MOBILE E-BIKE SHARING SYSTEMS WITH INTEGRATED PHOTOVOLTAICS: ELECTRIC MOBILITY SOLUTIONS FOR LARGE EVENTS IN ÉVORA, PORTUGAL

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ABSTRACT: Mobile e-bike sharing stations integrated with photovoltaics are proposed for Évora to serve baseline urban demand and event-related surges while respecting heritage constraints. The system is powered primarily by photovoltaics, with optional grid-assist for resilience. We present a siting–sizing framework that (i) selects candidate locations via AHP and a p-median model based on origin–destination flows and travel times, and (ii) sizes PV and storage under two energy hypotheses: full-recharge of all e-bikes versus a usage-driven demand model (Wh/km × trip length × trips/bike). Using worst-month irradiance and aggregate conversion losses, a worked example shows that the full-recharge assumption yields higher capacities (≈6 kWp PV + 25 kWh storage per 10 bikes for event peaks), whereas the usage-driven model reduces sizing substantially while meeting service levels; both are reported to ensure robustness. This compact framework is directly applicable to heritage cities planning PV-micromobility for large events.
Keywords: Electric Mobility, Photovoltaic Energy, Smart City, Urban Planning

1 INTRODUCTION

This study proposes a practical and scalable solution for sustainable urban mobility in Évora, Portugal, through the implementation of mobile e-bike docking stations powered primarily by photovoltaic energy. These stations will be strategically distributed across the city and equipped with battery storage to enable 24-hour operation for both e-bike sharing and charging. The system will be supported by a digital monitoring application offering real-time data, user interface, and integrated security features.

The concept of mobile stations is particularly relevant given Évora's designation as the European Capital of Culture for 2027, which will attract large audiences to a historic urban environment recognized by UNESCO since 1986 [1]. The initiative aligns with Évora's smart city agenda and its participation in the EU-funded POCITYF project [2], which promotes climate-neutral innovation in heritage cities.

Portugal's National Strategy for Active Mobility sets ambitious targets for bicycle modal share in urban areas, 4% by 2025 and 10% by 2030 [3]. Évora already leads in electric public transport [4] and academic cycling initiatives [5], yet its transport sector remains the largest contributor to local GHG emissions (37.97%) [6]. This project aims to reduce emissions and foster long-term behavioral change by integrating clean energy and intelligent mobility infrastructure into the city's cultural and urban landscape.

The central region of the city of Évora (Figure 1) has a specific PV output of approximately 1652.0 kWh/kWp, as indicated by the data for annual and monthly average values of PV electricity (AC) supplied by a PV system and normalized to 1 kWp of installed capacity, from the Global Solar Atlas. This high output highlights the region's significant potential to harness solar energy, which can be effectively utilized to support sustainable mobility solutions. By leveraging this significant solar resource, Évora can improve its green infrastructure and contribute to reducing CO_2 emissions in the domestic transportation sector [7].

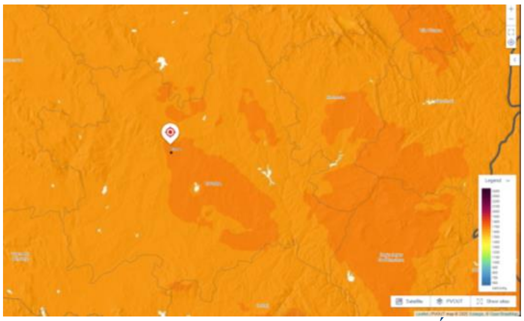

Figure 1: Specific photovoltaic power of Évora
Source: [7] (accessed: February 2025)

One of the objectives of this project is to gather recommendations for the implementation of a monitoring application that allows users to easily know the availability of e-bikes for rent, as well as available spaces for docking and charging, through an interactive map. This application should provide real-time monitoring of e-bikes, including location, battery status and availability.

The sharing stations will be strategically located to facilitate the daily routine of residents and users, integration with other existing means of public transport and the journey between different tourist attractions, events and nearby establishments.

2 RELATED WORKS

2.1 Integrated photovoltaic charging stations for electric micromobility

There are many examples of integrated photovoltaic charging stations for electric micromobility that inspire this work:

- An urban sharing platform in London, UK (2017), is a successful example of how data from a wide range of mobility measures, including e-bikes, e-cargo bikes, electric vehicle charging, smart parking and solar energy systems, can be combined and shared separately to inform policy decisions, generate financial savings and reduce CO_2 emissions [8].
- The SUNPOD CYCLO charging station, from the French company MOBENDI, is an example of a

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modular and scalable option, with solar energy production and integrated storage batteries, i.e. 100% self-sufficient in electricity [9].
- Swiftmile, a Californian company, is a complete charging and parking solution for e-bikes, e-scooters and e-mopeds, featuring advanced fleet management technology and available with integrated solar panels [10].

In Portugal, there are successful examples of electric bike sharing, such as Gira - Lisbon's Bicycle Sharing System, but only a few stations with modular infrastructure have the potential for solar power [11]. In contrast, there are companies in Portugal that develop and distribute mobile stations for electric bike sharing, with integrated charging, digital management, and solar solutions [12], and some even combine solar and wind power to ensure full autonomy in an off the grid setup [13].

Unlike fixed stations, mobile units can be deployed in smaller towns, rural areas, or university campuses with lower initial investment. These stations offer a high degree of spatial flexibility, allowing municipalities to adapt infrastructure to seasonal demand, temporary events, or urban renovations. In heritage cities like Évora, where permanent installations may face regulatory or aesthetic constraints, mobile units provide a non-invasive alternative that can be relocated or reconfigured as needed, as demonstrated by Beam Global's BeamBike system, which operates fully off-grid (Figure 2) and is designed for rapid deployment and relocation [14].

Figure 2: BeamBike system
Source: [14] (accessed: September 2025)

Given that the technology for mobile e-bike sharing stations powered by solar energy is already available and proven, this study focuses on the strategic planning of station placement. The effectiveness of the system depends largely on the selection of locations that ensure accessibility, user engagement, and integration with existing urban infrastructure.

3 METHODS

3.1 Demand modelling

To support the strategic deployment of solar-powered e-bike sharing stations in Évora, a demand modeling framework was developed to simulate usage patterns under different urban conditions. This model aims to inform station sizing, energy requirements, and operational flexibility, particularly in a city characterized by seasonal tourism, cultural events, and heritage constraints.

- Baseline Scenario: Typical Urban Day

The baseline scenario represents a standard weekday in Évora, capturing regular commuting flows, student mobility, and local errands. Key parameters include:
- Temporal distribution of trips by hour (morning/evening peaks), distinguishing between weekdays and weekends.
- Trip length percentiles (p50/p90), used to estimate average and upper-bound energy consumption per trip.
- OD (Origin–Destination) profiles across nine strategic points, including residential zones (e.g., Horta das Laranjeiras), commercial hubs (Évora Plaza), university areas, and heritage sites.

- Event Scenario: High-Demand Conditions

To account for fluctuations during cultural, academic, or seasonal events, a second scenario was modeled using a multiplicative factor applied to trip volumes and temporal peaks. This scenario reflects:
- Increased demand during festivals, conferences, and tourism surges.
- Shifted usage patterns, with extended evening activity and higher turnover rates at central stations.
- Stress testing of station capacity and solar generation adequacy under peak conditions.

- Application of the Model

The demand model supports:
- Station sizing: Estimating the number of bikes and charging docks required per location.
- Energy planning: Aligning solar generation profiles with usage peaks to optimize battery autonomy and reduce grid dependency.
- Operational logistics: Informing redistribution strategies, maintenance scheduling, and dynamic station placement (for mobile units).

- Origin–Destination Matrix

A simplified OD matrix was constructed to analyze trip flows between the nine proposed station sites. This matrix enables:
- Identification of high-demand corridors.
- Prioritization of intermodal integration zones.
- Validation of station placement based on real and projected mobility patterns.

3.2 Solar resource & system model[1]

To ensure autonomous operation of solar-powered e-bike sharing stations in Évora, a dimensioning model was developed based on local solar resource data, estimated daily energy demand per station, and system efficiency parameters. The goal is to guarantee energy availability even under worst-case conditions, such as low solar yield in winter and peak demand during urban events.

- Monthly Solar Yield ($Y[\frac{kWh}{kWp}.day]$)

According to PVGIS simulations for Évora [15], the average daily solar yield per installed kilowatt-peak (kWp) varies seasonally:
- Average 8.26 kWh/day in Summer.
- Average 4.51 kWh/day in Autumn.
- Average 2.62 kWh/day in Winter.
- Average 6.29 kWh/day in Spring.

These values reflect long-term averages and includes typical meteorological conditions, making it suitable for preliminary sizing.

[1] The system design follows applicable standards: EN 15194 (EPAC e-bikes), IEC 61215/61730 (PV modules), IEC 62109 (PV power converters), and IEC 62619/62133-2 (Li-ion stationary/portable batteries). Charging cabinets include thermal protection and ventilation; the EMS enforces SOC limits (20–90%) and rate control. Data handling complies with GDPR; the app/backend adopt privacy-by-design and standard cybersecurity controls.

- Estimated Daily Load per Station ($E_{load}[day]$)

Based on demand modeling (Section 3.1), each station is expected to support:

- Baseline load: ~2.5 kWh/day (charging 10 bikes with 250 Wh each)
- Event peak load: up to 7.5–12.5 kWh/day (factor 3–5× increase)

- System Efficiency and Losses

To account for real-world losses, a global system efficiency factor of 80–85% is applied, considering:

- MPPT (Maximum Power Point Tracking) and inverter losses
- Battery charge/discharge inefficiencies
- Cable and environmental losses

Thus, the effective solar yield becomes:

$$Y_{eff} = Y \times \eta_{sys}$$

- Robustness Criterion

To ensure robustness, the system must satisfy:

- Worst scenario: Winter ($Y \approx 2.62 \frac{kWh}{kWp}.day$)
- Peak event load: up to 12.5 kWh/day

Required installed capacity per station:

$$Required\ kWp = \frac{E_{load}}{Y_{eff}} = \frac{12.5}{2.62 \times 0.80} \approx 6.0\ kWp$$

Battery sizing (2 days autonomy):

$$Battery\ capacity = 2 \times 12.5 = 25\ kWh$$

- Design Implications

- Stations should be equipped with $\geq 6\ kWp$ solar panels and $\geq 25\ kWh$ battery storage to ensure full autonomy year-round.
- Modular configurations allow scaling based on location-specific demand.
- Hybrid systems (solar + wind) may be considered for enhanced resilience in low-radiation periods.

3.3 Energy sizing with two hypotheses (robustness check)

Let Y_m be the monthly specific PV yield (kWh/kWp·day) for Évora (worst case scenario value), and let η_{sys} be the aggregate system efficiency (MPPT/inverter/charge/distribution). The results are reported to $\eta_{\text{sys}} \in [0.80, 0.85]$.

H1: Full-recharge (upper bound).
Daily load assumes full recharge of N_b bikes with battery capacity C_b(kWh):

$$E_{\text{load}}^{\text{H1}} = N_b\, C_b \times f_{\text{util}},$$

with $f_{\text{util}} \leq 1$(fraction of capacity replenished daily; baseline $f_{\text{util}} = 1$for a conservative upper bound). Required PV and storage for autonomy of Ddays:

$$P_{\text{PV}}^{\text{H1}} = \frac{E_{\text{load}}^{\text{H1}}}{Y_m\, \eta_{\text{sys}}}, E_{\text{BESS}}^{\text{H1}} = \frac{D\, E_{\text{load}}^{\text{H1}}}{\text{DoD}}.$$

H2: Usage-driven (demand model).
Daily load derives from travel demand:

$$E_{\text{load}}^{\text{H2}} = N_b \times c_{\text{Wh/km}} \times L_{\text{trip}} \times T_{\text{per bike}} \times (1 + \ell),$$

where $c_{\text{Wh/km}}$is the specific e-bike consumption, $L_{\text{trip}}$the average trip length, $T_{\text{per bike}}$trips/bike/day, and ℓaccounts for charging/distribution losses. Sizing:

$$P_{\text{PV}}^{\text{H2}} = \frac{E_{\text{load}}^{\text{H2}}}{Y_m\, \eta_{\text{sys}}}, E_{\text{BESS}}^{\text{H2}} = \frac{D\, E_{\text{load}}^{\text{H2}}}{\text{DoD}}.$$

Worked example (10 bikes, worst case scenario sizing).

- Baseline (typical day): $c_{\text{Wh/km}} = 10$, $L_{\text{trip}} = 3$ km, $T_{\text{per bike}} = 2$, $\ell \approx 0.15$, $Y_m = 2.62$kWh/kWp·day, $\eta_{\text{sys}} = 0.80$, DoD = 80%, $D = 2$days.
- $E_{\text{load}}^{\text{H2}} \approx 0.71$kWh/day $\Rightarrow$ $P_{\text{PV}}^{\text{H2}} \approx 0.34$kWp; $E_{\text{BESS}}^{\text{H2}} \approx 1.8$kWh useful (~2.2 kWh nominal).
- Event peak (×5 trips): $E_{\text{load}}^{\text{H2}} \approx 3.5$kWh/day $\Rightarrow$ $P_{\text{PV}}^{\text{H2}} \approx 1.7$kWp; $E_{\text{BESS}}^{\text{H2}} \approx 7.1$kWh useful (~8.9 kWh nominal).

For comparison, **H1** with full-recharge of 10×0.25 kWh/day under the same Y_m, η_{sys} yields ≈ **6 kWp PV** and **25 kWh** storage for 2-day autonomy in event conditions. Reporting **both** H1/H2 makes the design robust yet realistic and aligns with the "primarily PV" positioning.

The Table 1 below summarizes the results under worst-case PV yield conditions for Évora (Y_m = 2.62 kWh/kWp·day), system efficiency η_{sys} = 0.80, and depth of discharge DoD = 80%.

Table 1: Energy sizing results under H1 and H2 hypotheses

Scenario	Daily Load (kWh)	PV Require d (kWp)	Storage Require d (kWh useful)	Storage Nominal (~kWh)
H1: Full Recharge	2.50	1.19	6.25	7.81
H2: Baseline Demand	0.69	0.33	1.72	2.15
H2: Event Peak	3.45	1.65	8.62	10.78

3.4 Location optimisation

To ensure strategic placement of solar-powered mobile e-bike stations in Évora, a location optimisation framework was developed combining multi-criteria decision analysis (MCDA) and spatial allocation models. The goal is to balance operational efficiency, user accessibility, and urban constraints, particularly in heritage zones.

- Multi-Criteria Decision Analysis (MCDA)

An Analytic Hierarchy Process (AHP) was applied to evaluate candidate locations based on the following criteria (Table 2):

Table 2: Multicriteria Decision Analysis

Criterion	Description
Demand density	Estimated trip volume from demand modeling (Section 3.1)
Intermodality	Proximity to bus stops, parking lots, and pedestrian zones
Solar exposure	Average insolation and shading conditions (from PVGIS/GSA)
Heritage constraints	Restrictions on permanent infrastructure in protected urban areas
Safety and vandalism risk	Historical data on theft, vandalism, and nighttime visibility
Visual impact	Integration with urban aesthetics and minimization of visual clutter

Criteria were weighted via AHP (Demand 0.30, Intermodality 0.25, Solar exposure 0.10, Heritage constraints 0.10, Safety/Vandalism 0.10, Visual impact 0.15). The pairwise matrix yielded a Consistency Ratio (CR)=0.05, below the 0.10 threshold, indicating acceptable internal consistency.

Location–allocation used a p-median model with K=8 facilities to minimize demand-weighted travel time from OD pairs; we solved it with OR-Tools CP-SAT to optimality (gap 0%). A sensitivity sweep $K \in [6,10]$ is provided in the supplement.

Each criterion was weighted based on stakeholder input and urban planning priorities. The resulting composite score guided the ranking of the nine proposed locations.

- Spatial Allocation Model

To refine the station network, a p-median model was applied to minimize the weighted average distance between origin–destination flows and station locations. The model uses:

- OD matrix from Section 3.1
- Flow weights based on simulated trip volumes
- Constraints on station mobility and solar exposure

This approach ensures that stations are placed where they serve the highest demand with minimal detour, while respecting urbanistic and patrimonial limitations.

- Seed Network and Refinement

The initial set of nine strategic points, including Évora Plaza, University of Évora, Centro Histórico, and peripheral residential zones, served as a seed network. These locations were refined using the MCDA-AHP scores and flow-weighted spatial allocation, resulting in a robust and context-sensitive station layout.

The Estimated Shading classification was inferred based on the criteria of visual impact and patrimonial sensitivity, according to the weights defined in the AHP model. The logic applied was:

- Low shadow: points with low visual impact (≤ 0.55) and lower heritage sensitivity (≤ 0.85), indicating a lower risk of aesthetic or cultural interference.
- High shade: points with high visual impact (≥ 0.90) or high heritage sensitivity (≥ 0.90), requiring greater care in urban integration.
- Medium shade: intermediate cases, where the criteria indicate neither high risk nor absence of restrictions.

4 CASE STUDY: ÉVORA

4.1 Cycle path network and opportunities for sustainable electric mobility in Évora

The existing and planned cycle paths in the city of Évora, in addition to meeting adequate urban conditions, motivate the purpose of this study. Évora has 4 cycle paths in operation, implemented on the outskirts of the historic center, plus the Ecopista route that starts in the urban center and crosses the entire city towards the city of Arraiolos (± 25 km). Furthermore, the project includes connecting these cycle paths to the wall of the Historic Center and extending them to the Évora Industrial and Technological Park (PITE). It also includes the development of a Cycle Path along Avenida Dr. Francisco Barahona, between the Rossio roundabout and the train station [16].

The Historic Center has limited paid parking, with designated areas for residents, visitors, and people with reduced mobility. Parking lots in Évora could be strategic assets for this electric mobility project with e-bike sharing, especially if integrated with solar infrastructure, docking stations, and urban intermodality.

Parking lots outside the city walls, such as Porta da Lagoa and Avenida Túlio Espanca, offer better accessibility and physical space. Two parks, Av. Túlio Espanca and Rua Eng. Arantes e Oliveira, are being equipped with photovoltaic systems for energy production as part of the European POCITYF project [17].

For the academic community and tourists, having bicycles at shared docking stations available with the ease of returning them after use at different points in the city often solves the problem of physical space in homes and accommodations. In addition, it is important to offer an e-bike in usable condition, with charging and green, safe and smart parking. This makes the option accessible to those who have difficulty driving on the terrain of the city, which is predominantly flat (Figure 3), but with gentle hills and elevations that require greater physical effort [18].

Figure 3: Topographic map of Évora
Source: [18] (accessed: January 2025)

4.2 Initial Investment Strategies for Solar-Powered E-Bike Sharing Stations in Évora

The initial investment required for installing solar-powered charging stations often represents a major barrier to large-scale implementation, particularly in cities with constrained public budgets and heritage-sensitive urban environments such as Évora.

To support the implementation of solar-powered e-bike sharing stations in Évora, the following table summarizes key financing alternatives, highlighting their mechanisms, benefits, and contextual relevance to the city's urban and heritage constraints (Table 3).

Table 3: Initial Investment Strategies for Solar-Powered E-Bike Sharing Stations in Évora

Financing Model	Description	Relevance to Évora
Public–Private Partnerships	Collaboration between local government and private sector for installation and maintenance, often via concession agreements.	Enables flexible deployment in heritage-sensitive areas; reduces municipal burden while ensuring service quality.
Green Financing Instruments	Includes tax incentives, low-interest loans, and dedicated credit lines for clean energy and mobility projects.	Aligns with Évora's sustainability goals and can support solar infrastructure in public parking areas (e.g., Água de Prata).
Public Sector Grants	Funding from municipal, regional, or EU programs (e.g., Horizon Europe, POCITYF) targeting renewable energy and smart mobility.	Can be leveraged for pilot stations near cultural hubs and university zones, especially during EU2027 events.

Financing Model	Description	Relevance to Évora
Crowdfunding & Donations	Community-based funding involving citizens, local businesses, and institutions to support station deployment.	Encourages civic engagement and ownership, particularly in residential areas like António Gedeão and Horta das Laranjeiras.
Corporate Sponsorship	Branding and co-investment by companies in exchange for visibility and social responsibility recognition.	Ideal for commercial zones like Évora Plaza; promotes private sector involvement in sustainable urban mobility.
Energy Cooperatives	Local energy communities invest in solar infrastructure and share benefits from energy generation and mobility services.	Could be explored in partnership with University of Évora and local stakeholders for long-term energy autonomy.

4.3 Maintenance and Operational Efficiency: Ensuring Long-Term System Performance in Évora

One of the key concerns in deploying solar-powered infrastructure for electric mobility, particularly in high-traffic urban areas such as charging stations, is ensuring sustained operational efficiency over time. In Évora, where heritage constraints and seasonal fluctuations in demand must be considered, maintenance strategies must be both technically robust and context sensitive:

a. **Preventive Maintenance and Remote:** Monitoring Modern technologies allow real-time monitoring of station performance, enabling early detection of faults and minimizing service disruptions. In Évora's historic center, where physical interventions must be minimal, remote diagnostics and predictive maintenance protocols are essential to preserve both infrastructure and urban aesthetics.

b. **Local Technical Training and Workforce Development:** To ensure sustained system availability, it is crucial to train local maintenance teams in solar and mobility technologies. This not only reduces downtime but also fosters local employment and strengthens Évora's technical capacity in renewable energy and sustainable transport, aligning with the city's long-term strategic goals.

c. **Long-Life Batteries and Modular Systems:** Using durable batteries and modular components (such as inverters and docking units) allows for phased upgrades and simplified replacements. In Évora, where flexibility is key due to frequent cultural events and spatial constraints, modularity supports rapid reconfiguration and ensures that the system evolves alongside technological advancements.

5 RESULTS

The study proposes prioritizing mobile stations within the Historic Center of Évora to ensure flexibility in the management of electric bike-sharing infrastructure, allowing for the relocation of facilities in response to temporary changes in the urban space resulting from major events. This approach respects the city's heritage and ensures the continuity of sustainable mobility services, even in contexts of high land use.

To ensure that the implementation of solar-powered e-bike sharing stations, with integrated batteries for uninterrupted docking, charging, rental, and monitoring, is compatible with the city's spatial and operational realities, the following locational criteria were considered essential:

- Historic Center prioritization: enabling relocation when major events require local adjustments.
- User-oriented planning: proximity to parking lots, schools, shops, markets, restaurants, and tourist attractions, supporting key traffic routes and ensuring pleasant, accessible journeys.
- Public transport integration: proximity to bus and train stations, stops, and taxi hubs, especially for events attracting large groups from nearby cities.
- Solar exposure optimization: preference for less shaded areas to maximize photovoltaic efficiency.

The AHP matrix was applied to the nine proposed station sites, generating a composite score for each location. These scores were then used to refine the initial seed network, prioritizing points with high demand density, strong intermodal connections, and favorable solar exposure, while respecting heritage constraints and minimizing visual impact.

In parallel, a p-median location-allocation model was implemented using the OD matrix from Section 3.1. This model minimizes the flow-weighted average distance between trip origins/destinations and station locations, ensuring operational efficiency and user accessibility.

The combination of MCDA and spatial optimization resulted in a robust, context-aware station layout, adaptable to seasonal variation and event-based demand. The mobile nature of the infrastructure allows for periodic reallocation based on updated demand profiles and urban dynamics.

From the nine candidate sites evaluated, eight were selected based on technical, urbanistic, and functional criteria. The selection of these eight points reflects a balance between spatial efficiency, heritage sensitivity and operational feasibility. The multicriteria approach allows for the technical justification of each inclusion and exclusion, aligning with the objectives of sustainable mobility and respect for the urban context of Évora. Table 4 presents the decision-making indexes:

Table 4: Summary Table:Strategic Point Evaluation

STRATEGIC POINT	AHP SCORE	ESTIMATED SHADING[2]	AVG. OD DISTANCE (M)	DECISION
António Gedeão	0.838	Low	1211.	Include
Évora Plaza	0.795	Low	2367.	Include
Porta de Aviz	0.863	High	1291.	Include

[2] Estimated Shading: inferred from visual impact and heritage sensitivity scores. Points with lower visual interference and reduced patrimonial constraints were classified as having low shading.

Água de Prata Parking Lot	0.89	High	1494.	Include
Horta das Laranjeiras	0.878	High	812.	Include
Giraldo Square	0.958	High	1033.	Include
Rodoviária do Alentejo	0.82	Low	1392.	Include
Évora Train Station	0.792	Low	1327.	Include
Fire service	0.73	Medium	1210.	Exclude

The resulting network is strategically balanced, encompassing high-traffic corridors, intermodal hubs, student residences, commercial zones, and green spaces, including the following points:

- António Gedeão University Residence (38.561199, -7.912974): A residential location with a large number of students. This station promotes daily e-bike use as an alternative to motorized transportation for the commuting of students, in addition to reducing pressure on local parking.
- Évora Plaza (38.548690, -7.905595): A commercial center with a large flow of visitors and workers. The presence of a station at this location favors short trips for shopping, leisure, and services, in addition to allowing integration with peripheral residential areas.
- Porta de Aviz (38.576884, -7.910092): A strategic entrance to the Historic Center, with the potential to serve as a transition point between heritage and modern areas. Electric mobility here helps reduce car traffic within the city walls.
- Água de Prata Parking Lot (38.576187, -7.914491): A park with solar infrastructure under development (POCITYF), ideal for installing green charging stations. It can function as an intermodal hub, especially during events or peak hours.
- Horta das Laranjeiras (38.567196, -7.907665): A green and recreational space, excellent for promoting the tourist and leisure use of e-bikes. The installation here reinforces the project's sustainable nature and expands access to low-density urban areas.
- Giraldo Square (38.570567, -7.908990): The symbolic and functional heart of the city. The presence of a station at this location ensures visibility, tourist engagement, and quick access to services, commerce, and heritage.
- Rodoviária do Alentejo, S.A. (38.567404, -7.917300): Bus terminal with high passenger turnover. Installing a station at this location favors intermodality and expands the reach of the shared system for those arriving from outside the city.
- Évora Train Station (38.560774, -7.907245): Railway entry point to the city. Integration with the e-bike system allows for quick travel to the historic center, universities, and shopping areas, promoting a fluid and sustainable mobility experience.

To assess the spatial coverage of the proposed e-bike system, we generated isochrones of 5, 10 and 15 minutes of travel time from a central location (38.5711, -7.9106, Serpa Pinto Street - Évora), using the OpenRouteService (ORS) API with the cycling-electric profile. This profile accounts for the specific performance of e-bikes, including acceleration and average speeds on the road network. The resulting polygons represent the maximum area that can be reached within each time threshold, providing a realistic measure of accessibility that complements the set of eight candidate stations previously identified. Isochrone generation was implemented in R with the openrouteservice, sf and leaflet packages, and the approach is fully reproducible. Figure 4 illustrates the 5/10/15-minute isochrones, which will be used to benchmark system coverage in both baseline and event scenarios [19].

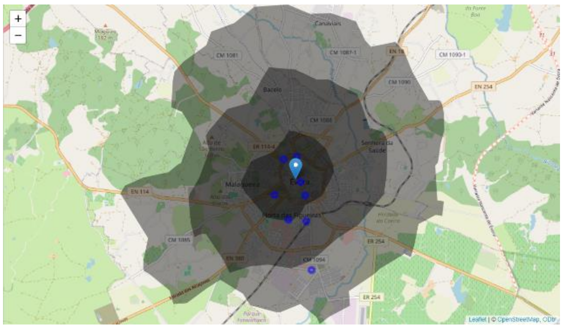

Figure 4: Isochrones of 5, 10 and 15 minutes for e-bike trips from the city centre (Serpa Pinto Street, Évora), generated with HeiGIT gGmbH, OpenRouteService[3]
Source: [19]; ORS, processed in R (openrouteservice, sf, leaflet packages) (accessed: September 2025)

Most of the eight selected candidate stations fall within the 10-minute isochrone, ensuring accessibility for daily commuting and intermodal trips, while the 15-minute coverage extends the system's reach to peripheral residential and leisure areas. This confirms that the proposed network provides adequate spatial coverage under both baseline and event scenarios.

To support the strategic deployment of solar-powered e-bike sharing stations in Évora, a demand simulation was conducted using synthetic data modeled in R. The results are presented in four visualizations (Figure 5a–5d) that inform key operational and locational decisions:

• Temporal Distribution of Trips Figure 5a illustrates the hourly distribution of trips across weekdays and weekends. Weekday demand shows pronounced peaks around 8:00 and 17:00, consistent with commuting patterns, while weekend usage is more evenly distributed throughout the day. These findings suggest that:

– Stations near residential and employment zones should prioritize early morning and late afternoon availability.

– Weekend demand may require broader coverage in leisure and tourism areas, with extended operational windows.

• Trip Length Percentiles Figure 5b presents the P50 and P90 percentiles of trip duration, estimated from a bimodal distribution modeled in R. The P50 value (~15 minutes) reflects typical intra-urban mobility, while the P90 (~30+ minutes) indicates outlier trips that may require higher battery autonomy or strategic redistribution. These metrics support:

– Sizing of battery capacity per station.

[3] HEIGIT - Heidelberg Institute for Geoinformation Technology. OpenRouteService (accessed: September 2025). From https://openrouteservice.org.

– Estimation of solar generation needs based on average energy consumption per trip.

• Origin–Destination Matrix Figure 5c shows the simulated OD flows between nine strategic points in Évora. The heatmap highlights asymmetric demand patterns, with certain nodes acting as major trip generators or attractors. This analysis informs:

– Prioritization of station placement in high-flow corridors.

– Identification of intermodal integration points (e.g., university ↔ historic center ↔ commercial zones).

– Dynamic reallocation strategies for mobile stations based on temporal and spatial demand.

• Estimated Travel Time Matrix Figure 5d presents the simulated travel times (in minutes) between the nine proposed station sites, calculated from geodesic distances and assuming an average e-bike speed of 15 km/h. This visualization complements the OD flow analysis by introducing a temporal dimension to spatial accessibility. Key insights include:

– Identification of time-efficient corridors, where short travel durations align with high trip volumes, reinforcing their suitability for station placement and redistribution logistics.

– Detection of peripheral nodes with longer travel times, which may require additional battery autonomy or serve as candidates for grid-assist fallback strategies.

– Support for dynamic routing and fleet balancing, especially during peak hours or event-driven demand shifts.

Together, these visualizations enhance the operational planning framework by linking spatial layout to real-world

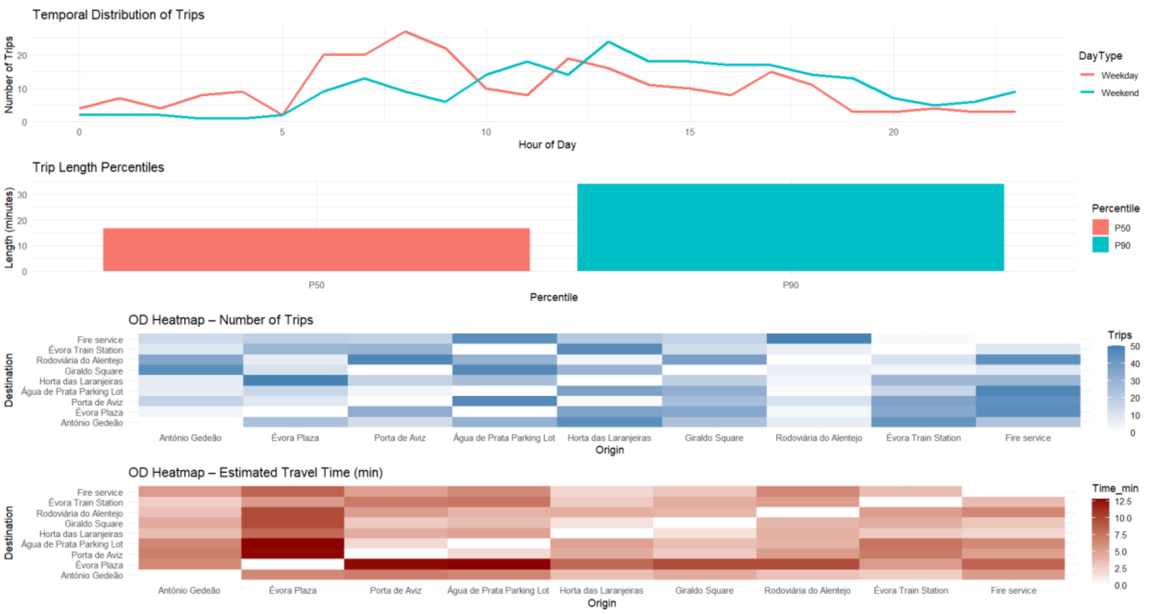

Figure 5: Demand modelling

travel behavior, ensuring that station deployment responds not only to demand intensity but also to temporal feasibility and urban dynamics.

From the nine candidate locations evaluated through the AHP matrix and spatial optimization, eight were selected for initial deployment. This decision reflects a balance between maximizing coverage and maintaining operational feasibility.

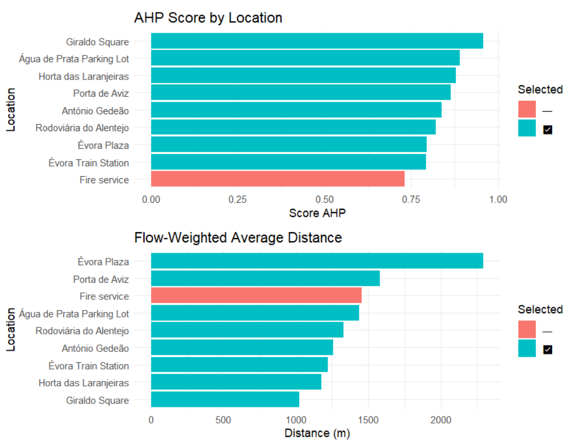

Figure 6: Station Selection Strategy

The exclusion of one site was based on its comparatively lower composite score and higher flow-weighted average distance, indicating reduced accessibility and strategic relevance within the current demand scenario (Figure 6).

The selection process prioritized locations that offer strong intermodal connectivity, favorable solar exposure, and proximity to high-demand corridors. The modular nature of the infrastructure allows for future inclusion or rotation of sites as demand patterns evolve, ensuring that the system remains responsive and scalable.

6 DISCUSSIONS

- **Trade-offs: "Primarily PV" vs. "Grid-Assist"**

The decision to operate stations primarily on photovoltaic energy reflects a commitment to full autonomy and carbon neutrality. However, this choice entails important trade-offs:

- Advantages of Primarily PV: Zero operational emissions and full energy independence; Simplified permitting in heritage zones (no grid connection or trenching); Symbolic value in showcasing clean energy leadership.
- Limitations: Vulnerability to seasonal variation and shading (especially in winter or dense urban areas);

Need for oversizing PV and battery systems to meet peak demand, increasing cost and footprint; Limited fallback options during extreme weather or prolonged overcast periods.
- Grid-Assist Alternative: Allows for smaller PV arrays and batteries, reducing upfront investment; Ensures uninterrupted service during low-generation periods; Enables smart charging strategies (e.g., grid charging during off-peak hours).

The choice between these models depends on site-specific constraints, policy priorities, and operational resilience goals. In Évora, where heritage preservation and visual impact are critical, a mobile, PV-exclusive model may be preferable, but hybrid configurations could be considered for high-demand or shaded locations.

- **Operational Dynamics During Events**

Cultural, academic, and tourism events in Évora introduce temporary spikes in mobility demand, which challenge the static assumptions of baseline station sizing. Key considerations include:
- Temporal reallocation: Mobile stations can be repositioned to event zones (e.g., festival venues, university campuses) to absorb demand surges.
- Energy stress: Higher trip volumes increase charging cycles, requiring robust battery autonomy or temporary energy support.
- User behavior shifts: Events may alter trip timing (e.g., extended evening use), duration, and origin–destination patterns.

Operational strategies should include:
- Predictive modeling: Using historical event calendars and demand simulations to anticipate peak loads.
- Flexible logistics: Rapid deployment protocols, mobile maintenance units, and real-time monitoring.
- Fallback planning: Optional grid-assist or mobile powerbanks to ensure continuity without compromising the PV-first principle.

These dynamics reinforce the value of modularity and mobility in station design, allowing the system to adapt to urban rhythms without permanent infrastructure.

7 CONCLUSIONS

The combined analysis of AHP criteria, shading estimation and flow-weighted average distance reveals a robust selection of strategic points for the implementation of e-bike stations in Évora.

Giraldo Square has the highest AHP score (0.958), standing out as the most balanced point between demand, intermodality and low equity interference. Its average distance (1033 m) reinforces the operational centrality.

Horta das Laranjeiras combines a high AHP score (0.878) with the shortest average distance (812 m), suggesting strong coverage potential with low travel cost.

Água de Prata Parking Lot and Porta de Aviz have high scores (≥ 0.86) and high shading, which requires attention to visual and heritage integration, but are compensated by good connectivity.

Évora Plaza, despite having the longest average distance (2367 m), was included due to its intermodal relevance and consistent demand, evidenced by the AHP score (0.795).

Fire Service, with the lowest AHP score (0.730) and average shading, was excluded from the final selection because it had lower relative performance in the combined criteria, despite its average distance being competitive (1210 m).

The innovative contribution of this study lies in its strategic approach to integrating solar-powered mobility infrastructure within the urban and heritage context of Évora. By focusing on the deployment of mobile and modular e-bike sharing stations powered by renewable energy, the project addresses critical challenges related to sustainable transport, energy transition, and urban planning in medium-sized cities with historical constraints.

Rather than emphasizing technological novelty alone, the study prioritizes contextual feasibility, identifying optimal station locations based on accessibility, solar exposure, and urban dynamics. This includes the use of public parking areas with photovoltaic potential, intermodal hubs, and flexible deployment zones within the historic center, ensuring that mobility solutions remain adaptable to seasonal events and spatial limitations.

The proposed model contributes to the broader goals of climate adaptation and decarbonization by promoting low-emission transport and efficient land use. It also reinforces the importance of interoperability, local workforce training, and preventive maintenance as pillars for long-term operational sustainability.

Ultimately, this study offers a replicable framework for other heritage cities seeking to balance environmental goals with mobility innovation. It aligns with national and European strategies for smart cities, energy efficiency, and inclusive urban development, positioning Évora as a reference in the integration of clean energy and sustainable transport systems.

8 FUTURE WORK

The potential of Évora to lead innovative actions in sustainable urban mobility and renewable energy integration is considerable and deserves further exploration. Building on the design and methodology proposed in this study, which prioritizes flexible, solar-powered e-bike sharing stations adapted to heritage and urban constraints, several avenues for future research and implementation are identified.

1. Energy and Infrastructure Enhancements
- Energy efficiency optimization: Investigate passive cooling systems and smart energy management for solar charging stations, especially in high-exposure zones such as public parking areas and intermodal hubs.
- Fallback energy strategies: Evaluate the feasibility of auxiliary power sources (e.g., grid connection, mobile power banks) for extreme weather conditions or justify exclusive PV operation through oversizing and autonomy modeling.
- Battery management protocols: Define operational thresholds for state-of-charge (SOC), thermal safety, and charge/discharge cycles to ensure system reliability.

2. Environmental and Operational Impact
- Carbon mitigation assessment: Quantify the modal shift from fossil-fueled transport to electric micromobility, supported by solar infrastructure and behavioral incentives.
- Performance indicators: Develop KPIs such as trips per bike per day, solar kWh delivered, CO_2 avoided, station uptime, and Levelized Cost of Charge

(LCOC) to evaluate system efficiency and cost-effectiveness.

- Resilience and adaptability: Analyze how modular stations respond to seasonal demand, urban events, and spatial reconfiguration needs within the historic center.

3. Urban Integration and Safety

- Heritage-sensitive deployment: Explore mobile, non-invasive station designs with concealed cabling, low-profile solar pallets, and no ground perforation to comply with heritage preservation standards.
- Shading and solar losses: Conduct photometric sampling or develop seasonal shadow maps to assess real-world solar exposure and optimize station placement.
- Electrical and fire safety: Include a technical review of Li-ion charging risks, ventilation requirements, thermal cutoff mechanisms, and applicable IEC/EN standards.
- Cybersecurity and data governance: Address privacy and security concerns related to geolocation, user tracking, and GDPR compliance within the app and backend systems.

4. Smart City and Socioeconomic Integration

- Platform interoperability: Investigate integration with public transport, energy grids, and digital mobility services to enhance user experience and operational intelligence.
- Community and workforce engagement: Study the socioeconomic impacts of solar mobility, including local job creation, inclusive access, and contributions to low-carbon urban development.

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