# ENHANCING THE ENVIRONMENTAL SUSTAINABILITY OF MARITIME GREENWICH IN LONDON: NEGATIVE OR SCRUBBING SUGGESTED SOLUTIONS TO GREENHOUSE GAS AND POLLUTANTS EMISSIONS

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## ABBREVIATION

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| BIM | Building Information Management |
| $CO_2$ | Carbon Dioxide |
| $CH_4$ | Methane |
| DAC | Direct Air Capture |
| DACCS | Direct Air Carbon Capture and Storage |
| GHG | Greenhouse Gas |
| $H_2CO_3$ | Carbonic Acid |
| IDE | Integrated Development Environment |
| LCA | Life Cycle Assessment |
| MPa | Megapascal |
| NDIR | Non-dispersive infrared |
| NES | Negative Emissions Strategy |
| NET | Negative Emissions Technology |
| $N_2O$ | Nitrous Oxide |
| $NO_3^-$ | Nitrate Ion |
| OS | Optimization Strategy |
| $PM_{2.5}$, $PM_{10}$ | Particulate Matters |
| $SO_2$ | Sulfur Dioxide |
| USB | Universal Serial Bus |
| UV | Ultraviolet |

## INTRODUCTION

Maritime Greenwich, a UNESCO (United Nations Educational, Scientific, and Cultural Organization) World Heritage Site in London, is a globally recognized historical touristic destination.[1] However, increasing pressures from mass tourism pose significant threats to the area's cultural and environmental integrity, underscoring the urgent need for the implementation of sustainable tourism

principles.[2] Sustainable tourism aims to accommodate current tourism demands while preserving cultural and natural heritage; thereby safeguarding opportunities for future generations.[3]
This paper proposes strategic solutions to address the complex demands of environmentally responsible tourism. These solutions are designed not only for Maritime Greenwich; their application may be extended to major urban zones worldwide, i.e., contributing to climate change mitigation approaches.

## Environmental Sustainability

The 2022 wildfires in London underscored the escalating climate crisis impacting the metropolis, posing threats to both cultural heritage and green spaces.[4] Historical Maritime Greenwich, highlighted broadly in the red zone on the map – Figure 1, lies at the center of this concern. Considering the urgent need for environmental sustainability, several critical questions arise: Is Maritime Greenwich affected by pollution? What are the primary identified pollutants? What defines green tourism? And how can it be effectively implemented?


*Figure 1. Urban plan of historical Maritime Greenwich - London*

Based on recent environmental assessments, London — including Maritime Greenwich — may be classified as an urban area with significant pollution levels.[5] These pollutants can be classified into two main categories. Category One includes greenhouse gas (GHG), which contribute to climate change.[6] Category Two comprises pollutants that directly impact human health.[7] The former are regulated by Climate & Energy Policies,[8] while the latter are regulated by Air Quality Regulations.[9] It is important to note that this classification is preliminary, as greenhouse gas may also adversely impact human health through indirect effects.[10]

Accordingly, the primary GHG in London include carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous Oxide ($N_2O$).[11] The main air pollutants in the Royal Borough of Greenwich are nitrogen dioxide ($NO_2$) and particulate matter ($PM_{2.5}$ and $PM_{10}$).[12] Green tourism aims to minimize the negative social, economic, and environmental impacts of tourism while promoting long-term sustainability. In this context, eco-efficiency refers not only to optimizing human activities and energy consumption to reduce pollutant emissions but also to actively removing pollutants that exceed acceptable thresholds through environmentally "friendly" solutions.
Why is it necessary to scrub/remove or absorb atmospheric pollutants that exceed allowable thresholds? This question arises from the fact that once certain GHG and pollutants are released into the atmosphere, they can persist for centuries. For instance, released methane and nitrous oxides can remain in the atmosphere for hundreds to thousands of years.[13] Consequently, merely optimizing emissions is insufficient to achieve a pollution-free environment and may fall short of meeting the targets set by the Paris Agreement.[14] Active and passive pollutant removal—through scrubbing, absorption, or other environmental remediation techniques—is essential for ensuring a clean and healthy environment, particularly in touristic areas. The approach proposed in this paper is specifically applicable to Maritime Greenwich; however, it can also be adapted for implementation in other densely populated urban areas.

## METHODOLOGY

As discussed above, addressing atmospheric environmental issues requires remediation and mitigation strategies that step beyond the mere optimization and reduction of current and future emissions. Given that this paradigm remains relatively novel in contemporary environmental research, three methods were adopted to develop plausible solutions. First, a comprehensive literature review was conducted using advanced bibliometric analysis tools.[15] Second, a virtual laboratory was developed on high-performing computer platforms to simulate energy performance and associated emission of pollutants. These simulations investigated various building envelope layouts and materials composition, utilizing advanced analytical software such as COMSOL Multiphysics, EnergyPlus, and DesignBuilder, integrated with Building Information Management (BIM) tools. Third, novel experimental investigations were undertaken—initially in a non-controlled environment and subsequently within controlled laboratory settings—using advanced instrumentation to test and validate proposed solutions.

### Literature Review

The literature review enabled the identification and analysis of state-of-the-art technologies for the removal of air pollutants such as $CO_2$. Among these, Direct Air Capture (DAC) emerged as a promising solution. This technology operates by drawing ambient air through a fan and directing it over a surface coated with chemical sorbents that selectively bind to $CO_2$ molecules. However, the high operational costs, the use of chemicals, and the complexities associated with the logistics of carbon storage[16] – commonly referred to as Direct Air Carbon Capture and Storage (DACCS)[17] operation - represent significant challenges to the large-scale implementation of this technology.
From a different perspective, a leading Italian firm has developed a photocatalytic cement capable of reducing nitrogen oxides ($NO_x$) in the atmosphere.[18] This innovative cementitious material incorporates titanium dioxide ($TiO_2$), forming $TiO_2$-cement composites that initiate a photocatalytic reaction in the presence of ultraviolet (UV) radiation. The concrete can be applied as a finishing material on external walls, roofs, and ground surfaces. It adds air purification capabilities to the treated surfaces, along with additional benefits such as antibacterial, anti-dirt properties, and heat-

island reduction effects. Many projects have been executed using this green cement product in various construction applications.

### Virtual Laboratory Set-up

Through the virtual laboratory setting, the effects of various building-envelope layouts and material compositions on the external urban environment were simulated, then evaluated by analyzing their associated greenhouse-gas emissions. Initially, the impact of a single-layer concrete wall versus a double-layer concrete wall was assessed in terms of energy performance and associated emissions to the external environment. Subsequently, various composite wall assemblies were investigated, including configurations with a concrete core, a glazed ceramic external finish with cork paneling selectively applied to specific areas rather than uniformly across the entire exterior wall surfaces. This latter assessment provided valuable insights for the experimental analysis detailed in the Section "The Fan-Cork Experiment".

### Advanced Instrumentation and Laboratories

The advanced laboratory and experimental setup enabled a comprehensive parametric analysis of the proposed novel approaches. For this purpose, various experimental tools were employed, including Arduino-based sensors and associated software configurations, to record non-controlled ambient external $CO_2$ levels. The Arduino[19] setup consisted of a microcontroller unit connected to a non-dispersive infrared (NDIR) $CO_2$ sensor, powered via Universal Serial Bus (USB) and programmed using the Arduino Integrated Development Environment (IDE) to log real-time data at fixed intervals for further analysis – Figure 2.

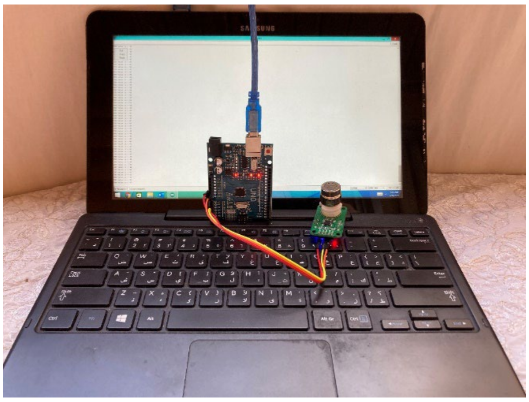

*Figure 2. Arduino sensor and platform*

To analyze the performance of the living concrete, advanced laboratory instruments were employed. The experiment was conducted in dedicated laboratories at the Department of Biotechnology, University of Verona, in collaboration with the Department of Architecture, Built Environment and Construction Engineering of Politecnico di Milano. The growth of microalgae on the concrete tile surface was monitored within a sanitized, sealed, and controlled chamber. Photosynthetic chlorophyll fluorescence was measured using a closed FluorCam FC 800-C imaging system[20] to assess the biological activity on the concrete surface.

## STRATEGIES

As explained earlier, achieving pre-industrial carbon levels requires not only optimizing energy systems and adopting net-zero technologies but also incorporating carbon – and other pollutants -scrubbing techniques. To address this need, the "Methodology" section above outlined the approaches used to develop relevant solutions. These methods were broadly classified into three categories: first, a literature review to extract key insights; second, the establishment of a virtual laboratory for simulation and performance assessment; and third, the application of advanced laboratory techniques to capture photosynthetic activity and assess related parameters.

Tailored to the case of Maritime Greenwich, two strategies have been identified as suitable for enhancing environmental sustainability and promoting green tourism. These are: first, an Optimization Strategy (OS), and second, a Negative Emissions Strategy (NES). These approaches will be described in the two paragraphs below.

### An Optimization Strategy

The first strategy is the Optimization Strategy (OS). It focuses on optimizing pollutant emissions associated with any proposed future activity within the Maritime Greenwich area and its buffer zone. This can be effectively evaluated through the implementation of Life Cycle Assessment (LCA) studies conducted prior to the initiation of such activities. The LCA process follows four main steps: 1. definition of the scope and goal(s); 2. compilation of an inventory of anticipated pollutant emissions; 3. assessment of the environmental impacts of these emissions; and 4. interpretation of the results to inform sustainable decision-making – Figure 3. This process should be conducted in alignment with the ISO 14040/44 standards for environmental management and life cycle assessment.[21]


*Figure 3. Steps of a Life Cycle Assessment*

For instance, if a team intends to build a concrete structure in the peripheral area of the Maritime Greenwich, then the team would revert to green concrete[22] applicable through the life cycle phases of the building material: 1. Production / Execution phase, 2. Use phase, and 3. End of Life phase.[23]

Moreover, energy consumption and transportation impacts—both within each phase and across the life cycle stages — should be thoroughly evaluated to ensure a comprehensive approach to environmental sustainability – Figure 4.

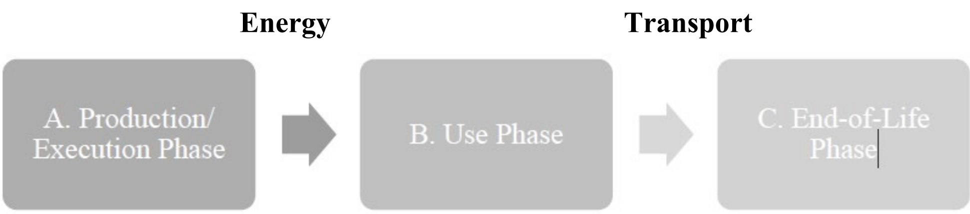


*Figure 4. Life Cycle Phases of Concrete*

### A Negative Emissions Strategy

While most scientists and industry stakeholders are focused on optimizing pollutant emissions — aiming to reduce them to zero through net-zero technologies — this approach alone proves insufficient to eliminate the harmful effects of existing pollutants. Consequently, a Negative Emissions Strategy (NES) becomes essential. This strategy involves the active/passive removal, scrubbing, or absorption of pollutants from the atmosphere. Our approach to implementing this strategy is framed through a "negative thinking" construct, which refers to a methodological research process aimed at identifying effective pollutant scrubbing solutions from the external environment. These solutions must be efficient, economically viable, and practical for implementation, with minimal technical or operational complexity for end users. This negative thinking approach can be applicable in Maritime Greenwich through three key steps: 1. Assessing and Mapping Pollutants, 2. Developing Mitigation Solutions, and 3. Testing and Monitoring. These key steps will be explained in the paragraphs below.

### Assessing and Mapping Pollutants

Identifying and mapping the prevalent pollutants that exceed established environmental thresholds within the area is a critical first step. This can be accomplished by deploying a network of environmental sensors to monitor the actual concentrations of greenhouse gas (GHG) and/or other identified noxious pollutants. Should the measured levels exceed the allowable thresholds,[24] then immediate intervention is required to scrub through one or more of the three proposed negative emissions or scrubbing solutions outlined below. In the case of Maritime Greenwich, sensors have been strategically positioned to detect NOx, $PM_{2.5,}$ and $PM_{10}$ concentration levels.[25] The reading of the current level shows a slight excess of NOx concentration in comparison to the targeted annual mean.

### Developing Mitigation Solutions

Based on a thorough assessment of the excess pollutants, mitigation solutions can be developed using a negative emissions approach derived from one or more of the three following realms: 1. The chemical realm, 2. The physical realm, and/or 3. the biological realm. Each realm offers distinct mechanisms for pollutant removal, which can be selected or combined depending on site-specific conditions and pollutant characteristics.

Chemical realm solutions involve neutralizing pollutants through targeted chemical reactions that convert harmful compounds into inert or less harmful forms. Physical realm solutions utilize devices and technologies — such as filtration systems, scrubbers, or adsorption units — to capture and remove pollutants from the environment. Biological realm solutions rely on cultivating specific organisms, such as microalgae or other photosynthetic species, capable of absorbing pollutants and releasing oxygen in return, thereby enhancing environmental quality through natural regenerative processes.

### Testing and Monitoring

Implementing the proposed solutions requires continuously testing and monitoring their effectiveness to ensure long-term success and environmental integrity. This involves both laboratory-based and in-situ measurements to evaluate the performance, durability, and environmental impact of the deployed solutions. Monitoring includes historical and real-time continuous data collection on key air quality indicators, using sensor networks and advanced analytical equipment. Additionally, periodic validation through standardized testing protocols ensures the reliability, scalability, and sustained efficacy of the mitigation strategies over time.

## RESEARCH AND EXPERIMENTATION RESULTS

Building upon the constructs, methodologies, and strategies outlined above, the following paragraphs present proposed solutions derived from key insights obtained through the literature review, analyses conducted within the virtual laboratory setup, and novel experiments carried out in both controlled and non-controlled laboratory environments.

### NOx abatement and $CO_2$ Aqueous Absorption

As indicated earlier, photocatalytic concrete - used for coatings, pavement, roof tiles, precast panels, and as a finish material – can abate high NOx concentrations through a series of chemical reactions, i.e., a sequential oxidation process.[26] This process is activated by light and may be traced as follows:

$$NO \rightarrow HNO_2 \rightarrow NO_2 \rightarrow NO_3^- \quad (1)$$

The resulting nitrate ion ($NO_3^-$) is non-toxic and is washed away by rain.

After extensive research on the properties of carbon dioxide, it was confirmed that $CO_2$ is soluble in water. In brief, $CO_2$ enters water through its interface with the atmosphere. Once dissolved, aqueous carbon dioxide ($CO_2(aq)$) reacts with water to form carbonic acid ($H_2CO_3(aq)$) via a reversible reaction.[27]

$$CO_2(aq) + H_2O \rightleftharpoons H_2CO_3(aq) \quad (2)$$

Carbonic acid ($H_2CO_3$) is considered non-harmful under normal environmental or physiological conditions.[28]

### The Fan-Cork Experiment

This experiment involved pressurizing atmospheric air onto a cork panel using a standard fan in a non-controlled environment. The setup was conducted in April within an urban Mediterranean climatic zone, specifically on the loggia of a fourth-floor apartment, where ambient $CO_2$ concentrations ranged between 450 and 480 ppm. The cork panel used measured 100 cm × 70 cm × 0.5 cm. Upon directing pressurized air over the panel, $CO_2$ levels recorded by an Arduino-based sensor platform decreased significantly to a range of 100–150 ppm – Figure 5.

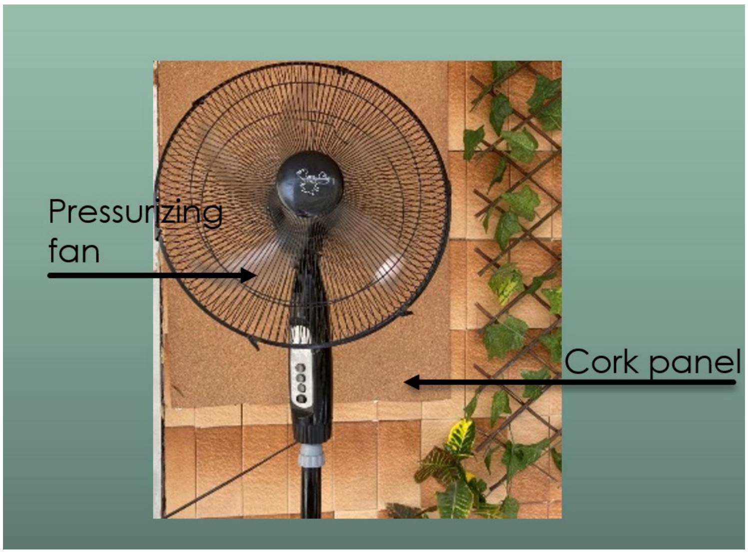


*Figure 5. Setup of the Fan-Cork Experiment*

Cork is a sustainable material,[29] harvested without harming the tree, as it regenerates its outer bark. It is also known for its porosity and thermal insulation properties. The observed $CO_2$ reduction is likely attributed to the porous structure of cork, which may facilitate the physical adsorption of $CO_2$, analogous to its application in wine bottles stoppers.[30] Once saturated, the cork panel can be safely buried in soil, where it naturally decomposes without disrupting the ecological balance.


*Figure 6. $CO_2$ levels recording*

## The Symbiotic Living Concrete Tile

The symbiotic living concrete tile was developed through a two-stage process. Stage One served as an exploratory experiment, while Stage Two involved advanced laboratory analysis.

In Stage One, the macroalgae *Ulva lactuca* was introduced to symbiose with a concrete tile submerged in a seawater aquarium. The concrete mix was designed to perform at a compressive strength of 35 MPa in 28 days. Adjacent to the setup, an Arduino-based platform was used to monitor ambient $CO_2$ concentration levels, which showed a significant decrease from 450 ppm to 100–150 ppm during the experiment[31] - Figure 6.

In Stage Two, *Chlorella vulgaris*, a species of microalgae, was cultivated on the surface of an ASTM (American Society for Testing and Materials)-certified concrete finish block in dedicated laboratory conditions. The living concrete tile exhibited sustained photosynthetic activity from Day 0 through Day 18, at which point the experiment was deliberately concluded.[32]

## DISCUSSION

This paper presents a novel methodology and suggests strategies to transform Maritime Greenwich into a model for green tourism by adopting “user-friendly” negative emissions technologies (NET)s. Though still exploratory, it proposes an integrated threefold approach — physical, chemical, and biological — to mitigate greenhouse gas (GHG) and other pollutants. The ultimate objective is to position Maritime Greenwich as a reference for sustainable tourism. While promising for localized remediation, these solutions require further scientific validation in the event of broader applicability.

To support targeted mitigation, sensor networks should monitor pollutants that may exceed regulatory thresholds. These values must be assessed against national/international standards to ensure compliance and effectiveness.

Among the biological approaches, the photosynthetic living concrete tile — with *Chlorella vulgaris* — offers a low-cost, low-maintenance alternative to conventional green infrastructure like trees and vegetated walls. Further potential lies in optimizing microalgae performance through species beyond *Chlorella*, which may offer enhanced carbon capture and durability.[33]

Other avenues include $CO_2$ absorption by cork, pending the determination of the saturation level and the testing in an advanced laboratory setup. Expanding cork forests can provide both paneling material and carbon sinks. Likewise, remediating Thames River discharges — and extrapolating globally — can help restore freshwater flows that absorb $CO_2$. Though ambitious, these systemic strategies offer strong potential in climate mitigation.

## CONCLUSION

The study evaluates three proposed solutions — chemical, physical, and biological — for scrubbing carbon dioxide ($CO_2$), the main global warming agent. The framework may also apply to other GHG such as methane ($CH_4$) and other pollutants like sulfur dioxide ($SO_2$). Similarly, the green concrete approach could extend to limestone materials that passively absorb atmospheric $CO_2$.

These interventions aim to localize a global challenge within Maritime Greenwich, considered a model urban module – Figure 7. Scaling such approaches across other modules — by identifying pollutants and implementing mitigation strategies — can collectively yield meaningful environmental impact. This modular, place-based methodology offers a scalable path to planetary health.

*Figure 7. Scaling down a global issue*

Although technically simple, the proposed solutions have profound implications. Their success requires interdisciplinary collaboration, refinement, and sustained commitment. With adequate testing, validation, and policy support, Maritime Greenwich could become a living laboratory and replicable model for climate-responsive urban transformation.

## PATENT

The findings are patented under the French Law:
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