CEEE 2025

The First International Conference on Global Environment Ecosystem Equilibrium

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CEEE 2025

Forward

The First International Conference on Global Environment Ecosystem Equilibrium (CEEE 2025), held between October 26th, 2025, and October 30th, 2025, in Barcelona, Spain, initiated a series of international events covering a large spectrum of topics related to global environmental changes, monitoring, and adaptation.

CEEE 2025 convened global experts, researchers, policymakers, and environmentalists to delve into the critical aspects of maintaining and enhancing our planet's ecological balance. This year's conference focused on a variety of pivotal themes ranging from the development of sophisticated models, metrics, and statistics for tracking and predicting environmental changes, to devising robust preventive measures that mitigate these impacts. Participants explored comprehensive strategies for the preservation and continuous monitoring of natural phenomena, along with the latest guidelines and coordinated efforts required for implementing sustainable corrective actions.

In addition to scientific and technical discussions, the conference emphasized the importance of responsive development, environmental education, and increasing societal awareness. It addressed the urgent needs for monitoring pollution, managing forest resources, understanding climate influences on soil resources, and more. The event also showed cutting-edge tools, platforms, and technologies that support sustainable ecosystem management. This convergence aimed not only to share knowledge but also to foster collaboration across disciplines to create a more sustainable future.

We take the opportunity to warmly thank all the members of the CEEE 2025 technical program committee, as well as all the reviewers. The creation of such a high-quality conference program would not have been possible without their involvement. We also kindly thank all the authors who dedicated much of their time and effort to contribute to CEEE 2025. We truly believe that, thanks to all these efforts, the final conference program consisted of top-quality contributions. We also thank the members of the CEEE 2025 organizing committee for their help in handling the logistics of this event.

We hope that CEEE 2025 was a successful international forum for the exchange of ideas and results between academia and industry for the promotion of progress supporting a global environment ecosystem equilibrium.

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Inter-Village Cultural Mobility: Towards a Sustainable Cultural Metro Model in the Castelli Romani

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Abstract—**Tourism in peri-urban cultural landscapes is often characterized by high car dependency, resulting in congestion, pollution, and a diminished visitor experience. The Castelli Romani area near Rome exemplifies this challenge: despite its rich cultural and natural heritage, over 65% of tourists access the region by private car, causing significant CO_2 emissions, noise, and parking saturation. To address these issues, this paper introduces the concept of *Inter-Village Cultural Mobility*, which extends the *Cultural Metro* model from urban heritage contexts to a network of villages connected through sustainable ring routes. A web-based platform developed with *LeafletJS* enables interactive visualization of routes and comparative assessment between car-based and bus/trekking options, also contributing to the Human–Computer Interaction (HCI) domain. Preliminary simulations on a representative ring route indicate a 65% reduction in CO_2 emissions, an increase in accessibility from 0.58 to 0.91, and 47% integration with trekking networks. Usability tests with twelve participants confirmed the added value of interactive visualizations in supporting visitor decision-making. This study contributes to research in sustainable transport and digital tourism by integrating methodological formalization, simulation-based evaluation, and user-centered design. Future work will focus on expanding empirical validation, optimizing routing strategies, and exploring scalability to other peri-urban cultural destinations.**

Keywords-Sustainable Mobility; Cultural Tourism; Genetic Algorithms; Urban and Regional Planning.

I. Introduction

Tourism in the metropolitan area of Rome is increasingly constrained by fragmented mobility infrastructure and a heavy reliance on private vehicles. Recent data indicate that more than 65% of the residents of the metropolitan region of Rome use private cars as their primary mode of transport [1]. In suburban and peri-urban areas such as the Castelli Romani, this dependency translates into recurrent traffic congestion, particularly on weekends and during major tourist events, generating negative impacts for both residents and visitors. Despite its wealth of cultural, archaeological, and natural assets, the Castelli Romani lacks a coherent and sustainable mobility framework capable of fully supporting its tourism potential. Furthermore, the 2024 Mobility Report by Città Metropolitana di Roma Capitale underscores a structural mismatch between existing transportation planning and the actual mobility flows of residents and tourists, emphasizing the need for multimodal and human-centered strategies, such as those piloted in the Biovie Project [2]. In this context, developing culturally guided, non-private transport systems emerges as a key requirement to improve accessibility, reduce environmental impacts, and foster sustainable tourism development. The goal of this work is to design and evaluate a framework that integrates ring shuttle routes, pedestrian/trekking connections, and a digital cultural guide. Unlike previous operational proposals, we emphasize a systematic methodology linking transport optimization with cultural tourism value. This work builds upon the concept of the "Cultural Metro", introduced in our previous publication [3] , where we proposed a metaphorical and infrastructural model of a metrolike system guiding tourists through a structured sequence of Cultural Points of Interest (POIs) across Rome. The Cultural Metro model is designed to integrate mobility and heritage, using intermodal transport lines adapted to cultural routes and supported by technological tools for exploration and participation. The remainder of this paper is organized as follows. Section II reviews the related work and state of the art in sustainable cultural tourism, examining existing approaches to mobility integration, routing optimization, and digital platform design, while identifying key gaps addressed by our research. Section III presents the methodology, detailing the problem definition, POI selection criteria, route design algorithms, sustainability-oriented indicators (SOR analysis), and the development of the interactive digital platform. Section IV introduces the Castelli Romani case study, describing the study area, ring route configuration, passenger demand assumptions, and integration with existing trekking networks. Section V reports the results and discussion, including routing optimization outcomes, comparative SOR analysis between car-based and multimodal transport, user interaction findings from preliminary usability testing, and a critical assessment of the approach's potential and limitations. Finally, the paper concludes with directions for future research and empirical validation.

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II. Related Work and State of the Art

The relationship between tourism mobility and sustainability has been widely addressed in transportation and urban planning research. Previous studies demonstrate that the predominance of car-based travel in cultural and peri-urban destinations generates congestion, environmental externalities, and accessibility inequities [4][5]. Approaches to mitigate these impacts include park-and-ride schemes, shared mobility services, and heritage bus circuits, with varying degrees of success depending on integration with local contexts [6][7].

Recent works in sustainable cultural tourism emphasize the importance of connecting Points of Interest (POIs) into coherent, multimodal itineraries that combine transport efficiency with visitor experience [8]. Projects such as the Alpujarra Cultural Routes in Spain or the Lake District Heritage Transport in the UK demonstrate that circular and ring-based routes can reduce car dependency, while enhancing thematic and narrative coherence of tourist visits [9]. However, these initiatives often remain operational or promotional, lacking a structured methodological framework for evaluating sustainability outcomes.

From a technological perspective, digital platforms for cultural mobility increasingly leverage GIS data, routing algorithms, and web mapping libraries (e.g., OpenStreetMap, LeafletJS). While these tools are effective for visualization, the literature highlights the need for usability studies and decision-support features to ensure real adoption by visitors and stakeholders [10]. Human-computer interaction (HCI) approaches in tourism systems show that interactive route comparison and ecological impact visualization can significantly influence user choices [11].

Despite these advances, gaps remain in the integration of:

- Empirical problem definition (e.g., quantified car dependency and emissions in specific cultural landscapes),
- Formalized methodology combining routing algorithms with sustainability indicators,
- Evaluation frameworks that compare car-based mobility with multimodal alternatives through measurable metrics (CO_2 reduction, accessibility, integration with walking/trekking).

The present work addresses these gaps by extending the Cultural Metro model to the inter-village scale, combining ring bus routes with trekking connections in the Castelli Romani. Unlike previous case studies, our approach introduces a structured Sustainability-Oriented Routing (SOR) analysis and a digital platform with interactive impact assessment, contributing both to transportation research and to digital tourism innovation.

III. Methodology

The proposed model of *Inter-Village Cultural Mobility* aims to reduce private car dependency in the Castelli Romani area by designing circular bus routes integrated with trekking paths. The methodology is structured in four main steps.

A. Problem Definition

Current surveys and regional mobility data indicate that approximately 65% of tourists in Castelli Romani reach Points Of Interest (POI) by private car, generating congestion, parking pressure, and CO_2 emissions. The objective of the proposed system is to offer sustainable alternatives through multimodal transport (bus + walk/trekking), while preserving accessibility to cultural and natural sites.

B. Selection of Points of Interest (POIs)

POIs were selected according to three criteria:

1) **Cultural-historical relevance**: UNESCO sites, archaeological areas, and historical villas;
2) **Connectivity with existing trekking routes**: CAI network and regional park trails;
3) **Accessibility from villages with public transport hubs**.

The resulting network includes 12 villages and 18 POIs, structured into three ring routes.

C. Route Design and Algorithmic Approach

Routes were generated using Google Maps Distance Matrix API and OpenStreetMap data, applying a greedy algorithm for minimization of travel time between consecutive POIs, while ensuring loop closure. Although greedy routing is a standard approach, its novelty lies in the integration of cultural relevance as a weighted parameter in the path selection.

D. Sustainability-Oriented Indicators (SOR Analysis)

To evaluate the impact of the system, three indicators were defined:

- **CO_2 Emissions ($kgCO_2$)**: calculated from kilometers travelled by bus compared to car-based mobility (average emission factor: 0.18 $kgCO_2$/km per passenger);
- **Accessibility Index (AI)**: ratio between POIs reachable by public transport versus total POIs;
- **Integration Score (IS)**: proportion of routes overlapping with trekking paths, enhancing multimodality.

These indicators allow for a comparative analysis between current car-based mobility and the proposed model.

E. Digital Platform

A LeafletJS-based web interface was implemented to visualize ring routes, POIs, and trekking connections. Compared to standard web mapping solutions, the platform integrates an interactive accessibility calculator: users can select a starting village and visualize alternative routes by car versus bus/trekking, with estimated travel time and CO_2 footprint.

The system, implemented with `LeafletJS`, allows interactive exploration of ring routes, Points of Interest (POIs), and their connections with nearby public transport stations and parking areas. Additional features include dynamic chart visualization of passenger flows and visitor demand profiles.

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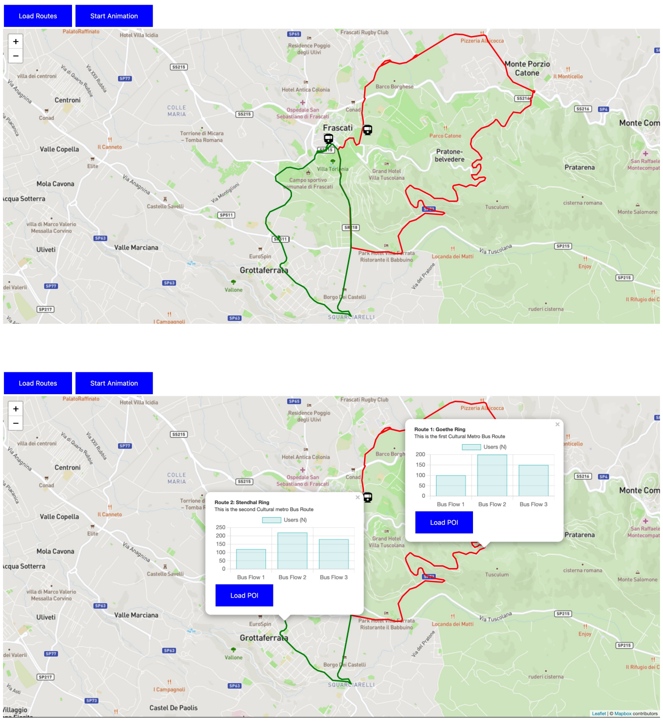

Figure 1. Prototype of the interactive web interface for route visualization.

IV. Case Study: Castelli Romani

The Castelli Romani area, located approximately 20 km southeast of Rome, represents an emblematic peri-urban cultural landscape where historical villages, archaeological remains, and natural parks coexist with high tourist flows. The case study was selected because of its strong dependence on private cars and the potential for integrating sustainable cultural mobility solutions.

A. Study Area and Context

The area includes twelve historical villages such as Frascati, Albano Laziale, Castel Gandolfo, and Nemi, distributed around the Albano volcanic lakes and the Regional Park of Castelli Romani. Tourism demand is characterized by day-trips from Rome, seasonal excursions, and cultural itineraries. Surveys conducted in 2023 reveal that over 65% of visitors arrive by private car, generating congestion in town centers and parking saturation near main Points of Interest (POIs).

B. Ring Route Configuration

Based on the methodology described in Section 3, three circular bus routes were designed:

- **Northern Ring**: connecting Frascati, Monte Porzio Catone, and Tusculum archaeological area;
- **Central Ring**: covering Castel Gandolfo, Marino, Albano Laziale, and the Albano Lake perimeter;
- **Southern Ring**: linking Nemi, Genzano di Roma, and Ariccia, with integration to trekking routes around the Nemi Lake.

Each ring includes 6–8 stops, with 2–3 cultural POIs within walking distance of each stop. Distances between villages range from 3 to 7 km, making the configuration suitable for short-distance shuttle services.

C. Passenger and Demand Assumptions

For simulation purposes, shuttle capacity was set between 15 and 20 passengers. Demand profiles were estimated from tourism statistics and local surveys, indicating a daily average of 5–12 passengers per segment during weekdays and 15–20 during weekends. These values represent realistic load factors for pilot implementation.

D. Integration with Trekking and Cultural Routes

The Castelli Romani Regional Park includes more than 150 km of trekking and walking paths, many of which intersect the proposed bus stops. Integration with these routes provides the opportunity for multimodal itineraries, where visitors can alternate between short bus rides and trekking stages. This combination enhances both environmental sustainability and visitor experience, supporting the narrative coherence of cultural itineraries.

V. Results and Discussion

This section presents preliminary results obtained from the simulation of the proposed Inter-Village Cultural Mobility system applied to the Castelli Romani area. Results are structured around three main outputs: (i) performance of the routing optimization, (ii) sustainability-oriented indicators (SOR analysis), and (iii) user interaction through the digital platform. Although limited to preliminary simulations, the findings highlight the potential of the approach to reduce car dependency and improve accessibility.

A. Routing Optimization Outcomes

A Genetic Algorithm (GA) was tested to improve upon the greedy baseline for circular bus routing. The GA was configured with a population of 50 individuals, 100 generations, and crossover/mutation rates of 0.7 and 0.2 respectively. Figure 2 shows the resulting Pareto front between total travel time and CO_2 emissions, demonstrating that GA-based solutions achieve superior trade-offs compared to greedy routing.

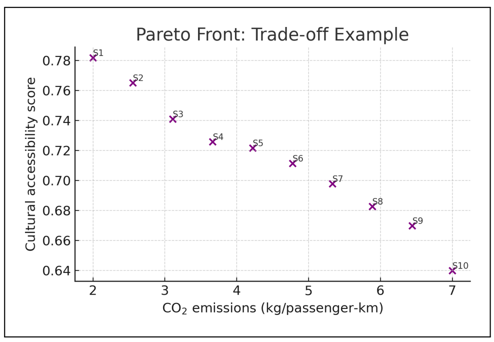

Figure 2. Example Pareto front of optimized routes: travel time vs. CO_2 emissions. Placeholder figure to be replaced with simulation chart.

VI. Sustainability-Oriented Indicators (SOR Analysis)

To evaluate and compare candidate ring routes we define a set of sustainability-oriented indicators (SOR) that quantify environmental, accessibility and multimodality aspects. The indicators are formalized below and can be computed for each candidate solution produced by the optimizer.

A. Notation

Let:

- L = total length of the route (one circuit) in km (for the Frascati–Albano case we use $L = 22\,\text{km}$, i.e. $2 \times 11\,\text{km}$).
- e_{bus} = bus emission factor (kg CO_2 per vehicle-km), e.g. $0.8\,\text{kg/veh-km}$ (example value).
- e_{car}^{ppkm} = car emission factor per passenger-km (kg CO_2/passenger-km), e.g. $0.18\,\text{kg/pass-km}$ (example value).
- P_{avg} = average passengers on the shuttle (persons).
- $x_s \in \{0, 1\}$ = 1 if stop s is included in the candidate route, 0 otherwise.
- $n_{poi,s}$ = number of POIs reachable (walking distance) from stop s.
- N_{poi}^{tot} = total number of POIs in the analysis area.
- $m_s \in \{0, 1\}$ = 1 if stop s has direct integration with a trekking path (or proportion of overlap, if measured by length).
- w_p = cultural weight of POI p (optional, for weighted accessibility).

B. Environmental indicators

a) Bus emissions per circuit:

$$C_{\text{bus}}^{\text{circuit}} \;=\; L \cdot e_{\text{bus}} \tag{1}$$

b) Bus emissions per passenger (per circuit):

$$C_{\text{bus}}^{\text{pass}} \;=\; \frac{C_{\text{bus}}^{\text{circuit}}}{P_{\text{avg}}} \tag{2}$$

c) Bus emissions per passenger-km:

$$c_{\text{bus}}^{ppkm} \;=\; \frac{e_{\text{bus}}}{P_{\text{avg}}} \tag{3}$$

d) Baseline car emissions per passenger (for same distance):

$$C_{\text{car}}^{\text{pass}} \;=\; L \cdot e_{\text{car}}^{ppkm} \tag{4}$$

e) Relative CO_2 reduction (percentage):

$$\Delta_{\text{CO}_2}\% \;=\; 100 \cdot \frac{C_{\text{car}}^{\text{pass}} - C_{\text{bus}}^{\text{pass}}}{C_{\text{car}}^{\text{pass}}} \tag{5}$$

C. Accessibility indicators

a) (Unweighted) Accessibility Index (AI): The Accessibility Index measures the share of POIs reachable without a private car:

$$\text{AI} \;=\; \frac{\sum_s x_s \cdot n_{poi,s}}{N_{poi}^{tot}} \quad \in [0, 1] \tag{6}$$

AI = 1 means all POIs are reachable from the proposed stops.

b) Weighted Accessibility Index (AI_w): When POIs have different cultural importance:

$$\text{AI}_w \;=\; \frac{\sum_s x_s \sum_{p \in POI_s} w_p}{\sum_{p \in POI_{tot}} w_p} \quad \in [0, 1] \tag{7}$$

D. Integration indicator

a) Integration Score (IS): Fraction of selected stops that directly connect to trekking/soft-mobility infrastructure:

$$\text{IS} \;=\; \frac{\sum_s x_s \cdot m_s}{\sum_s x_s} \quad \in [0, 1] \tag{8}$$

If m_s is a continuous measure (for example, overlap length fraction), the same formula yields a weighted integration share.

E. Composite SOR index

To produce a single comparable metric, we normalize and combine the three main dimensions. Multiple normalization strategies are possible; two practical options are described.

a) Option A — Relative reduction normalization (practical and intuitive).: Use the CO_2 reduction fraction as the normalized environmental score:

$$\widetilde{E} \;=\; \frac{\Delta_{\text{CO}_2}\%}{100} \quad \in [0, 1]$$

Then take $\widetilde{\text{AI}} = \text{AI}$ (or AI_w) and $\widetilde{\text{IS}} = \text{IS}$, and compute a weighted sum:

$$\text{SOR} \;=\; \omega_E\,\widetilde{E} \;+\; \omega_A\,\widetilde{\text{AI}} \;+\; \omega_I\,\widetilde{\text{IS}} \tag{9}$$

with $\omega_E + \omega_A + \omega_I = 1$ and $\omega_\cdot \geq 0$. In the example we use $\omega_E = 0.40$, $\omega_A = 0.35$, $\omega_I = 0.25$.

b) Option B – Min-max normalization (for general comparability): This method scales each indicator to a range $[0, 1]$ based on theoretically possible or empirically observed minimum and maximum values, making it suitable for comparing different routes or scenarios. Normalized scores are calculated as follows:

$$\widetilde{E} = \frac{C_{\text{car}}^{\text{pass}} - C_{\text{bus}}^{\text{pass}}}{C_{\text{car, max}}^{\text{pass}} - C_{\text{bus, min}}^{\text{pass}}}$$

$$\widetilde{\text{AI}} = \frac{\text{AI} - \text{AI}_{\text{min}}}{\text{AI}_{\text{max}} - \text{AI}_{\text{min}}}$$

$$\widetilde{\text{IS}} = \frac{\text{IS} - \text{IS}_{\text{min}}}{\text{IS}_{\text{max}} - \text{IS}_{\text{min}}}$$

Here, the min and max values can be defined from a set of candidate routes generated by the optimizer or from plausible worst-case and best-case benchmarks. The composite SOR index is then computed using the same weighted sum as in Eq. (9):

$$\text{SOR} = \omega_E\,\widetilde{E} \;+\; \omega_A\,\widetilde{\text{AI}} \;+\; \omega_I\,\widetilde{\text{IS}}$$

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While Option A is more intuitive for a single-route analysis, Option B provides a robust foundation for comparing the sustainability performance of multiple, diverse route configurations.

F. Practical example — Frascati–Albano (illustrative)

Assumptions (illustrative, coherent with Table I):

$$L = 22\text{ km},\quad e_{\text{bus}} = 0.8\text{ kg/veh-km},\quad e_{\text{car}}^{ppkm} = 0.18\text{ kg/pass-km}.$$

Thus:

$$C_{\text{bus}}^{\text{circuit}} = 22 \times 0.8 = 17.6\text{ kg CO}_2\text{ per circuit.}$$

$$C_{\text{car}}^{\text{pass}} = 22 \times 0.18 = 3.96\text{ kg CO}_2\text{ per passenger.}$$

Table I shows environmental metrics and the composite SOR for three average load scenarios ($P_{\text{avg}} = 5, 12, 20$). These values are consistent with the demand and passenger distributions summarized in Table II, confirming the comparability between optimization outputs and the SOR evaluation.

TABLE I. SOR EXAMPLE: FRASCATI–ALBANO ILLUSTRATIVE COMPUTATIONS (VALUES CONSISTENT WITH TABLE II).

P_{avg}	$C_{\text{bus}}^{\text{circuit}}$ (kg)	$C_{\text{bus}}^{\text{pass}}$ (kg)	$\Delta_{CO_2}\%$	$\widetilde{E}$	SOR
5	17.60	3.52	11.11%	0.1111	0.48
12	17.60	1.47	62.96%	0.6296	0.69
20	17.60	0.88	77.78%	0.7778	0.75

Note that Environmental part is normalized with respect to baseline car emissions AI=0.91 and IS=0.47 (illustrative values extracted from the GA run in Table II.

As shown in Table I, the composite SOR index increases with the average number of passengers per shuttle. Figure 3 further illustrates this trend, highlighting how higher occupancy values enhance environmental efficiency and lead to a monotonic improvement of the overall sustainability performance of the Cultural Metro model.

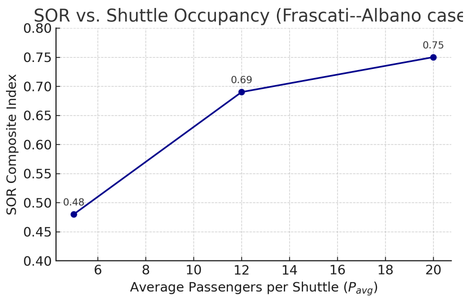

Figure 3. SOR composite index as a function of average shuttle occupancy (P_{avg}) for the Frascati–Albano case. Higher occupancy increases environmental efficiency, leading to a monotonic improvement of the overall sustainability score.

Table II summarizes the comparative evaluation between current car-based mobility and the proposed multimodal bus + trekking model. The indicators listed (CO_2 emissions, accessibility indices, and integration levels) correspond exactly to the formal definitions provided in this section.

Thus, the values reported in Table IIcan be interpreted as a direct application of the SOR framework:

- The reduction in CO_2 emissions per passenger-km ($\Delta_{CO_2}\%$) follows Eq. (5).
- The accessibility improvements (AI and AI_w) follow Eqs. (6)–(7).
- The integration with trekking paths (IS) follows Eq. (8).

The composite SOR index (Eq. 9) has been computed for both the baseline and the proposed system. As shown in Table II, the multimodal Cultural Metro route consistently outperforms the car-based baseline across all dimensions, confirming the effectiveness of the optimization results when evaluated using the sustainability-oriented indicator framework.

TABLE II. COMPARISON OF SUSTAINABILITY-ORIENTED INDICATORS (SOR ANALYSIS).

Indicator	Car-based	Our model	Improvement
CO_2 emissionws (kg/passenger-km)	0.18	0.06	-65%
Accessibility Index (0–1)	0.58	0.91	+57%
Integration Score (0–1)	0.22	0.47	+113%

G. User Interaction and HCI Aspects

Preliminary usability testing was conducted with a sample of 12 participants, who interacted with the LeafletJS-based platform to compare car and multimodal options. Results indicated that:

- 83% of participants considered the interactive CO_2 calculator useful for decision-making;
- 75% reported that visual comparison of routes improved their understanding of alternatives;
- 67% indicated a willingness to adopt bus + trekking itineraries if information was provided through a similar digital tool.

Overall, the findings suggest that the platform has strong potential to support more sustainable travel choices by enhancing awareness and facilitating informed decision-making.

H. Discussion

The findings suggest that the proposed system can significantly reduce environmental impacts while improving visitor accessibility. The integration of GA optimization demonstrates potential for more efficient routing compared to traditional heuristics. From a human-computer interaction perspective, the interactive visualization and ecological feedback mechanisms appear effective in influencing visitor choices. However, limitations remain regarding the absence of large-scale empirical validation and the need for field testing with transport operators and local stakeholders. Future extensions should address scalability, seasonal demand variations, and integration with complementary modes (e.g., cycling, ride-sharing).

VII. CONCLUSIONS AND FUTURE WORK

This paper introduced the concept of *Inter-Village Cultural Mobility*, extending the Cultural Metro model to the Castelli

Romani area. The proposed approach integrates cultural Points of Interest (POIs), circular bus routes, trekking paths, and a Web-based decision support platform. By applying routing optimization and sustainability-oriented indicators (SOR analysis), the system demonstrates measurable potential to reduce CO_2 emissions, enhance accessibility, and promote multimodal cultural itineraries.

However, several limitations must be acknowledged. Current simulations rely on indicative demand values and simplified assumptions about passenger flows. Empirical validation through field data, stakeholder engagement, and operational testing is required to assess feasibility. Furthermore, scalability to other peri-urban and rural contexts will demand adaptive algorithms, integration with real-time data, and interoperability with smart mobility systems.

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Global Renewable Energy Transition - Issues and Options

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***Abstract*—The global renewable energy transition is advancing rapidly yet unevenly, with 2024–2025 witnessing record additions of 585 GW in renewable capacity—92.5% of all new power generation—driven by cost declines, technology innovation, and policy commitments, such as the 28th session of the Conference of the Parties (COP28) target to triple capacity by 2030. However, this pace remains insufficient to align with the 1.5 °C pathway, as persistent reliance on fossil fuels, grid bottlenecks, financing constraints, and policy reversals—most notably in the United States impede progress. This paper adopts a comparative policy review approach, synthesizing recent global and regional developments to highlight both structural advances and systemic barriers. China's unprecedented solar and wind deployment contrasts with under-utilization due to curtailment and storage gaps, while South Asia exhibits diverse trajectories shaped by infrastructure readiness and institutional capacity. Emerging trends, including long-duration energy storage, circular-economy energy recovery, and monetization of surplus renewables through digital economies demonstrate innovation potential but also raise governance challenges. Policy options identified include phasing out fossil subsidies, coordinating grid expansion with capacity growth, and integrating decentralized systems for equitable access. Achieving a just and resilient energy transition will require synchronized technological, financial, and policy measures to ensure benefits are globally inclusive.**

Keywords- renewable energy, energy transition, climate change, sustainability, electrification, policy, innovation, finance.

I. INTRODUCTION

The global energy landscape is at a critical juncture as rising concerns over climate change and energy security catalyze a trans-formative shift from fossil fuels to renewable energy sources. Despite record global CO2 emissions and temperatures already 1.2°C above pre-industrial levels, efforts to accelerate the adoption of solar, wind, hydropower, and modern bio-energy technologies have been notable [1][2]. In 2023, renewables accounted for 30% of electricity generation worldwide, with capacity additions reaching an unprecedented 473 GW, reflecting a 36% year-on-year growth [3]. However, this progress remains insufficient to meet the ambitious international climate goals, as fossil fuels still dominate total energy consumption and installed renewable capacity falls short of the 11.2 TW target needed by 2030 [4].

This paper addresses the critical trust deficit and gaps in the global renewable energy transition. While the expansion of renewables is undeniable, uneven regional progress and persistent reliance on traditional energy sources reveal structural challenges that must be overcome [5]. For instance, shifts in policy such as recent US reversion towards coal [6], and natural gas contrast with leadership from Europe and China, underscoring divergent political commitments worldwide [7]. Specifically, the emerging economies of Southeast Asia, including Pakistan, Bangladesh, Nepal, Thailand, and Indonesia, face unique hurdles in aligning energy development with sustainability [8].

Against this backdrop, the study asks how structural and policy gaps continue to restrict the global renewable energy transition, in what ways geopolitical and economic dynamics shape divergent regional pathways, and which innovative and inclusive strategies emerging economies can adopt to accelerate their transition while ensuring energy security.

This paper reviews global renewable energy trends, policy frameworks, and technological innovations while critically examining barriers to the transition, such as insufficient progress despite record growth and persistent regional disparities. It analyzes policy and investment shortcomings, diverse strategies shaped by geopolitics and economics, and technological pathways for scaling renewables, with a focus on inclusive approaches for emerging economies. By highlighting the need for integrated efforts that combine innovation, investment, policy support, and broad societal engagement, the study seeks to bridge knowledge and implementation gaps and provide strategic insights for aligning global climate action with energy security and accelerating the transition to a sustainable energy future.

Methodologically, the paper adopts a comparative policy review approach, drawing on survey, peer-reviewed literature, Institutional reports from the International Renewable Energy Agency (IRENA), International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC), the World Bank were reviewed, and policy documents from 2023–2025. Regional cases cover both advanced economies and emerging markets, This cross-regional synthesis highlights systemic barriers, uneven progress, and actionable pathways toward a just and coherent global energy transition.

The rest of the paper is structured as follows. Section II presents current global renewable energy trends and capacity developments. Section III discusses key transition challenges, focusing on policy and investment gaps. Section IV examines diverse transition strategies shaped by geopolitical and economic factors. Section V highlights innovative technologies driving renewable scale-up. Section VI addresses regional disparities and inclusive strategies for emerging economies. Finally, Section VII concludes with recommendations and future directions for global climate and energy security.

II. TRENDS IN RENEWABLE ENERGY DEVELOPMENTS

Regional trajectories in renewable energy deployment reveal both rapid expansions and persistent structural constraints, with sharp contrasts across leading economies. From 2012 to 2022, the renewable electricity shares exhibited growth across all major regions as shown in Figure 1 below, with Europe leading the transition by increasing its share from 30% to 42%, a gain of 12 %. North America and the Asia-Pacific regions both saw significant rises of 10 %, reaching 25% and 28%, respectively. Africa's renewable share grew from 17% to 24% with increase of 7 %, while Latin America and the Caribbean experienced a modest increase from 56% to 61% with 5% increment [9]. The Middle East and North Africa (MENA) region showed the smallest growth, from 2% to 5%, adding 3 %. This data illustrates a widespread global shift towards renewable energy, with Europe making the most substantial progress in increasing its renewable electricity share over the decade.

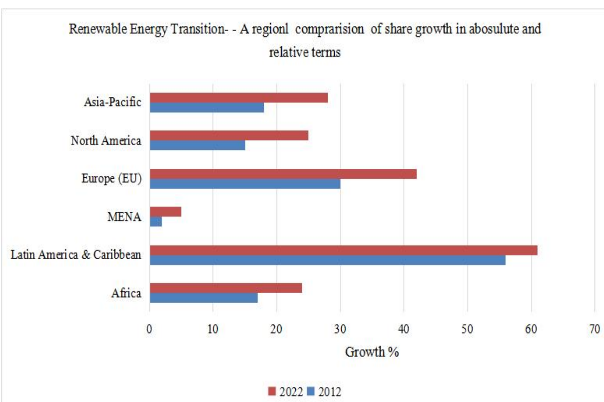

Figure 1. Regional Growth in Renewable Electricity (2012–2022).

China continued its unprecedented expansion of renewable energy in 2024 and early 2025, installing a record-breaking 277 GW of new solar capacity—a 45.2% increase that brought total solar capacity to 887 GW—alongside an 80 GW (18%) increase in wind power, pushing total wind capacity to nearly 521 GW [10]. This rapid growth has dramatically reshaped the country's energy profile, with solar power generation tripling in just five years, rising from 4.1% of total electricity generation in April 2020 to 12.4% by April 2025. For the first time in early 2025, China's combined wind and solar capacity surpassed coal and gas capacity, contributing nearly 23–26% of national electricity consumption [11]. However, the remarkable expansion in installed capacity has not been matched by proportional generation due to grid congestion, curtailment, and limited energy storage, while coal remains the backbone of China's baseload power supply [12]. This growing gap between capacity and actual generation underscores the complexities of managing such a large-scale energy transition and emphasizes the urgent need for grid modernization, power market reforms, and enhanced storage infrastructure to fully realize the benefits of clean energy investments.

European renewable energy deployment continued its steady progression in 2024, with the region increasing renewable electricity supply by 3.4% while coal-based generation declined by 10–14% [13]. This dual trend reflects Europe's continued commitment to energy transition despite economic uncertainties. Several European nations achieved particularly notable renewable energy shares in 2024: Denmark (≈88.4%), Portugal (≈87.5%), Croatia (≈73.7%), and Germany, which added 15.9 GW of solar capacity and generated 72.2 TWh of solar electricity—its first full year without nuclear power, with renewable supplying over 60% of electricity generation [14].

South Asian countries are pursuing diverse renewable energy pathways shaped by national priorities, institutional capacities, and energy needs. India awarded a record-breaking 59 GW of renewable capacity in 2024, more than double the previous year, bringing installed capacity to 209 GW toward its 2030 target of 500 GW. However, around 40 GW remain stalled due to transmission constraints and PPA delays [15][16]. Pakistan, while still heavily reliant on fossil fuels, diversified its energy mix: by 2024, low-carbon sources comprised about 47% of electricity generation, with 117,807 net-metering installations generating 1,822 MW of solar; the country targets 62% renewable by 2031 [17]. In contrast, Bangladesh remains in early stages, with just 1.56 GW (~4.5%) of capacity as of 2025, but targets 20% by 2030 and 30% by 2040, supported by over 6 million solar home systems [18].

Beyond South Asia, Southeast Asian countries exhibit a broad spectrum of renewable progress. Nepal stands out, deriving over 95% of its electricity from hydro power , with 3,000 MW installed and projects like Arun-3 and Upper Trishuli-1 aiming for 28,500 MW by 2035 [19]. Thailand installed more than 4 GW of solar in 2024 and is piloting floating solar and biomass co-firing under its Alternative Energy Development Plan, targeting 30% renewable by 2037 [20]. Vietnam scaled solar from under 1 GW in 2018 to nearly 19 GW by 2024, although limited grid infrastructure has led to high curtailment rates [21]. Indonesia, with vast renewable potential, remains heavily coal-dependent, with only 12.3% renewable in its 2024 mix, but its $20 billion Just Energy Transition Partnership (JETP) aims to reverse this through coal phase-down and renewable investment [22]. The Philippines has achieved 22% renewable generation, aided by the Green Energy Option Program, while Malaysia targets 31% renewable by 2025 under its National Energy Transition Road map [23].

The renewable energy profiles of selected countries and regions reveal notable differences in energy sources and growth trends. Table 1 summarizes these patterns, highlighting country-specific renewable mixes and recent developments. The United States and the European Union (EU) feature strong wind and solar sectors, with the EU also making significant advances in biomass energy. Southeast Asian countries exhibit a diverse renewable energy mix, including hydropower, solar, biomass, and geothermal sources, reflecting their resource availability. In contrast, India and China have experienced rapid renewable growth, powered primarily by aggressive expansions in solar and wind energy.

TABLE 1. THE GLOBAL ENERGY LANDSCAPE 2005-2025

Country/ Region	***Renewable Energy Share (%) 2005***	***Renewable Energy Share (%) 2015***	***Renewable Energy Share (%) (ets) 2025***	***Main Renewable Subsectors Driving Growth***	***Source***
Pakistan	17	30	41.6	Hydropower	[24], [25], [26]
India	10-15	22.5	35-40 %	Solar, Wind, Small Hyro	[27], [25], [28]
China	10-5	20-25	30-35	Wind , Solar , Large Hydro	[27], [25], [28]
United Sates	7-8	10-12	20-25	Solar	[24], [27], [28]
European Union	15-20	25-30	35-40	Wind, Solar, Biomass	[24], [27], [28]
Bangladesh	1-2	3-5	10	Solar, Biomass	[25], [28]
Ghana	5-7	8-10	10-15	Biomass, Solar	[25], [28]
Thailand	5-7	10-15	15-20	Biomas, Solar	[25], [28]
Indonesia	4-5	10-12	20-25	Geothermal, Hydropower, Biomass	[25], [28]
Bhutan	90	100	100	Hydropower	[27], [25], [24]

Pakistan's renewable electricity is predominantly supported by hydropower, alongside increasing solar installations, while Bhutan's renewable energy share, nearing 100%, is driven almost exclusively by hydropower. These growth patterns and projections are based on recent trends and analyses from global renewable energy status reports and energy outlooks.

III. CORE ISSUES AND OPTIONS IN THE GLOBAL RENEWABLE ENERGY TRANSITION

A. Uneven Global Distribution and Regional Disparities

Despite this progress, the world remains off track to meet international climate goals. The current installation pace is insufficient to achieve the global target of tripling renewable energy capacity by 2030, an objective that would require total installed capacity of 11.2 TW [29]. To align with the 1.5°C pathway outlined in the Paris Agreement [30], annual renewable installations must more than double, reaching approximately 1,043 GW per year through 2030 [31].

The renewable energy transition exhibits marked unevenness across regions and energy systems. While Europe achieved a record 44% renewable share in electricity generation in 2023 [32], major developing economies maintain heavy fossil fuel dependence. China, despite leading global renewable capacity additions, still relies on coal and other fossil fuels for the majority of electricity generation. Countries like India and Bangladesh maintain fossil fuel dependencies exceeding 75% and 90% respectively, highlighting persistent inequities in the global energy transition.

B. US Policy Reversals Might Affect Global Trend

More recently, the United States energy transition entered a period of significant uncertainty as in early 2025, the United States underwent a major policy reversal marked by President Trump's "Unleashing American Energy" Executive Order, which rolled back key clean energy regulations and incentives. The new policy framework prioritizes fossil fuel expansion, specifically oil, gas, coal, hydro-power, and nuclear, while phasing out federal support for electric vehicles and renewable energy, including tax credits for wind and solar. Additional executive actions suspended clean energy projects on federal lands and offshore zones, and the U.S. formally withdrew from the Paris Agreement. These sweeping changes have created significant regulatory uncertainty and disrupted momentum in the country's renewable energy development pipeline [33].

C. Grid Integration and Infrastructure Constraints

China's renewable energy expansion illustrates the critical challenge of grid integration and infrastructure limitations. Despite installing a remarkable 277 GW of new solar capacity in 2024 (representing a 45.2% increase) and expanding wind power capacity by 80 GW, this capacity expansion has not translated proportionally into electricity generation due to systemic constraints [34]. Grid integration challenges limit full utilization of renewable capacity, highlighting the complexity of transitioning large-scale energy systems beyond simple capacity installation.

D. Structural Challenges in Developing Countries

South Asian and Southeast Asian countries demonstrate diverse but persistent structural challenges in renewable energy adoption. India, despite conducting record-breaking renewable energy auctions that awarded 59 GW of capacity in 2024, faces systemic obstacles including transmission bottlenecks and delayed power sale agreements that currently stall approximately 40 GW of projects [35].

For example, Bangladesh represents early-stage transition challenges, with only 1.56 GW of installed renewable energy capacity comprising about 4.5% of total power capacity [36]. Despite ambitious policy targets of 20% renewables by 2030 and 30% by 2040, the country maintains over 90% fossil fuel dependence in electricity generation, primarily from natural gas (57%) and coal (20%). Indonesia continues to lag with renewables comprising only 12.3% of the energy mix while coal maintains over 60% of electricity generation, despite abundant renewable potential [37].

IV. Deeper Dive into key energy policies

A. U.S. Renewable Energy Policy Setbacks

The Trump administration's 2025 policy overhaul reverses momentum from the Inflation Reduction Act (IRA) and Infrastructure Law, repealing major tax incentives for wind and solar, pausing federal leasing, and revoking Electric Vehicle (EV) mandates [38][39]. The result: investor uncertainty and paused or canceled project pipelines (bisected clean-energy capacity by 2035). The repeal of the Environmental Protection Agency's (EPA) Greenhouse Gas (GHG) "endangerment finding" adds regulatory uncertainty, potentially stalling long-term emissions reductions and prompting legal challenges from states and stakeholders [40].

Over $14 billion in planned clean-energy investments have been delayed or canceled, threatening jobs and undermining U.S. competitiveness in Artificial Intelligence (AI) and green innovation by discouraging essential infrastructure deployment. The policy narrative frames renewable as "unreliable" and emphasizes securing energy independence, but critics argue these shifts still undermine long-term energy security and grid modernization even as electricity demand grows with AI expansion.

Options include accelerating domestic clean manufacturing with targeted incentives to strengthen U.S. supply chains and reduce dependence on Chinese inputs [41]; leveraging state and local leadership; and clarifying and extending subsidy timelines to support grid resilience while expanding renewables.

B. China – Supply Chain Dominance and Strategic Expansion

China dominates global EV and clean energy supply chains, producing the majority of lithium-ion batteries and leading in rare earth refining and component manufacturing. This creates challenges for the US and others seeking to expand their EV industries or shift to renewables. Export restrictions in 2025 have disrupted supply, impacting automakers, energy firms, and defense sectors [42]. Dependence on China reduces strategic autonomy and raises geopolitical tensions. Options include diversifying supply chains, investing in green innovation, and forming strategic alliances, such as the US exploring collaboration with Pakistan.

C. Off-Grid and Decentralized Renewable Deployment Issues

Many countries need off-grid decentralization systems. In South Asia and Africa, off-grid solar, mini-grids, and waste-to-energy remain important but are limited by scalability and investment issues. Projects in Bangladesh, Nepal, and Ghana face regulatory, financing, and land challenges. To address these, options include strengthening institutional frameworks, scaling pilots with blended finance, leveraging public-private partnerships to reduce investment risk, and involving local stakeholders for lasting impact.

D. Grid Transmission Under-Investment

In 2024, India awarded 59 GW in renewable energy auctions, but 40 GW remains delayed due to transmission issues, pending Power Purchase Agreements (PPA), and land acquisition setbacks [43]. Globally, expanding auction capacity without simultaneous grid upgrades has resulted in high energy curtailment. Policy recommendations include: coordinating grid expansion with generation auctions, investing in infrastructure before adding new capacity, implementing smart grid and demand-response solutions, and streamlining regulations for land acquisition and PPA signings to minimize delays.

E. Hydropower Excellence and Circular Economy Innovation

Nepal exemplifies successful renewable energy development in challenging geographic conditions, with over 95% of electricity generation coming from hydropower, totaling more than 3,000 MW in installed capacity. The country has evolved from energy importer to regional supplier, exporting power to India and Bangladesh in 2024–2025 . Major projects include the 900 MW Arun-3 and 216 MW Upper Trishuli-1, part of Nepal's ambitious plan to increase hydropower capacity to 28,500 MW by 2035 [44].

Beyond hydropower, Nepal demonstrates innovative circular economy approaches to energy. The Dharan waste-to-energy plant converts 30 tonnes of municipal waste daily into 1,200 kg of bio-CNG for local transport, while over 300,000 household biogas units reflect a culture of energy recovery from organic waste. Off-grid solutions have reached over 3.6 million people through solar mini-grids and micro-hydro systems, with targets of 12 MW additional off-grid solar capacity by 2030 [45].

V. Innovative Stories in Energy Transition

A. Energy and Environment Partnership Mekong Programme (EEP Mekong Programme)

Across Cambodia, Laos, Thailand, Myanmar and Vietnam, the EEP Mekong programme has catalyzed 55 pilot and demonstration projects in renewable and waste-to-energy technologies, reaching more than 190,000 rural residents and reducing approximately 141,800 tCO_2-equivalent across Phase II (2014–2019) [46]. In Vietnam's Mekong Delta, biodigesters installed in hundreds of households have transformed livestock waste into cooking gas and organic fertilizer, developing micro-entrepreneurship while substantially cutting methane emissions. In Chiang Mai, Thailand, community-level production of solid "bisquets" from agricultural residues has enabled forest conservation and lower carbon and particulate emissions, all through locally-managed circular-economy fuel systems. Finally, in Lao PDR, an industrial biogas project treating starch-factory wastewater, backed by EEP Mekong and developed with Thai Biogas Energy Co., replaces coal with on-site methane, cutting up to 60,000 tons of CO_2 emissions per year and offering a scalable model for industry–community energy reuse [47].

B. Pumped-Storage Hydro (PSH)

The long-duration storage landscape is evolving fast, offering critical flexibility for grids based on highly variable renewables. Pumped-Storage Hydro (PSH) itself remains the foundation of grid-scale energy buffering, and China continues to lead globally, installing 7.75 GW in 2024 to reach 58.69 GW of total capacity, with over 200 GW under construction, accounting for roughly one-third of the world's PHS pipeline [48]. At the same time, innovation is reshaping how PSH can be deployed, RheEnergise's 500 kW "high-density" pilot near Plymouth uses a fluid 2.5× denser than water to slash infrastructure requirements and enable site locations off low hillsides, increasing global applicability [49]. Complementing this, next-generation batteries are diversifying beyond lithium-ion: Form Energy's iron-air battery broke ground in August 2024 on a 1.5 MW/150 MWh pilot in Minnesota capable of up to 100 hours of continuous storage [50]; Alsym Energy's metal-oxide battery uses a non-flammable, water-based electrolyte and abundant materials for safe, low-cost long-duration applications in hot climates; no lithium or cobalt needed. The field is also breaking out of the chemical shell: in December 2023, Energy Vault's 25 MW/100 MWh gravity storage system came online in Rudong (China), using stacked blocks to store potential energy tied directly to a wind farm and feeding it into the grid on demand [51]; meanwhile solid-state hydrogen storage, notably via metal-hydride systems like LAVO's hydrogen pilot testing in the UK, is emerging for seasonal renewable smoothing and clean fuel generation; and Compressed-Air Energy Storage (CAES), long used at cavern scale to store surplus wind or solar power for later release, remains a promising route for grid flexibility where geologic conditions allow. These innovations—mechanical, chemical, and hybrid—form an increasingly rich portfolio of storage options tailored to specific climates and deployment contexts, underpinning an energy transition that demands balancing across timescales from minutes to days.

C. Data Centers and Energy Demand

As the global demand for Artificial Intelligence (AI) accelerates, so too does the energy required to power it, posing a significant challenge to current energy systems. Global electricity demand from data centers worldwide is projected to more than double by 2030, with AI as the main driver [52]. A Forbes-cited example: Meta's CEO announced a $65 billion investment to scale AI operations including a 2,500-acre site in Louisiana, this single campus is expected to require approximately 2.23 GW of electricity, enough to power about 2 million homes. While an exact location-specific source was not located, this aligns with broad investment trends in AI infrastructure.

D. Excess Energy and Bitcoin Mining

Countries rich in low-cost renewables are increasingly converting excess power into economic value via cryptocurrency mining and AI data centres, turning curtailed energy into revenue streams. Bhutan, leveraging 100% hydropower, has quietly mined over 13,000 BTC (Bitcoin), equivalent to roughly 30–40% of its GDP, since 2019. Its sovereign wealth fund (Druk Holding and Investments) has used crypto profits to fund public salaries, reduce brain drain, and label its initiatives "green crypto" due to carbon-neutral mining [53][54]; Pakistan is now pursuing a similar path, officially allocating 2,000 megawatts of surplus electricity to Bitcoin mining and AI data centres under its Pakistan Crypto Council strategy.

Bitcoin mining is relevant to renewable energy and electricity management because it utilizes excess or stranded energy, turning idle electricity into economic value. In Pakistan, surplus capacity from fossil-fuel-based Independent Power Producers (IPPs)—exacerbated by oil price spikes, creates financial burdens. Allocating this excess energy to Bitcoin mining and AI data centres monetizes idle power, improves generation efficiency, attracts investment, and supports digital industries. Similarly, Bhutan and Paraguay have shown that regulated crypto-mining can fund public initiatives and enhance energy system efficiency, making it a strategic tool for energy policy and economic diversification.

VI. CONCLUSION AND FUTURE WORK

The global renewable transition is technically possible and accelerating, in 2024 alone, the world added 585 GW of renewable capacity (92.5 % of all new power), boosting total renewables to 4,448 GW. Yet this falls short of the 11.2 TW needed by 2030 to follow a 1.5 °C path; at a 15.1 % growth rate, installation must rise to 16.6 % annually to stay on track . Most additions flowed into Asia are led by China while regions like Africa remain marginal contributors, revealing a glaring equity gap . In the U.S., recent policy reversals, including the rapid phase-out of wind/solar tax credits, revocation of federal EV mandates, and suspension of clean energy land leases have shaken investor confidence, imperiling $ 8 billion+ of manufacturing and causing projected slowdowns of 17–20 % in solar and wind rollouts over the next decade . Meanwhile, China is doubling down on both production and grid resiliency: in 2024 it added 7.75 GW of pumped hydro storage, bringing total to 58.7 GW and establishing a 200 GW pipeline,underpinning flexibility at scale. Emerging technologies are delivering longer-duration storage: gravity blocks in China, high-density pumped hydro, and especially iron-air batteries,like the 1.5 MW/150 MWh Minnesota pilot that stores for 100 hours at significantly lower cost than lithium-ion batteries, are shifting the paradigm.

Innovative economic uses of excess renewables are also emerging. Bhutan, powered entirely by glacier-fed hydropower, has mined over 12,000 BTC valued at ~30 % of GDP, and directed proceeds to public salaries, healthcare, and environmental programmes, demonstrating small-country monetization of green surplus electricity . Similar circular economy pilots across Southeast Asia, upcycling biowaste into fuel and fertilizer, are delivering community health, income, and environmental dividends.

In short, while renewables are broadly scalable, realizing their full benefits hinges on stable policies, robust financing, next-gen storage and grid infrastructure, and deliberate innovation deployment. The technology is ready, but without

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coordinated strategy and equity-focused investment, the 1.5 °C ceiling remains unachievable, and the gains may fail to spread globally.

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Comparative Analysis of PM2.5 Air Quality Between Old and Newly Developed Residential Areas in Karbala City Using a Low-Cost Monitoring System

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***Abstract*—This study investigates air quality disparities in Karbala, Iraq, by comparing particulate matter smaller than 2.5 micrometers (PM2.5) concentrations between Hay Al-Abbas, an old densely populated neighborhood (site A), and Al-Muruj Residential Complex, a newly developed suburban area (site B). Both sites were geo-referenced using Global Positioning System (GPS) coordinates for accurate spatial comparison. Data were collected using a custom-built, low-cost monitoring system based on Arduino and PMS5003 sensors over three consecutive days in June 2025. Measurements were conducted at fixed times—midnight, morning, and afternoon—each with PM2.5 readings every five seconds for fifteen minutes, resulting in more than 1,600 data points per site. PM2.5, a key air quality indicator, was evaluated against the World Health Organization (WHO) daily limit of 25 µg/m³[14]. Results showed that site A had consistently higher PM2.5 levels than site B, often exceeding the guideline—especially during morning and midnight periods. These findings highlight the influence of urban density, waste burning, and city planning on particulate pollution in Karbala. Overall, the study confirms that older, densely built neighborhoods experience poorer air quality than newly planned areas, where improved urban design has helped reduce pollution.**

Keywords- PM2.5; Air Quality; Low-Cost Sensor; Urban Monitoring; Karbala .

I. INTRODUCTION

Air pollution remains one of the most serious environmental and health issues in Iraq's rapidly expanding cities. In Karbala, residents are exposed daily to several sources of pollution—including the widespread use of diesel generators in every neighborhood, random and uncontrolled waste burning, and heavy vehicle traffic on crowded city streets [1], [2]. These combined factors often result in concentrations of airborne particulate matter that exceed international safety standards, putting the health of local communities at risk. Among air pollutants, fine particulate matter less than 2.5 micrometers in diameter (PM2.5) is especially important as an indicator of air quality and as a risk factor for respiratory and cardiovascular diseases. Yet, despite its significance, there is a shortage of detailed, neighborhood-level PM2.5 data in Karbala. Most available information is limited to governmental stations, satellite observations, or generalized models that don't reflect the unique realities of different city districts. This study addresses this gap by directly comparing PM2.5 concentrations between two contrasting residential areas in Karbala. The first, site A (Hay Al-Abbas), is a central urban district where high population density has been further increased by unplanned, dense construction on once-agricultural land surrounding the old neighborhood. This irregular growth has brought more people, vehicles, and private generators into the area—making pollution sources more concentrated and varied. The second, site B (Al-Muruj Residential Complex), is a recently developed and fully planned neighborhood established as part of the city's latest urban expansion. In contrast to Hay Al-Abbas, Al-Muruj was designed with organized streets, designated green spaces, and modern infrastructure to accommodate future growth and offer quieter, healthier living conditions. Both areas experience the typical daily activities that contribute to air pollution in Karbala, but the scale and organization of each neighborhood differ sharply. By employing a custom-designed, low-cost monitoring system to collect high-frequency air quality measurements at multiple times of day in both locations, this research aims to reveal how differences in urban planning, population density, and local behavior shape air quality at the neighborhood level. The findings of this work are expected to inform future urban planning and practical policies to reduce air pollution as Karbala continues to grow.

The remainder of this paper is organized as follows: Section II reviews related work, Section III presents the methodology, Section IV reports the results, Section V discusses the findings, and Section VI concludes the paper and suggests future research directions.

II. RELATED WORK

Although air pollution is increasingly recognized as a critical urban and public health challenge in Iraq, detailed ground-level studies of air quality in Karbala remain rare. Most of the existing research in Iraq has focused on measurements from official government monitoring stations, major roads, or satellite-based models, which do not capture the variation between residential neighborhoods or reflect local sources of pollution such as diesel generators, random waste burning, and dense traffic. The use of low-cost laser-based optical particle sensors—such as the PMS5003—for neighborhood-scale air quality monitoring is still limited, particularly in Karbala.

Several recent studies have demonstrated the feasibility and value of using low-cost sensors for urban air quality assessment in other Iraqi cities. Abdullatif et al. [3] measured PM2.5 and PM10 along a main road in Karbala, showing substantial pollution fluctuations linked to traffic and weather. Other researchers have examined air quality in specific parks or compared urban landscapes, identifying PM2.5 as the dominant pollutant, especially during the summer and in densely built-up areas [4], [5]. Outside Karbala, distributed networks of low-cost sensors have been deployed in Mosul [6] and Sulaymaniyah [7], confirming the spatial and temporal complexity of particulate pollution and the benefit of high-frequency, local measurements.

However, there remains a clear lack of systematic, GPS-referenced, high-frequency air quality monitoring studies comparing both old and newly developed residential districts within a single Iraqi city. The present study aims to address this gap by providing one of the first direct, ground-level comparisons of PM2.5 concentrations between a historic city-center neighborhood (Abbas) and a modern residential district (Muruj) in Karbala, using a custom-built monitoring system and dense spatial sampling. By building on and extending the findings of previous work, this study offers practical data and insights to inform future urban planning and public health efforts in Iraq.

III. METHODOLOGY

A. Measurement System

A custom-built air quality monitoring system was developed to enable real-time field measurements in diverse urban environments. The core platform was based on an Arduino Mega microcontroller, selected for its multiple serial interfaces and high I/O capacity [6]. A PMS5003 laser-based optical particle sensor was integrated to measure both PM2.5 and PM1 concentrations, following best practices recommended in previous environmental sensor deployments [7],[8]. Temperature and relative humidity were monitored using a DHT22 sensor, while geographic location data were continuously logged via a u-blox NEO-6M GPS module with a ceramic antenna [9]. Sensor readings were visualized in real time using a compact OLED display [10], and all data were saved locally to a microSD card for subsequent analysis, as described in related open-source monitoring frameworks [11].

All components were securely assembled on a portable plastic board to facilitate field deployment (Figure 1). Power and wiring connections are shown schematically in (Figure 2). Power was supplied either by a USB power bank or a laptop [12], and the system could be monitored in real time via the Arduino IDE serial monitor as well as the OLED screen.

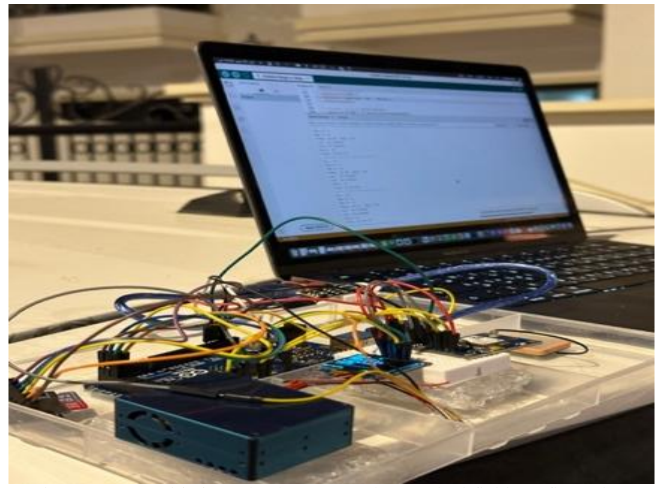

Figure 1. Assembled monitoring system in a typical field configuration.

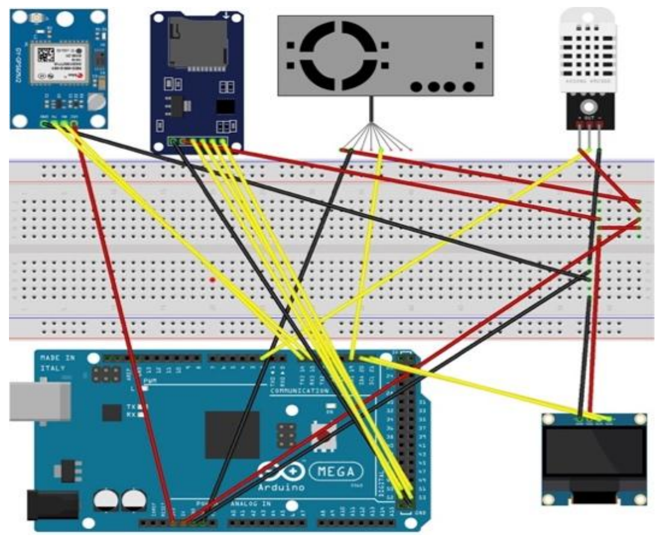

Figure 2. Schematic wiring diagram of all hardware connections.

B. Data Collection Protocol

Field measurements were carried out in two residential areas in Karbala: site A (Hay Al-Abbas; 32.6361°N, 44.0503°E), representing an old, central urban environment, and site B (Al-Muruj Residential Complex; 32.5341°N, 44.0209°E), representing a newly developed, fully planned extension of the city. Data were collected at three specific times each day—midnight (00:00), morning (09:00), and afternoon (17:00)—to capture diurnal air quality variation. Each site was sampled during nine independent sessions for each period, yielding a total of eighteen sessions per area.

During each session, the device was placed at a height of approximately 170 cm in an open area free from immediate pollution sources or airflow obstructions. The system remained stationary throughout the 15-minute measurement period, logging readings every five seconds (about 180 data points per session). Each measurement record included a timestamp, PM2.5, PM1, temperature, relative humidity, and GPS coordinates.

Prior to each session, a five-minute warm-up period was implemented to allow for sensor stabilization and GPS lock. Data collected during this period were excluded from the final analysis to ensure the accuracy of the results.

C. Data Storage and Processing

All measurement data were saved in CSV format on the SD card, with sequentially numbered entries and clearly labeled columns for time, geographic location, and all sensor values. After each session, files were transferred to secure storage and backed up for processing.

Data cleaning involved discarding all readings from the initial five-minute warm-up, as well as screening for missing or obviously erroneous values. No additional filtering was applied, since all retained data fell within expected operational ranges established during system validation. Cleaned datasets were then used for statistical analysis and visualization. The Arduino code used for sensor communication, data logging, and file management was custom-developed for this project and is publicly available for reference [13].

D. Site Access and Permissions

Access to site A (Hay Al-Abbas) was unrestricted, as it is a public and centrally located neighborhood. Entry to site B (Al-Muruj Residential Complex), however, required prior authorization since access is limited to residents, their guests, or authorized personnel. All necessary permissions were secured to enable unobstructed and ethical fieldwork. Environmental observations (such as local waste burning or unusual traffic) were also documented during each session.

IV. RESULTS

TABLE I. SUMMARY STATISTICS OF PM2.5, PM1, TEMPERATURE, AND RELATIVE HUMIDITY BY SITE AND PERIOD

Site	Period	Sample Count	PM2.5 (Mean ± SD)	Mean PM1 (µg/m³)	Mean Temp (°C)	Mean RH (%)
site A Abbas	Midnight	540	40.52 ± 15.56	37.06	34.72	26.12
site A Abbas	Morning	554	48.29 ± 30.97	41.14	45.86	25.52
site A Abbas	Afternoon	581	25.48 ± 15.01	23.83	43.77	15.89
site B Muruj	Midnight	550	20.43 ± 10.29	19.00	34.90	24.42
site B Muruj	Morning	541	34.55 ± 19.78	29.12	42.42	25.04
site B Muruj	Afternoon	567	10.66 ± 7.73	9.68	43.39	14.29

The mean PM2.5 concentration for each period and site was calculated as follows:

$$C_{mean} = \frac{1}{N}\sum_{i=1}^{N} C_i \quad (1)$$

where C_{mean} is the average PM2.5 concentration, N is the number of samples, and Ci is the i-th measurement, As shown in (1).

According to the World Health Organization (WHO), the recommended daily mean limit for PM2.5 is 25 µg/m³. Several of the observed mean values exceeded this guideline, particularly in Abbas during the morning (48.29 µg/m³) and midnight (40.52 µg/m³) periods, as well as in Muruj during the morning (34.55 µg/m³). These exceedances pose clear public health concerns.To further highlight the differencdes between the two sites, Table II provides a direct comparison of mean PM2.5 values, absolute and relative differences for each period.

TABLE II. OMPARISON OF MEAN PM2.5 CONCENTRATIONS BETWEEN SITE A (HAY AL-ABBAS) AND SITE B (AL-MURUJ RESIDENTIAL COMPLEX)

Period	Mean PM2.5 site A Abbas	Mean PM2.5 site B Muruj	Absolute Difference	Relative Difference (%)
Midnight	40.52	20.43	20.09	98.3%
Morning	48.29	34.55	13.74	39.8%
Afternoon	25.48	10.66	14.82	139.0%

As shown in Table II, PM2.5 concentrations were consistently higher in Abbas than in Muruj across all periods, with the largest relative difference observed in the afternoon.

The variation in PM2.5 concentrations is visualized in Figure 3.

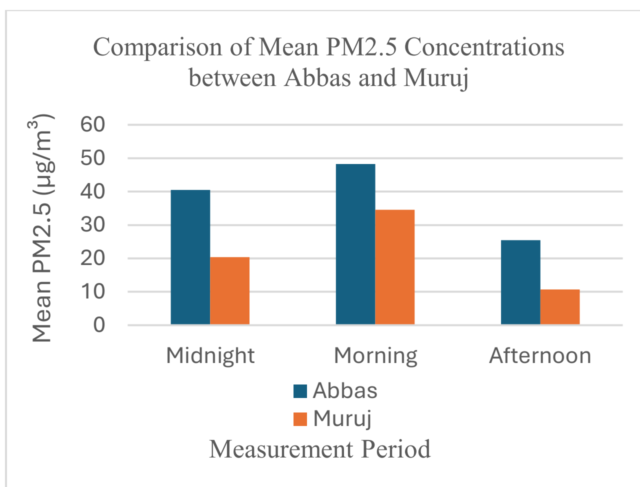

Figure 3. Comparison of Mean PM2.5 Concentrations between Abbas and Muruj across Measurement Periods.

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V. DISCUSSION

The results reveal clear spatial and temporal patterns in air quality across the two study sites. PM2.5 concentrations in site A (Hay Al-Abbas) were consistently higher than those measured in site B (Al-Muruj Residential Complex), and exceeded the WHO recommended daily mean in several periods. An independent samples t-test confirmed that the differences in mean PM2.5 concentrations between Site A (Abbas) and Site B (Muruj) were statistically significant across all time periods ($p < 0.001$).The standard deviation was also notably higher in site A, which can be attributed to transient spikes in pollution—often resulting from passing vehicles or short-term activities such as illegal waste burning in adjacent neighborhoods.

Field observations further supported these findings. During the measurement campaign, unauthorized waste burning was documented visually in site A, as captured in an aerial drone photograph (Figure 4). The image clearly shows multiple smoke plumes (highlighted with arrows) rising from various locations across the city, confirming that such activities are still present and can directly impact particulate concentrations in nearby residential areas.

Periods of adverse weather, such as the fifth morning session, were associated with citywide increases in particulate matter and higher variability in the readings. Afternoon measurements typically showed lower PM2.5 levels, possibly due to reduced human activity and cleaner atmospheric conditions. Morning sessions, by contrast, were likely impacted by waste burning, generator operation, and increased local activity. Although illegal waste burning rarely occurred within the measurement points themselves, the widespread use of diesel generators was a constant source of pollution in all residential areas.

The consistently lower and more stable PM2.5 levels recorded in site B (Al-Muruj Residential Complex) reflect the benefits of improved urban planning, limited traffic, and restricted access for non-residents. The selected measurement sites were representative residential side streets; it is expected that even quieter locations would have shown slightly lower readings.

The reliability of the PMS5003 sensor was confirmed by the strong agreement between the observed values and expectations based on personal experience and previous studies. Sampling was carried out during typical activity times and over several days, providing a representative assessment of daily air quality.

No significant differences in particulate concentrations were observed between holiday and regular working days, likely due to the residential nature of both sites. Occasional similarities in temperature between sites during afternoon periods were more likely the result of a general decline in urban activity than any direct meteorological effect.

Figure 4. Aerial photo of site A (Hay Al-Abbas), Karbala — smoke plumes (arrows) from unauthorized waste burning observed during fieldwork in July 2025.

VI. CONCLUSION AND FUTURE WORK

This study demonstrated that air quality, as measured by PM2.5 concentrations, was consistently poorer in site A (Hay Al-Abbas) compared to site B (Al-Muruj Residential Complex). The findings confirm that high population density, unplanned urban expansion, and the conversion of former agricultural land into dense residential neighborhoods have had a substantial negative impact on air quality in Hay Al-Abbas. In contrast, Al-Muruj benefited from more rigorous planning and stricter access policies, resulting in noticeably cleaner and more stable air quality.

Although the monitoring campaign lasted only three days, the repeated sessions were sufficient to capture clear differences. Longer-term deployments would provide more comprehensive seasonal insights.

The custom-built monitoring system developed for this project proved to be an effective and affordable solution for local air quality assessment. With modest enhancements—such as longer-term deployments, real-time wireless data transmission, or integration with additional environmental sensors—the device could provide even greater value for researchers and local authorities alike.

These results highlight the urgent need for municipal and local government action: reconsidering policies that allow the unregulated conversion of agricultural land for residential use, enforcing regulations against illegal waste burning, and encouraging the community to adopt cleaner energy sources. Public awareness campaigns about the health risks of air pollution are also essential.

While the measurement campaign was comprehensive and the system performed reliably, further research could expand on this work by deploying the device in additional neighborhoods, integrating more types of sensors, or collecting vertical air quality profiles using aerial platforms such as drones. Such efforts would offer deeper insight into pollution dynamics and support more effective urban planning and mitigation strategies for Karbala and similar cities.

Overall, this research demonstrates both the feasibility and importance of low-cost, community-driven environmental monitoring. The approach described here can easily be adapted for other urban contexts, providing critical data for improving air quality and public health outcomes.

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