.	3.97E-04	3.70E-04	3.28E-04	-6.8%	-17%
Human toxicity, non-cancer effects (HTNC)	CTUh	1.67E-04	1.59E-04	1.47E-04	-4.6%	-12%
Human toxicity, cancer effects (HTC)	CTUh	2.23E-05	2.16E-05	2.07E-05	-2.8%	-7.1%
Acidification (A)	mol H^+ eq	8.36E+01	6.44E+01	3.48E+01	-23%	-58%
Eutrophication, aquatic freshwater (EAF)	kg P eq	3.89E+00	3.20E+00	2.14E+00	-18%	-45%
Eutrophication, aquatic marine (EAM)	kg N eq	1.26E+01	9.59E+00	5.01E+00	-24%	-60%
Eutrophication, terrestrial (ET)	mol N eq	1.30E+02	9.88E+01	5.08E+01	-24%	-61%
Ecotoxicity freshwater (EF)	CTUe	1.89E+05	1.67E+05	1.34E+05	-11%	-29%
Land use (LU)	Pt	4.75E+04	3.92E+04	2.64E+04	-17%	-44%
Water use (WU)	m^3 depriv.	8.78E+03	7.42E+03	5.34E+03	-15%	-39%
Resource use, energy carriers (RUE)	MJ	2.14E+05	1.59E+05	7.42E+04	-26%	-65%
Resource use, mineral and metals (RUM)	kg Sb eq	1.32E-01	1.56E-01	1.93E-01	18%	46%

From the detailed analysis of the impact categories of each stage of the pilot plant, considering chromium steel electrodes - scenario 2, and electricity source of scenario b (Figure 3), the most relevant burden is related to "Electricity consumption" (stage G, up to 85% of overall contribution in the category IR), followed by "Production, installation, decommissioning, end-of-life of electrodes" (stage A, up to 74% of overall contribution in HTC) and "Production and use of chemicals" (Stage I, up to 31% in OD). About stage A, most of the potential impacts are related to the production of the electrodes. The choice of on site renewable energy can, however, partially mitigate the impacts of this electrode material.

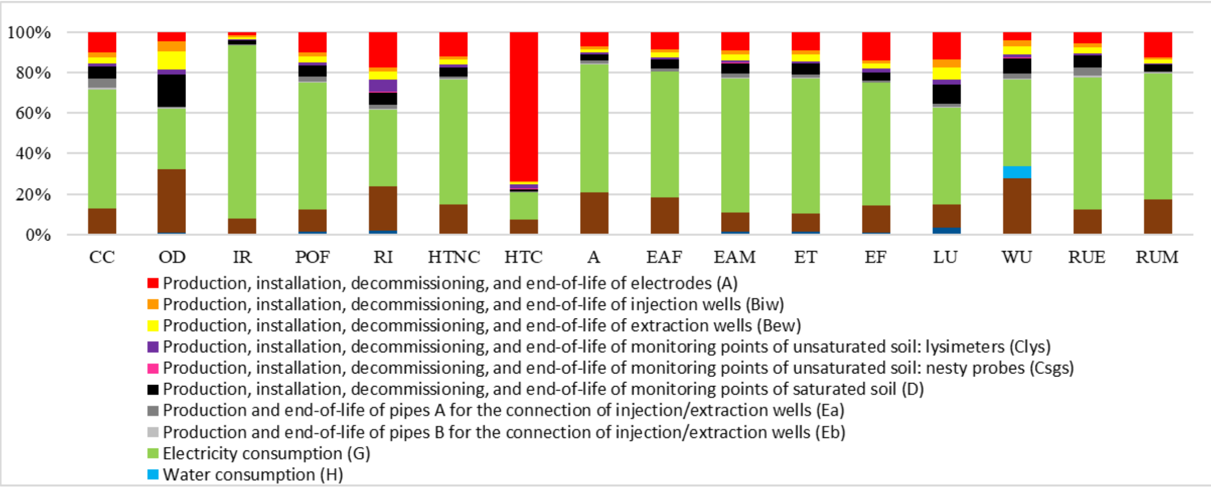

Figure 3 *Impacts contributions for the overall pilot test with chromium steel (scenario 2) as the electrode material and use of PPs + national grid electricity (scenario b). For impact categories, see Table 2.*

5. CONCLUSIONS

LCA allowed identifying the field-scale pilot test key elements that might be improved to reduce the environmental impacts and increase the ERASE technology's environmental performance. In detail, the main contributions of the potential impacts of the technology are related to “Electricity consumption”, “Production, installation, decommissioning, and end-of-life of electrodes” and “Production and use of chemicals”. Useful suggestions came from the outcomes of the comparison of different electrode materials (titanium, chromium steel, and graphite) and electricity sources (grid energy, photovoltaic energy, or a combination of them). Chromium steel electrodes, better than graphite in terms of resistance to corrosion, and energy partially from renewable sources (photovoltaic panels) ensure a significant reduction in the potential impacts of the remediation intervention (between -6 to -74% when compared to titanium electrodes and pilot plant entirely powered by the national grid).

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Rethymno City map – SUSTENG 2024

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