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Article

Integrated Infrastructure for Photovoltaics, Electric Vehicle Charging, and eVTOL Readiness in a Medium-Sized City: A GIS–MCDA Pipeline with AHP/WLC and Sensitivity Analysis in Juiz de Fora (MG)

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Abstract: Urban decarbonisation and the electrification of mobility require location decisions that integrate energy and transport infrastructure into a single agenda, especially in mediumsized cities in emerging countries. This article proposes and applies a GIS–MCDA (Geographic Information Systems and Multi-Criteria Analysis) pipeline to prioritise urban locations suitable for the phased implementation of integrated photovoltaic (PV) and electric vehicle (EV) charging hubs in the short term, incorporating the requirement for urban air mobility readiness (eVTOL-ready) in the medium term. The method combines explicit definition of technical, urban, and environmental criteria, weighting by AHP with consistency checking, normalisation to a common scale, and aggregation by WLC, as well as a sensitivity analysis based on weighting scenarios. The case study in Juiz de Fora (MG) evaluates five representative alternatives (UFJF, Praça Halfeld, Bus Station (Rodoviária), Benfica–Praça CEU and Aeroporto da Serrinha), resulting in a prioritisation map and comparative ranking. The findings highlight the coexistence of high-power, large-scale hubs (Bus Station and Serrinha) and territorial capillarity solutions (UFJF and Benfica), while dense centralities (Praça Halfeld) tend to be more suitable as service points than as large-scale PV generators. Finally, the article proposes a conceptual operational layer to connect the locational result to service design guidelines (AC/DC mix, queues, and potential role of storage), reinforcing the usefulness of the pipeline as a planning and governance tool for phased implementation.

Keywords: multi-criteria analysis; GIS; AHP; WLC; urban photovoltaics; electric vehicle charging; eVTOL-ready; medium-sized cities

1. Introduction

The transition to low-carbon cities has accelerated the need to integrate energy planning and mobility planning into a single urban infrastructure agenda, aligned with the Sustainable Development Goals, with emphasis on SDG 7 (clean and affordable energy) and SDG 11 (sustainable cities and communities. In practice, the expansion of electrified mobility shifts a significant part of the decarbonisation challenge to the territory: where to deploy infrastructure, how to reconcile land use, how to meet demand with quality of service, and how to reduce impacts on the electricity grid. In this context, multi-criteria spatial analysis approaches in GIS (GIS-MCDA) have become particularly suitable for supporting location decisions by combining technical, urban, and environmental criteria in suitability maps and transparent rankings [1,2].

Internationally, the debate has evolved from the ‘recharging point’ to the concept of integrated mobility and energy hubs, capable of coordinating local generation (e.g., photovoltaics in carports), AC/DC infrastructure, connectivity/intermodality and, where necessary, peak mitigation strategies through storage and smart management [1,3]. In parallel, the emergence of Urban Air Mobility (UAM) and eVTOL aircraft adds a horizon of transformation: areas with spatial continuity, low obstruction and modal integration tend to gain relevance for a “futureready” infrastructure, i.e., prepared to evolve in phases and accommodate, in the medium term, requirements for vertiport readiness (eVTOL-ready) [4–8].

Despite these advances, there is still a significant gap: much of the literature deals with urban photovoltaics, electric vehicle charging, and eVTOL/UAM infrastructure in a segmented manner, with little evidence of integrated hubs that already incorporate explicit phasing (short-term PV + EV and medium-term eVTOL-ready), especially in medium-sized cities in emerging countries, where area limitations, urban restrictions, and uncertainties about network capacity are decisive for prioritisation [1,2,4]. In addition, GIS–MCDA studies often vary in their degree of transparency regarding criteria, standardisation, weights and ranking stability, which are critical elements for reproducibility and for converting results into implementation and governance guidelines [1,2].

Given this, this study investigates where and how to prioritise urban locations in Juiz de Fora (MG) to implement photovoltaics (PV) + electric vehicle (EV) charging in the short term and organise an eVTOL-ready infrastructure trajectory in the medium term, considering technical, urban, and environmental criteria. The study is based on a local survey that characterises five representative points: UFJF, Praça Halfeld, Bus Station, Benfica (Praça CEU) and Aeroporto da Serrinha, with summaries of insolation, shading, land use, accessibility and modal integration. In this set, the potential of the Bus Station as a high-turnover hub for fast DC charging (150–350 kW) and the strategic feasibility of Serrinha Airport as a multimodal hub with PV carports and the possibility of future evolution to eVTOL stand out [5,7,8].

To guide the work, the following research questions (RQs) were defined:

- RQ1. What technical, urban, and environmental criteria are most relevant for prioritising locations for PV + EV charging in Juiz de Fora (MG) using a multicriteria approach in GIS?
- RQ2. How do these criteria translate into a ranking/prioritisation among the five points studied (UFJF, Halfeld, Bus Station, Benfica, Serrinha) and what implementation scenarios emerge for the short and medium term?
- RQ3. How does the introduction of the “eVTOL-ready” requirement change the understanding of locational suitability and favour a vision of staggered multimodal hubs?

The article makes three contributions: (C1) a multi-criteria mapping in GIS for Juiz de Fora with explicit criteria and weightings, aimed at prioritising infrastructure and integrated energy-mobility ; (C2) a comparative analysis of locational feasibility for five strategic points, indicating priorities and implementation scenarios in the short term (PV + EV) and medium term (eVTOL-ready); and (C3) a bridge between planning and operation of the charging service, discussing operational implications of hub design (e.g., AC/DC mix, queue management, and potential storage role) without shifting the focus of the article to internal battery modelling.

Finally, the article is organised as follows: Section 2 presents related work; Section 3 describes the study area, data, and proxies; Section 4 details the GIS–MCDA pipeline, weighting and sensitivity, and the operational layer; Section 5 presents maps and comparative results; Section 6 discusses implications and comparisons; and Section 7 presents conclusions, limitations, and future work.

2. Theoretical Framework and Related Work

2.1. Distributed PV Generation in Urban Areas (Rooftops and Carports) and PV + BESS Microgrids

Distributed photovoltaic (PV) generation in urban areas has been treated as a strategic component to support the electrification of mobility, especially when installed on rooftops and solar carports over car parks. This arrangement has territorial and architectural advantages: it uses already consolidated surfaces, reduces competition for land and, in the case of carports, improves the parking space with shade and greater environmental comfort, while creating a local supply base for recharging services [3].

However, the performance of urban PV depends not only on regional solar potential, but above all on physical and spatial constraints that vary greatly between dense urban centres and open areas: effective usable area, spatial continuity, orientation, obstructions, and shading. In scenarios involving integration with recharging, these factors are no longer just about “energy generated” but also influence the operational viability of the hub, for example, the ability to meet recharging needs at critical times and grid dependence in areas with high losses [1,2].

For this reason, recent literature has highlighted architectures with PV + storage (BESS) microgrids as a mechanism to reduce service uncertainty and cushion power peaks, with direct impacts on cost and service quality, especially when fast DC charging is relevant [1,2]. Thus, urban PV and BESS are better understood as "infrastructure" elements of the hub, rather than as isolated components.

2.2. Charging Infrastructure for EVs and Location with GIS–MCDA

Public charging infrastructure is often organised as a portfolio of AC (7–22 kW) solutions associated with longer stays on campuses, in neighbourhoods and service centres, and DC (50–350 kW) solutions aimed at high-turnover corridors and hubs, where the user experience is strongly influenced by waiting time and speed of service [3]. In different scenarios, integration with PV and BESS appears as an alternative to reduce costs and demand peaks, in addition to increasing service predictability [1,2].

From a territorial planning perspective, deciding where to locate public charging stations is a problem with multiple objectives and constraints: potential demand, accessibility, urban compatibility, environmental limitations, and electrical connection feasibility. This explains the adoption of GIS–MCDA to produce suitability maps and rank alternatives with explicit criteria, appropriate for both public policy and private investment decisions [1].

A point increasingly emphasised by recent studies is that, especially for fast charging, implementation is conditioned by electrical feasibility and possible reinforcements. Although detailed network data are not always available in initial studies, planning can represent this dimension through consistent proxies (e.g., urban typology, connectivity, and infrastructure indicators), avoiding location recommendations that would be unfeasible in practice [9]. From this perspective, charging is no longer just a "mobility" service but also a "network and operation" issue.

2.3. Electric Air Mobility (eVTOL/UAM) and Vertiport Readiness (eVTOL-Ready)

Urban air mobility (UAM) and the advancement of eVTOL aircraft broaden the debate on future-ready infrastructure, requiring urban planning to consider criteria such as continuous area, obstacles, operational safety, access, and modal integration with ground transport. Recent reviews and studies show that these requirements are decisive for site eligibility and the systemic performance of vertiport networks, reinforcing that location decisions involve stricter constraints than conventional ground recharging [4,6].

From an energy perspective, contemporary guidelines highlight that vertiports may require high power and reliability, with concentrated demand windows and direct implications for distribution planning, power quality, and peak mitigation strategies. This brings the problem closer to that of DC fast charging, but with potentially more restrictive operating envelopes and greater sensitivity to service security and availability [7].

In this scenario, the literature converges on phased planning: implementing, in the short term, already justifiable electric mobility infrastructure (PV + EV charging) and incorporating eVTOL-ready requirements as a design dimension, reducing risk in the face of regulatory and market uncertainties [4,6].

2.4. Connection between Planning and Operation: SoC-Oriented Charging (Operational Layer)

Although the location literature helps to prioritise areas and alternatives, the performance of a hub also depends on operational choices: AC/DC mix, queue policy, and peak mitigation mechanisms. Recent studies show that strategies for managing charging events and organising service can reduce waiting times and improve the utilisation of the charger fleet, especially in high-turnover contexts [10].

When recharging is integrated with PV and, eventually, BESS, the operation incorporates an energy dispatch dimension: switching between local energy, grid and storage according to demand and limitations. In this context, SoC can be treated as a simple and explainable operational variable to guide screening and prioritisation (e.g., criticality thresholds), support AC/DC allocation, and justify BESS activation triggers at peak times without the article needing to delve into internal battery modelling [1,2].

Thus, the state of the art suggests that an important contribution, especially for mediumsized cities, is to connect the locational result (map/ranking) to a minimum operational layer, sufficient to translate spatial suitability into design decisions and service performance. To synthesise this articulation, Table 1 summarises how the main reference blocks discussed in Sections 2.1–2.4 feed the analytical pipeline adopted in this study, linking the theoretical framework to the criteria, layers, and operational logic used in the GIS–MCDA approach.

Table 1. Mini-table—How the Reference Framework "feeds" the study pipeline.

Where It Enters the Pipeline	Reference Block	What It Theoretically Supports (Sections)
Urban PV assessment	Relevance of PV on roofs/carports; technical criteria (solar potential, usable area, shading)	Urban PV + role of BESS in peak mitigation; PV + BESS impact of shading/usable area layer (BESS)—Sections 3 and 4
Recharging infrastructure decision	AC/DC structure; need for location decision; transparency of criteria and proxies; electrical feasibility	Urban and electrical criteria; GIS–MCDA weighting and WLC—Sections 3 and 4
eVTOL/UAM integration	Area/obstacle requirements; modal integration; power/reliability	eVTOL-ready/intermodality criteria + phased interpretation—Sections 4–6
Planning–operation interface	Queue/service rules; allocation; connection to service performance	AC/DC operational layer (rules, pseudo-algorithm, metrics) + practical operation (SoC) discussion—Sections 4–6

Source: Prepared by the authors, 2025.

3. Study Area and Data

3.1. Study Area: Juiz de Fora as a Medium-Sized City in an Emerging Context

Juiz de Fora (MG) is a medium-sized municipality located in the Zona da Mata region of Minas Gerais and plays a central role in the region in terms of services, commerce, and intermunicipal travel. According to the IBGE, the municipality has an estimated population of approximately 567,000 inhabitants and presents urban dynamics typical of medium-sized Brazilian cities, combining consolidated centrality, vectors of expansion and spatial inequalities that directly impact infrastructure decisions [11]. Its urban structure is conditioned by a central valley where centralities and structural corridors are concentrated and by neighbourhoods at higher elevations, which produces relevant contrasts for the implementation of integrated energy and mobility infrastructure, especially in terms of usable area**,** obstructions/shading**,** accessibility and physicaloperational constraints [11].

To represent different urban typologies and demand profiles, five candidate locations with complementary functions in the urban system were selected: UFJF (São Pedro Campus), Praça Halfeld, Bus Station, Benfica—Praça CEU and Aeroporto da Serrinha (JDF). The selection was guided by territorial representativeness and consistency with the phased implementation strategy discussed in the article. UFJF represents an institutional hub with long-term permanence and potential for a pilot project; Praça Halfeld represents a consolidated high-flow centrality, but with physical limitations and shading; the Bus Station represents a high-turnover inter-municipal mobility hub, suitable for rapid recharging; Benfica–Praça CEU represents community equipment in a residential area with potential for local service and democratisation of access; and Serrinha Airport represents a site with great spatial availability and potential for evolution into a multimodal eVTOL-ready hub in the medium term [12,13].

3.2. Data Sources and Pre-Processing (Reproducible Pipeline)

The empirical basis was organised in a GIS environment and structured to support the GIS–MCDA pipeline, based on municipal data, cartographic bases, and derived inputs to compose thematic layers. Table 2 summarises the main sources and how they were used in the study, with a focus on reproducibility [11–13].

Pre-processing and spatial standardisation. To enable integration between layers and calculation of the composite score, all features and rasters were standardised in the SIRGAS 2000/UTM Zone 23S system, suitable for urban measurements (distances and areas). The layers were then cut out by the municipal boundary to ensure common extension and spatial consistency [11]. The five candidate sites were inserted as point features and the usable areas were delineated by vectorisation/measurements in GIS, with a cartographic reference base ([12]; Technical Survey, 2025).

Buffers, rasterisation and reclassification. To operationalise urban variables (accessibility, centrality, modal integration) and build proxies, buffers were applied around relevant axes and points, with subsequent conversion to raster. The vector layers (points/lines/polygons) were rasterised at a common resolution, compatible with the adopted urban decision scale, allowing for normalisation and weighted overlay. Finally, the layers were reclassified and normalised to [0, 1] according to their direction (benefit/cost/constraint), and constraints were treated as eligibility or penalty masks, as detailed in Section 4 (Technical survey; [13]).

Table 2. Dataset/Resolution/Year/Source/How it was used Year.

Dataset/Layer	Resolution/Scale	Year	Source	How It Was Used in the Study
Municipal indicators (population, density, area)	N/A	2025	IBGE—Cities and States	Contextualisation and justification of the case study (Section 3.1). [11].
Municipal boundary (territorial grid)	Municipal grid	2025	IBGE—Territorial Grids	Delimitation of the study area and spatial clipping of all layers. [11].
Cartographic base/reference imagery (roads, accesses, centralities, POIs)	Visualisation scale	2025	Google Maps	Vectorisation and spatial measurements for urban layers, and support for the urban flow proxy. [12].
Location of the five candidate points	N/A	2025	Google Maps	Georeferencing of alternatives and generation of distances and buffers. [12].
Useful areas per location (car parks/candidate surfaces)	N/A (GIS measurement)	2025	Google Maps + vectorisation	Basis for the usable area criterion and input for PV system sizing. ([12] Technical Survey, 2025).
Evidence of shading and solar exposure by location	N/A	2025	Shadowmap	Support for the shading criterion and application of penalties in dense urban areas. [13].
Assumptions and energy calculations (kWp, kWh/month, losses, recharge equivalencies)	N/A	2025	Technical Survey	Standardisation of capacity and energy generation for technical comparison across locations. (Technical Survey, 2025).
Urban and environmental restrictions (mask/penalty layers)	GIS scale	2025	Technical Survey	Application of ineligibility masks and penalties related to implementation conflicts. (Technical Survey, 2025).

Source: Prepared by the authors, 2025.

3.3. Derived Variables and Proxies

As the objective of the study is to support location decisions in a real context in which detailed operational data (high-resolution traffic counts or point-to-point electrical capacity) may not be available, reproducible proxies were defined to represent two critical dimensions of the problem: (i) demand/attractiveness (urban flow) and (ii) plausibility of electrical service (access to the grid). These proxies were constructed from the sources in Section 3.2 and were normalised to [0, 1], ensuring comparability in multicriteria aggregation [12].

3.3.1. Urban Flow Proxy

The urban flow proxy represents the propensity for demand for recharging and the attractiveness of the location based on a composite index of accessibility and centrality. It was operationalised by combining three components: centralities/generating poles, proximity to arterial corridors, and density of points of interest (POIs) and public transport. Centralities and hubs (e.g., consolidated centre, inter-municipal terminal, campus, and public facilities) were represented by features and areas of influence; arterial corridors were vectorised as connectivity axes; and POIs/elements of urban use were incorporated as evidence of permanence and modal transfer. Each component was then converted into a score by distance classes (buffers) and normalised, producing a final urban flow index in [0, 1] for application in the WLC ([12]; Technical Survey, 2025).

3.3.2. Grid Access Proxy

The grid access proxy was defined as a spatial indicator of preliminary connection/service plausibility, recognising that detailed network diagnostics are typically limited. Grid access was constructed by combining: (a) evidence of consolidated urban infrastructure and connectivity, (b) compatibility and implementation limitations (including urban/environmental restrictions), and (c) site typology (terminal, campus, public facility, airport), treated as indirect evidence of service to relevant loads and possibility of expansion. The components were reclassified on a scale of [0, 1], with the application of a mask/penalty for restrictions, resulting in an index that can be interpreted as a preliminary screening of electrical feasibility ([12]; Technical survey, 2025).

3.3.3. Proxy Plausibility and Face-Validity Checks

Because urban flow and grid access are proxies, we provide a brief plausibility assessment to reduce the risk of site-type bias (e.g., systematically favouring terminals or institutional areas). First, the urban flow proxy is consistent with the known centrality and mobility corridors of Juiz de Fora (the city centre and main arterial avenues), which concentrate public transport, services and through-movement. This face-validity check aligns with the high-flow character of Halfeld Square and the Bus Station.

Second, the grid access proxy is interpreted as early-stage connection plausibility rather than verified available capacity; therefore, sites with pre-existing infrastructure typologies (terminal, campus, airport) may score higher. This does not replace a utility interconnection study and is explicitly treated as a limitation. To make this explicit for planners, we report which sites change position when grid-related weights are increased (Section 5.4) and discuss when priorities become governance-dependent (Section 6.3). Table 3 summarises the construction of both proxies, their operational meaning in the model, and the main sources of potential bias and mitigation adopted in the study.

Table 3. Proxy construction summary (components and rationale).

Proxy	Main Components	Operational Meaning	Potential Bias/Mitigation
Urban flow (C4)	Centralities & trip generators; proximity to arterials; POIs and public transport presence	Demand/attractiveness surrogate for public charging	May favour centralities/terminals; mitigated by including PV feasibility (C1–C3) and reporting sensitivity (Section 5.4).
Grid access (C5)	Infrastructure typology; connectivity; compatibility constraints; proximity indicators	Early-stage plausibility of electrical service for AC/DC deployment	May favour sites with existing large facilities; mitigated by stating ‘plausibility’ (not capacity) and recommending utility studies.

Source: Prepared by the authors, 2025.

4. Methodology

The methodology combines multi-criteria spatial analysis in GIS (GIS–MCDA), consolidation of energy inputs, and a conceptual layer of operational design to translate the locational result into implementation and service guidelines. The objective is to produce, in a reproducible and auditable manner, (i) a suitability map and ranking for five candidate sites and (ii) recommendations for phased implementation of PV + EV charging (short term) and eVTOL-ready (medium term). The method follows a closed pipeline logic, connecting data → criteria → weights → normalisation → score → ranking → sensitivity → operational layer [1–3,7,9].

4.1. Overview of the GIS–MCDA Pipeline

Figure 1 summarises the methodological pipeline adopted in the study: (1) input data and layers (Section 3), (2) definition of criteria and decision hierarchy, (3) weighting by AHP and consistency check, (4) normalisation/reclassification to [0, 1], (5) aggregation by WLC to obtain the spatial score, (6) extraction of the score by alternative and generation of ranking, (7) sensitivity analysis (scenarios and weight perturbation) and (8) SoC-guided operational layer for design/service guidelines. This structure reduces methodological “jumps” and allows replication in other urban contexts with equivalent datasets [1,2].

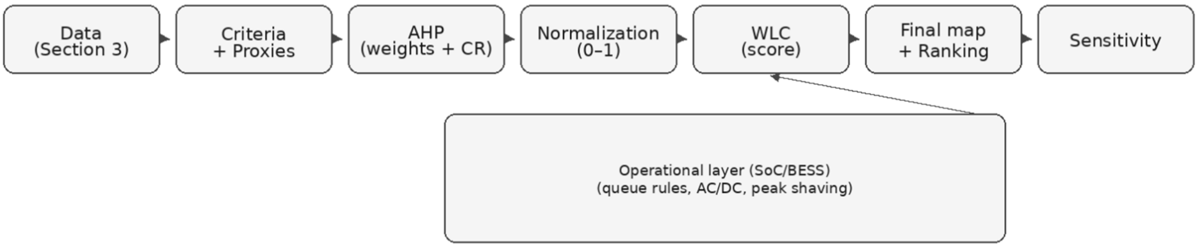

Figure 1. Overview of the GIS–MCDA pipeline adopted in the study. Source: Prepared by the authors, 2025.

4.2. Decision Hierarchy and Formal Definition of Criteria

The decision hierarchy was defined with the aim of prioritising locations suitable for the implementation of integrated energy and mobility hubs. Technical, urban and environmental criteria were employed, associated with layers/proxies described in Section 3 and classified according to direction (benefit/cost/constraint). The set of criteria consists of: C1 solar potential/exposure (benefit), C2 available usable area (benefit), C3 shading/losses (cost), C4 urban flow/accessibility (benefit; urban flow proxy), C5 grid access plausibility (benefit; grid access proxy), C6 urban/environmental restrictions (restriction/mask) and C7 intermodality and expansion readiness (benefit; includes eVTOL-ready). These criteria reflect established practices in charging infrastructure planning, PV + BESS integration, and emerging requirements associated with vertiport readiness, while maintaining transparency and traceability of multi-criteria judgement [1–4,6,7].

Epistemic basis of criteria and weights. Table 4 maps each criterion (C1–C7) to the supporting literature and the planning rationale. AHP weights were elicited from a structured session with all co-authors (domain expertise in architecture/urban planning and PV–EV infrastructure), and accepted only if CR ≤ 0.10.

Table 4. Criteria, evidence base and planning rationale.

Criterion	Direction/Layer	Planning Rationale	Key References
C1 Solar potential/exposure	Benefit; solar exposure layer	Maximises local PV yield and energy autonomy for the hub.	[1,2]
C2 Usable area	Benefit; digitised usable-area polygons	Enables scalable carport PV and the number of charging bays; critical for future-ready expansion.	[4,7]
C3 Shading	Cost; shading/ obstruction evidence	Reduces PV output and increases uncertainty; penalises dense urban canyons.	[1,2]
C4 Urban flow (proxy)	Benefit; accessibility/ centrality proxy	Surrogate for charging demand and service attractiveness in public networks.	[3]
C5 Grid access (proxy)	Benefit; connection plausibility proxy	Screens early-stage feasibility for AC/DC deployment where capacity data are unavailable.	[9]
C6 Urban/ environmental restrictions	Constraint mask m(p)	Avoids recommending ineligible/low-compatibility areas; improves implementability.	[1]
C7 Intermodality & eVTOL-ready	Benefit; intermodality + expansion readiness	Supports phased planning and future vertiport readiness, linking land and air mobility.	[4,6,7]

Source: Prepared by the authors, 2025.

4.3. AHP Weighting and Consistency

AHP judgements were elicited through a structured pairwise-comparison session conducted by the author team, who have domain expertise in urban/architectural planning and PV–EV charging infrastructure. The session followed the standard Saaty scale, reached consensus on each comparison, and the resulting matrix was accepted only if the consistency ratio satisfied CR ≤ 0.10. We acknowledge that the weights are expert-driven and not derived from a stakeholder survey; therefore, we explicitly report sensitivity scenarios and recommend future replications with utility and municipal stakeholders.

The relative importance among the criteria was obtained using the Analytic Hierarchy Process (AHP), with pair-wise comparisons and obtaining the weight vector w, normalised to $\sum w\_i = 1$. To ensure consistency of judgement, the Consistency Ratio (CR) was calculated, adopting the acceptance rule CR ≤ 0.10. The article reports the final weights applied to the WLC (and, where relevant, the paired matrix in the Appendix A), ensuring the auditability and reproducibility of the decision-making process [1,2].

Final AHP weight vector (w): C1 (Solar potential/exposure) = 0.10; C2 (Usable area) = 0.25; C3 (Shading; cost) = 0.15; C4 (Urban flow proxy) = 0.10; C5 (Grid access proxy) = 0.15; C6 (Restrictions mask) = 0.10; C7 (Intermodality & eVTOL-ready) = 0.15 ($\Sigma w\_i = 1.00$).

4.4. Normalisation and Weighted Overlap (WLC)

As the layers have different scales and natures, each criterion $xi(p)x\_i(p)xi(p)$ was converted to a common scale $ni(p) \in [0, 1]n\_i(p)\backslash in\ [0, 1]ni(p) \in [0, 1]$, enabling combination by weighted overlap. For benefit criteria (the higher, the better), min–max normalisation was used:

$$n\_i(p) = (x\_i(p) - \min(x\_i))/(\max(x\_i) - \min(x\_i)).$$

For cost criteria (the lower, the better), min–max inversion was used:

$$n\_i(p) = (\max(x\_i) - x\_i(p))/(\max(x\_i) - \min(x\_i)).$$

Urban/environmental restrictions were treated as an eligibility mask $m(p)$, where $m(p) = 1$ for eligible areas and $m(p) = 0$ for ineligible areas. The composite score $S(p)$ was calculated by WLC:

$$S(p) = m(p) \cdot \Sigma_{i = 1 \ldots n} (w_i \cdot n_i(p)).$$

The result is a continuous surface of suitability in [0, 1] for eligible areas, which can be discretised into classes (e.g., high/medium/low priority) for communication and decision-making. Next, the final score per alternative was obtained by extracting the score value in the area/point corresponding to each candidate location, generating a ranking and supporting comparative analyses [1,2].

4.5. Sensitivity Analysis

The robustness of the ranking and final map was assessed by sensitivity analysis at two levels: (i) parametric perturbation of weights at ±10% and ±20% (with renormalisation to maintain $\sum w_i = 1$), and (ii) thematic scenarios representing stakeholder preferences, such as: Energy Scenario (emphasis on C1–C3), Mobility Scenario (emphasis on C4 and C7), Network/Deployment Scenario (emphasis on C5 and C6) and Futureready Scenario (emphasis on C7).

Stability was measured by: (a) change in position in the ranking (Δrank), (b) stability of the Top-3 set and (c) Spearman's correlation ρ between the base ranking and rankings by scenario. This step allows us to identify "anchor" criteria for the result and trade-offs relevant to phased implementation [1,2].

4.6. SoC-Oriented Operational Design Layer (Framework)

To connect location planning to service performance, the study includes a conceptual layer of SoC-oriented operational design, understood as an operational variable (prioritisation and allocation) and not as a focus of internal battery modelling. The framework organises: (i) allocation between AC/DC chargers according to SoC criticality and hub profile, (ii) queue policy combining criticality and order of arrival, and (iii) BESS activation triggers for peak mitigation and service continuity. This approach is consistent with recent work discussing PV + BESS integration in charging stations and management strategies to reduce peaks and increase service predictability, as well as guidelines for electrical infrastructure in vertiports that highlight power and reliability requirements [1,2,7,10].

In summary, the operational pseudo-algorithm classifies vehicles by SoC thresholds (e.g., critical <20%<20%<20%), prioritises DC service for critical cases when available, and directs other vehicles to AC or off-peak windows, triggering the BESS when the required power exceeds local limits or when the queue exceeds a threshold. Operational metrics considered include average waiting time, charger utilisation, and energy delivered, allowing location results to be translated into hub design decisions and governance recommendations for phased deployment.

4.7. Method Implementation Summary (Replicability Checklist)

To facilitate replication, we summarise the implementation settings used in the GIS–MCDA workflow. (i) Coordinate reference system: SIRGAS 2000/UTM Zone 23S. (ii) Study extent: clipped to the municipal boundary of Juiz de Fora. (iii) Candidate alternatives: five pre-selected sites (UFJF, Halfeld Square, Bus Station, Benfica–CEU, Serrinha Airport). (iv) Layer preparation: vector layers were rasterised to a common grid; benefit/cost layers were normalised to [0, 1] using min–max and inverted min–max, respectively; categorical layers were reclassified to ordinal [0, 1] scores; restriction layers were applied as an eligibility mask $m(p)$ in the final score. (v) Aggregation: WLC composite score $S(p) = m(p) \cdot \Sigma(w_i \cdot n_i(p))$, with weights derived via AHP and accepted only if $CR \leq 0.10$. (vi) Site scoring: WLC values for each alternative were extracted from the corresponding site footprint/area (mean score over the delineated usable-area polygon). (vii) Sensitivity: ±10% and ±20% weight perturbations plus thematic scenarios (Energy, Mobility, Grid/Implementation, Future-ready), evaluated by rank changes, Top-3 stability and Spearman correlation.

5. Results

5.1. Final Prioritisation and Ranking Map of Locations

Figure 2 presents the final suitability (WLC) map, while Figure 3 decomposes the result into the main thematic layers. Table 5 reports the resulting site ranking and priority class, and Table 6 summarises the site-level quantitative evidence and phased deployment roles.

The performance of the five candidate locations was extracted from the map, producing the ranking shown in Table 5.

The ranking in Table 5 summarises the performance of the alternatives in the WLC score and confirms the coexistence of two implementation profiles: high-power, large-scale hubs (Serrinha Airport and the Bus Station) and longer-stay, territorial capillarity solutions (UFJF and Benfica). Praça Halfeld remains strategic in terms of flow and accessibility, but is limited for large-scale PV, being more appropriate as a service point and a connector to nearby hubs.

Table 5. Ranking and priority of candidate locations (WLC result).

Position	Location	WLC Score (0–1)	Priority Class
1	Serrinha Airport (JDF)	0.725	High
2	Bus Station	0.697	High
3	UFJF (São Pedro Campus)	0.538	High
4	Benfica—Praça CEU	0.339	Medium
5	Praça Halfeld	0.325	Medium

Source: Prepared by the authors (2025), based on the WLC aggregation of the GIS–MCDA pipeline.

Table 6. Consolidated comparison of the five candidate sites (energy–mobility–future-ready).

Site	WLC Score (0–1)	Class	PV Evidence (Capacity/Generation with 35% Losses)	Recommended Charging Profile	Role in the System (Short Term PV + EV)	Role in the System (Mid Term eVTOL-Ready)	Justification by Criteria (Summary)
Serrinha Airport (JDF)	0.725	High	6413.55 kWp (11,154 panels)/≈ 600,300 kWh/month	High-power DC + AC; BESS recommended	Largest-scale PV + EV hub in the municipality	eVTOL-ready core (vertiport), future-ready by phases	C1–C3: best performance (area and low obstruction); C4: flow depends on connectivity; C5: may require upgrades; C7: maximum readiness and continuous area
Bus Station	0.697	High	1674.4 kWp (2912 × 575 Wp)/≈ 156,723 kWh/month	DC 150–350 kW (priority) + supporting AC	High-turnover regional hub, inter-municipal service	Scalable multimodal hub, requiring grid/BESS coordination	C1–C3: strong potential and low obstruction; C4: very high flow; C5: plausible for high loads; C6: manageable restrictions; C7: strong intermodality and expansion capacity
UFJF (São Pedro Campus)	0.538	High	310.5 kWp (540 panels)/≈ 29 MWh/month	Predominantly AC 7–22 kW + complementary DC	Hybrid pilot and R&D base (smart charging and monitoring)	Future-ready testbed (smart management, PV + BESS integration)	C1–C3: good potential and low obstruction; C4: high and predictable flow; C5: institutional infrastructure; C7: good connectivity and governance
Benfica—CEU Square	0.339	Medium	179.4 kWp (312 panels) + 184 kWp (320 panels)/≈ 16.7–17.2 MWh/month	AC 7–22 kW	Community hub, local service and territorial capillarity	Modular expansion (micromobility and services)	C1–C3: good exposure; C4: moderate demand; C5: plausible at light scale; C6: compatible; C7: moderate intermodality
Halfeld Square	0.325	Medium	PV at limited scale (losses > 55% in scenarios)	Light AC/service + grid-based charging in adjacent structures	Central service point (convenience), not a generator	Urban connector to a network of nearby hubs	C4: extremely high flow; C1–C3: penalised by shading and area; C5: grid available; C7: high centrality and intermodality

Source: Prepared by the authors (2025), based on the GIS–MCDA pipeline and the technical survey.

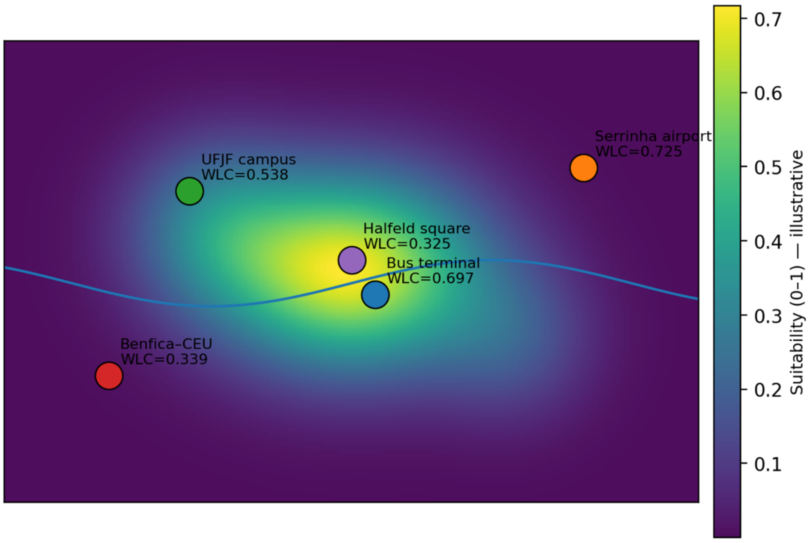

Figure 2. Final prioritization map (WLC score—schematic). Source: Prepared by the authors, 2025.

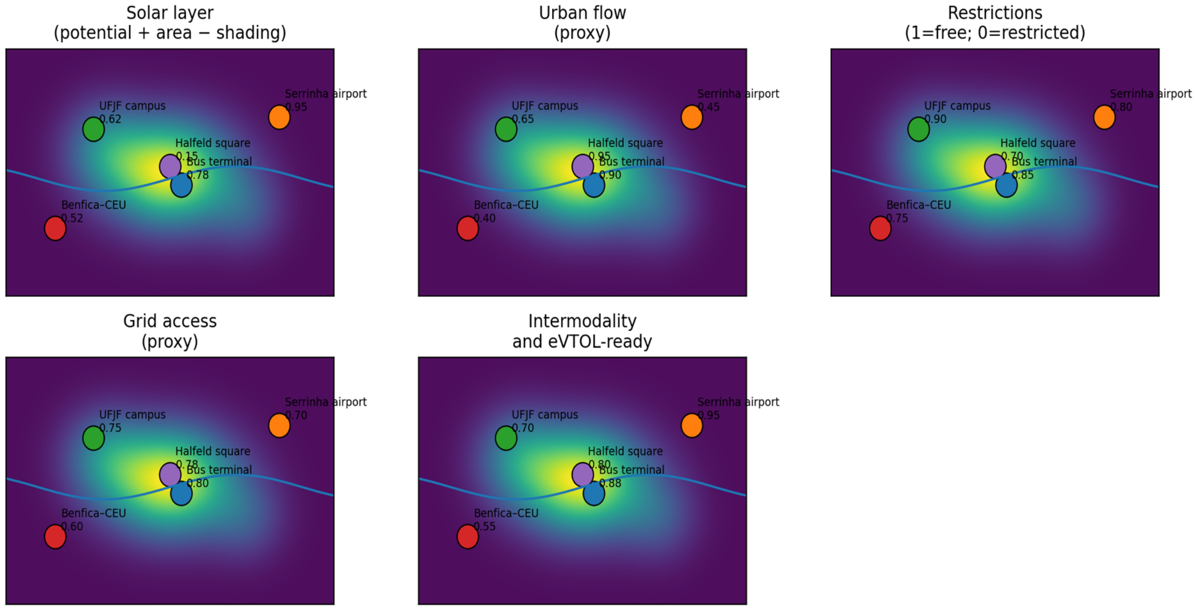

Figure 3. Layer mini-maps (normalized values—schematic). Source: Prepared by the authors, 2025.

5.2. Results by Layers (Mini-Maps)

To interpret the composite score and increase transparency, the main layers/criteria groupings are presented as mini-maps (Figure 3), highlighting the relative contribution of each dimension of the decision.

5.2.1. Solar Layer (PV Potential, Usable Area and Shading)

The solar layer highlights the decisive role of usable area availability and shading in enabling carports and large-scale generation. Locations with greater spatial continuity and less obstruction tend to have high suitability, while dense centralities show a drop in performance due to losses and physical limitations. This reading supports the differentiation between “generating” locations (capable of producing energy at scale) and “service provider” locations that are more dependent on the grid [1,2].

5.2.2. Urban Flow and Accessibility Layer (Urban Flow Proxy)

The urban flow proxy highlights centralities and mobility nodes with high attractiveness and potential demand for recharging. In general, locations with greater connectivity and service intensity are more suitable in this dimension, which explains the strategic role of central alternatives even when PV feasibility is limited [3].

5.2.3. Urban/Environmental Restrictions Layer

The restrictions layer acts as an eligibility and penalty element, reducing suitability in areas with implementation conflicts and/or territorial limitations. This component is critical to avoid unfeasible location recommendations and to make the final map applicable to licensing and preliminary design phases.

5.2.4. Grid Access Layer (Proxy Grid Access)

The grid access proxy indicates preliminary plausibility of service for recharging loads, with an emphasis on operational feasibility in higher-power DC scenarios. The relevance of this dimension is accentuated in high-turnover hubs, where reinforcement costs and deadlines can dominate the project. Recent literature reinforces that network constraints and upgrades are decisive for the implementation of fast charging, justifying their explicit presence in the multi-criteria model [9].

5.2.5. Intermodality and Expansion Readiness Layer (eVTOL-Ready)

The readiness layer highlights locations with greater potential for modal integration and with spatial conditions for phased evolution. The inclusion of this dimension shifts part of the decision from the “centre” to areas with high availability and low obstruction, consistent with the requirements discussed for the eligibility and operation of vertiports and future-ready infrastructure [4,6,7].

5.3. Comparison of the Five Locations (Technical Data Sheets and Implementation Scenarios)

This section summarises the results by location, preserving the energy calculations and explaining the suitability for short-term (PV + EV) and medium-term (eVTOL-ready) implementation.

Table 6 consolidates the energy evidence, the recommended recharging profile, and the short- and medium-term systemic function. This summary allows spatial prioritisation to be transformed into phased implementation guidelines, articulating PV + EV in the short term and eVTOL-ready in the medium term, with adaptation of the AC/DC mix and possible BESS support in the highest-power hubs.

5.3.1. UFJF—Campus (High Priority)

UFJF presents favourable conditions for the implementation of photovoltaic infrastructure integrated with electric vehicle charging. The availability of open areas, especially in the parking lots of the Community Centre, allows for the installation of solar carports. The technical survey indicates a capacity for 540 PV panels, totalling approximately 310.5 kWp. In a realistic scenario (35% losses), this configuration can generate ≈29 MWh/month, sufficient for 25 full recharges/day or more than 140 recharges of 50 km.

The constant presence of users and the predictability of demand favour a hybrid AC + DC operation. In addition, UFJF stands out as an appropriate site for technological piloting, instrumentation, monitoring, and validation of PV + BESS management and integration strategies on an urban scale [1,2]. Shortterm scenario: PV carports + AC charging predominant with complementary DC. Medium-term scenario: smart governance and operation pilot, with the possibility of phased integration with future-ready solutions.

5.3.2. Halfeld Square (Medium Priority)

Praça Halfeld has high urban and public transport flow, making it a strategic service point. However, the density of the surrounding area results in severe shading, which limits the implementation of PV on a large scale, especially when high losses reduce generation to levels that are not sufficient to sustain charging via local generation.

Thus, the technical recommendation is to treat the location as a service point, with smaller-scale solutions (compact totems, PV/lighting street furniture) and integration with charging associated with the network in adjacent structures (e.g., existing car parks). This result is consistent with the logic of complementary hubs: dense centralities may be relevant for access and convenience, even if they are not generation centres [3]. Short-term scenario: grid-dependent recharging service and ad hoc PV solutions. Medium-term scenario: “urban connector” function for a network of nearby hubs.

5.3.3. Bus Station (High Priority)

The bus station stands out as the most efficient location for fast DC charging (150–350 kW) due to the high inter-municipal traffic and its intermodal role connecting urban buses, electric vehicles, and future flows. The technical survey indicates that the area can accommodate 2912 × 575 Wp PV panels, reaching 1674.4 kWp installed, with monthly generation of ≈156,723 kWh in a realistic scenario (35% losses). This is equivalent to 137 full recharges/day or 770 recharges of 50 km/day, making the Bus Station the largest operational urban hub in the short term.

Its position associated with structural axes reinforces its function as a regional electric mobility hub, with strong adherence to the fast charging and high turnover profile. In terms of planning, this type of hub requires attention to network restrictions and upgrades and to peak mitigation operations, especially if there is DC expansion [9]. Short-term scenario: high-power DC hub with large-scale PV support. Mediumterm scenario: phased expansion with BESS and management for service quality and peak mitigation.

5.3.4. Benfica—Praça CEU (Medium Priority)

Praça CEU, in an elevated area with good sun exposure, has potential for community solar energy and electric mobility projects. Technical calculations indicate capacities of 312 panels (179.4 kWp) for the square and 320 panels (184 kWp) for the building, with monthly generation of ≈16.7–17.2 MWh under realistic losses (35%). This supports 14– 15 full recharges/day or more than 80 recharges of 50 km/day, compatible with local service.

The location is particularly suitable for 7–22 kW AC solutions, PV furniture and micromobility, functioning as a vector for democratising access and territorial distribution of the service, complementing higher-power hubs [3]. Short-term scenario: community AC hub with local PV and modular expansion. Medium-term scenario: integration with neighbourhood policies (active mobility, micromobility and public services).

5.3.5. Serrinha Airport—JDF (High Priority)

Serrinha Airport has the largest usable area and the greatest photovoltaic potential in the study. It is estimated that 11,154 PV panels could be installed, totalling 6413.55 kWp, with monthly generation of ≈600,300 kWh in a realistic scenario (35% losses). This volume would allow for 526 full recharges/day or 2951 recharges of 50 km/day, far exceeding the other locations analysed.

In addition to the energy scale, the flat topography and spatial continuity make Serrinha the most suitable location for future-ready evolution, including the implementation of a regional vertiport and integration between fast charging, PV carports, and future electric air mobility operations. This result is consistent with recent recommendations on electrical infrastructure and power and reliability requirements associated with vertiports [4,6,7]. Short-term scenario: PV + EV hub with high power and expansion potential. Medium-term scenario: eVTOL-ready core for multimodal solutions and phased growth.

5.4. Sensitivity Analysis (Empirical Evidence)

To assess the robustness of the ranking, the model was re-run under weight perturbations (±10% and ±20%) and thematic scenarios (Energy, Mobility, Network/Deployment, and Future-ready), as per Section 4.5. Table 7 summarises the baseline ranking and the main sensitivity scenarios, highlighting changes in rank position across alternatives and supporting the interpretation of robustness and governance dependence in the prioritisation results.

Table 7. Baseline vs key sensitivity scenarios (rank positions).

Site	Baseline	Energy	Mobility	Future-Ready
Serrinha Airport (JDF)	1	1	2	1
Bus Station	2	2	1	2
UFJF (São Pedro Campus)	3	3	3	3
Benfica—Praça CEU	4	4	5	4
Praça Halfeld	5	5	4	5

Source: Prepared by the authors, 2025. Note: Top-3 membership remains stable across scenarios; swaps occur mainly between the top two sites under mobility-centric preferences and between lower-tier sites under governance priorities.

Overall, the Top-3 set (Serrinha Airport, Bus Station, and UFJF) remained stable across all thematic scenarios and weight perturbations (±10% and ±20%), as illustrated in Figure 4. The first position is robust in most scenarios; it only becomes sensitive when the weight of usable area/solar deployment capacity (C2) is strongly reduced, in which case the Bus Station may temporarily overtake Serrinha due to its higher urban flow and intermodality. The lower positions (Benfica and Halfeld) are the most sensitive and may swap depending on whether mobility-related criteria (C4/C7) or restriction/grid plausibility (C6/C5) are emphasised. Spearman rank correlations between the base ranking and scenario rankings ranged from $\rho = 0.90$ to $\rho = 1.00$, indicating high ordinal stability. For planners, this means investment priorities are robust for the top sites, while the choice between smaller-scale/community and central service points is more governance-dependent.

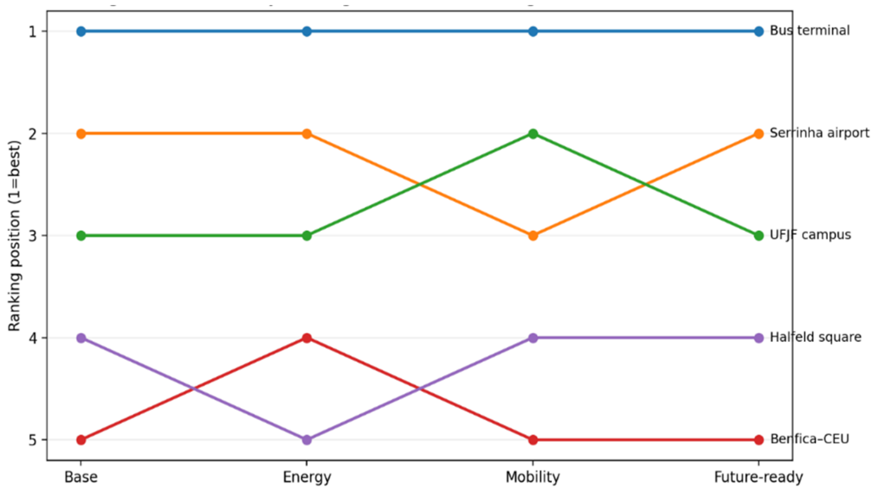

Figure 4. Sensitivity analysis: ranking variation under baseline and thematic weight scenarios (Energy, Mobility, Future-ready). Lines indicate each site's rank position; Top-3 stability highlights robustness for strategic investment. Source: Prepared by the authors, 2025.

5.5. Baseline Comparison and Quantitative Case Evidence

To strengthen the practical impact of the case study beyond a qualitative ranking, we report quantitative energy and charging capacity indicators derived from the technical survey and compare them with simple baseline siting logics. Under the realistic-loss assumption (35%), the four PV-scalable sites (UFJF, Bus Station, Benfica–CEU, and Serrinha Airport) sum to approximately 802.97 MWh/month of PV generation potential, of which Serrinha alone accounts for ~74.76%, the Bus Station for ~19.52%, UFJF for ~3.61% and Benfica–CEU for ~2.11%. In charging-equivalent terms, the same distribution holds (≈702.5 full charges/day in total), with Serrinha (~74.88%) and the Bus Station (~19.50%) dominating short-term service capacity.

Baseline A (PV-only): if sites were selected purely by PV generation potential (kWh/month), the resulting order would be Serrinha Airport > Bus Station > UFJF > Benfica–CEU > Halfeld, which matches the top part of the GIS–MCDA ranking. Baseline B (mobility-only): if sites were selected purely by urban flow/accessibility, the order would shift toward centralities and terminals (Halfeld ≈ Bus Station > UFJF > Benfica–CEU > Serrinha). The integrated GIS–MCDA pipeline reconciles these competing logics by penalising large-scale PV infeasibility in dense areas (Halfeld) while preserving high-service hubs (Bus Station) and future-ready expansion potential (Serrinha).

Sensitivity results (reported in Section 4.5) support the robustness of these conclusions: the Top-3 set remains stable across thematic scenarios and weight perturbations, while the lower positions are more governance-dependent. This provides planners with a clear interpretation: investment in Serrinha and the Bus Station is robust, whereas choosing between a community hub (Benfica) and a central service point (Halfeld) depends on whether equity/capillarity or central convenience is prioritised.

5.6. SoC-Oriented Operational Layer (Framework Applied to Site Profiles)

The SoC-oriented operational layer is used here as a bridge between the location result and service design and operation decisions (Section 4.6). In high-turnover, higher-power hubs (Bus Station and Serrinha), prioritisation by criticality (e.g., SoC < 20%) and preference for DC service reduce the risk of long queues and improve turnover, while the presence of large-scale PV and the possibility of BESS enable peak mitigation strategies and increase service predictability [1,2,9].

On the UFJF campus, where long-term profiles and recurring demand coexist, the SoC logic can support a hybrid AC + DC operation and, additionally, serve as a basis for instrumentation and testing of energy dispatch and charging governance strategies, maintaining consistency with PV + BESS architectures discussed in recent literature [1,2]. For Benfica, with a more predictable profile and light loads, simple scheduling policies and AC predominance tend to be sufficient, while Praça Halfeld consolidates itself as a support point with a focus on fast service and routing to nearby hubs when the criticality of autonomy requires DC service.

Finally, in the future-ready horizon, integration with eVTOL-ready requirements reinforces the need for phased planning and coordination with electrical infrastructure, since power and reliability envelopes may exceed the standard for ground recharging, requiring more rigorous governance and peak mitigation strategies [6,7].

6. Discussion

6.1. What Drives the Ranking (Quantitative Interpretation)

The WLC scores show that Serrinha Airport (0.725) and the Bus Station (0.697) form a clear high-priority tier, while UFJF (0.538) is a secondary but still high-priority option, and Benfica–CEU (0.339) and Halfeld Square (0.325) fall into the medium-priority tier. This separation is not merely descriptive: the PV-only baseline indicates that ~94.3% of the total PV generation potential among scalable sites is concentrated in Serrinha (~74.8%) and the Bus Station (~19.5%), which explains why the integrated model consistently keeps them in the Top-2. UFJF remains competitive despite lower PV scale because it scores well on urban-flow/intermodality and has favourable implementation conditions for a pilot AC + DC configuration. Conversely, Halfeld Square has very high urban flow but is structurally penalised by shading and limited usable area, making it more suitable as a central service point rather than a large PV-powered hub.

6.2. Robustness and Modelling Dependence

Sensitivity analysis indicates high ordinal robustness for strategic investment decisions: the Top-3 set (Serrinha, Bus Station, UFJF) remains stable across thematic scenarios and weight perturbations (±10% and ±20%), with Spearman correlations ranging from $\rho = 0.90$ to $\rho = 1.00$. The main modelling dependence appears in the lower tier, where Benfica–CEU and Halfeld can swap positions depending on whether planners emphasise capillarity/equity (community-oriented AC charging) or central convenience (high-flow service point).

Importantly, the first position only becomes sensitive under strong de-emphasis of PV deployment capacity (usable area/solar feasibility), which provides a clear planning interpretation: if policy goals prioritise energy autonomy and future-ready expansion, Serrinha remains the anchor; if the primary goal is immediate high-turnover service in the densest core, the Bus Station becomes comparatively stronger.

6.3. Limitations and Proxy Risks (Critical Appraisal)

Two limitations affect reliability and generalisability. First, urban flow and grid access were implemented as proxies due to data constraints. While they are face-valid for early-stage screening, they may bias results toward certain site typologies (terminals, campuses, airports). We mitigate this by (i) reporting proxy construction explicitly, (ii) testing robustness via sensitivity scenarios, and (iii) comparing against PV-only and mobility-only baselines. Second, the case study evaluates five pre-selected candidate sites rather than performing a city-wide exhaustive search. This choice supports practical planning discussions but limits claims about optimality. Future work should integrate primary mobility datasets (traffic counts/GTFS) and utility network data (feeders/substations and available capacity) and extend the search to a wider candidate set to validate and refine the proposed suitability surfaces.

6.4. Planning Implications and Phased Roadmap

From a governance perspective, the results support a phased deployment strategy. Phase 1 prioritises PV + EV charging implementation at the Bus Station (high-turnover DC focus) and UFJF (hybrid AC + DC pilot), complemented by Benfica–CEU as a community AC hub and Halfeld as a central service point. Phase 2 introduces smart charging and, where required, BESS-enabled peak shaving at high-power hubs to protect distribution constraints. Phase 3 consolidates Serrinha as the future-ready/eVTOL-ready core, in line with vertiport electrical infrastructure requirements and the need for high power and reliability. The sensitivity results provide planners with an explicit interpretation of when priorities become stakeholder-dependent, enabling transparent negotiation between energy autonomy, service convenience and equity.

7. Conclusions, Limitations, and Future Work

In terms of contribution, the study advances beyond prior GIS–MCDA siting work by explicitly integrating an eVTOL-ready criterion into the decision hierarchy and by translating suitability outputs into a phased roadmap and an operational design layer. The pipeline (criteria/proxy specification, AHP/WLC aggregation and robustness reporting) is transferable to other medium-sized cities; however, the resulting scores, thresholds and site-level recommendations are case-specific and should be recalibrated with local mobility and grid datasets.

This article investigated where and how to prioritise urban locations in Juiz de Fora (MG) to implement, in the short term, integrated photovoltaic (PV) + electric vehicle (EV) charging infrastructure and, in the medium term, establish a future-ready/eVTOL-ready trajectory, supported by a transparent GIS–MCDA pipeline (AHP/WLC), sensitivity analysis, and a conceptual layer of operational design. The results consolidated a prioritisation map and a ranking for five representative alternatives (UFJF, Praça Halfeld, Bus Station, Benfica–Praça CEU and Aeroporto da Serrinha), as well as guidelines for phased implementation and governance implications [1,3,4,6,7,9].

7.1. Summary of Key Findings and Answers to Research Questions

RQ1—Most relevant criteria. Location prioritisation proved to be dependent on a coherent set of technical, urban and environmental criteria, operationalised in layers and proxies: solar potential/exposure, usable area, shading, urban flow, grid access plausibility, urban/environmental restrictions and intermodality/expansion readiness (eVTOL-ready)**.** In practical terms, the results indicate that the feasibility of integrated hubs is dominated by physical implementation capacity (area/spatial continuity) and shading limitations, while flow and intermodality differentiate locations with a vocation for high-turnover service, and grid access acts as a plausibility filter for rapid recharging and expansion [1,3,9].

RQ2—Translation of criteria into ranking and implementation scenarios. The WLC score and the resulting ranking revealed two main profiles: (i) larger-scale, higher-power hubs and (ii) alternatives with territorial capillarity and a longer permanence profile. Based on the calculated scores, Serrinha Airport (0.725) and Bus Station (0.697) had the highest priority, followed by UFJF (0.538), while Benfica–Praça CEU (0.339) and Praça Halfeld (0.325) comprised the intermediate priority range. In terms of scenarios, Bus Station and Serrinha concentrate conditions for fast DC charging and large-scale implementation; UFJF supports a hybrid model (predominantly AC with complementary DC) and a pilot and monitoring vocation; Benfica favours an AC community hub; and Halfeld consolidates itself as a central service point, with dependence on the grid and specific PV solutions due to area limitations and shading.

RQ3—Effect of the eVTOL-ready requirement on the understanding of locational suitability. The explicit introduction of the eVTOL-ready criterion changed the understanding of the "best location" by shifting part of the priority to sites with spatial continuity, low obstruction, expansion capacity, and modal integration, in line with the requirements discussed for vertiports and UAM infrastructure. In this sense, Serrinha Airport emerges as an alternative that is more in line with the future-ready concept, suggesting that the city can reduce transition risk and cost by planning hubs whose terrestrial implementation (PV + EV) is useful in the short term and whose morphology is compatible with more restrictive requirements in the medium term.

7.2. Contributions and Practical Implications

The contributions of the article materialise on three levels: (C1) a reproducible GIS– MCDA pipeline with explicit criteria/proxies, standardisation and aggregation by WLC; (C2) a technical-territorial comparison of the five sites with ranking, energy evidence and systemic function (short and medium term); and (C3) the proposal of an operational layer (SoC-oriented framework, AC/DC mix and trigger for BESS), which connects location prioritisation to service performance without shifting the focus of the article to internal battery modelling.

From an implementation perspective, the results indicate a coherent strategy for mediumsized cities: combining a few large-scale hubs (Bus Station/Serrinha) with capillarity points (UFJF/Benfica) and central service (Halfeld), under phased and interoperable governance. For concessionaires and public policy makers, this implies coordinating urban planning, licensing, and electrical upgrades with service level targets, mitigating the risk of peaks and queues at DC hubs, and preparing the territory for future-ready evolution.

7.3. Limitations

We reiterate that the urban flow and grid access indices are proxies (not direct measurements of demand or feeder capacity). Face-validity checks were performed by comparing proxy patterns with known centralities, mobility corridors and infrastructure typologies in the city; however, future replications should validate these proxies using traffic counts/GTFS and utility network datasets.

This study has limitations typical of preliminary location analyses: (i) the urban flow and grid access proxies were constructed for reproducibility with accessible data, but can be refined with primary data (traffic counts, GTFS, network and feeder data, substations, and available capacity); (ii) the map classification and priority thresholds depend on the granularity and quality of the layers and the choice of discretisation; (iii) the operational layer was presented as a framework, without detailed stochastic simulation of queues and arrival profiles, which limits quantitative inferences about average waiting times in different scenarios. Nevertheless, the proposed pipeline is transparent and allows for incremental evolution with richer data.

7.4. Future Work

As a continuation, it is recommended to: (a) integrate empirical mobility data (counts, ticketing, GTFS, telemetry) to calibrate the urban flow proxy; (b) incorporate more detailed electrical layers (feeders, substations, capacity, and reinforcement costs) to make the grid access criterion more accurate; (c) running operational simulations (arrivals, power, queue, BESS) and reporting metrics such as average waiting time, utilisation, and energy delivered; (d) expanding the study to multiple medium-sized cities and conducting inter-municipal comparative analysis; and (e) further developing the eVTOL-ready module with regulatory and safety requirements as international guidelines and practices evolve.

In summary, the article demonstrates that a GIS–MCDA approach with methodological transparency, sensitivity, and phased planning can support integrated PV + EV infrastructure decisions and prepare medium-sized cities for a future-ready transition, reducing investment risk, improving territorial coherence, and laying the groundwork for phased expansion towards electric air mobility.

Author Contributions

All authors contributed equally to the conception, development, analysis, and writing of the work, having participated equivalently in all stages of the research. All authors have read and approved the final version of the manuscript and agree to its submission and publication, taking full responsibility for the content presented.

Data Availability Statement

The data will be made publicly available by mid-July, when one of the authors, Vitor Silva Coimbra, defends his master's dissertation. His work will be fully accessible in the dissertation repository of the Federal University of Juiz de Fora (UFJF).

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Appendix A. Simplified AHP Pairwise Comparison Matrix (Rounded Saaty Scale)

The Table A1 below presents a simplified AHP pairwise comparison matrix for the seven criteria (C1–C7) used in the GIS–MCDA. Rows and columns correspond to criteria, and each entry aija_{ij}aij indicates how much more important criterion CiC_iCi is than criterion CjC_jCj, based on the Saaty fundamental scale. Values equal to 1 indicate equal importance; values greater than 1 (e.g., 2, 3, 5, 7, 9) indicate increasing strength of preference for CiC_iCi over CjC_jCj (from weak/moderate to very strong/extreme); and values less than 1 are shown as reciprocals (e.g., 1/2, 1/3, 1/5) indicating that CiC_iCi is less important than CjC_jCj. The diagonal entries are 1 and the matrix is reciprocal, i.e., aji = 1/aija_{ji} = 1/a_{ij}aji = 1/aij. This matrix was derived from the final weight vector by approximating the ratios wi/wjw_i/w_jwi/wj to the nearest Saaty scale value, and it is provided to improve transparency and reproducibility of the weighting step prior to the WLC aggregation.

Table A1. Simplified AHP pairwise comparison matrix for criteria C1–C7, based on the rounded Saaty scale.

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
C1	1	1/3	1/2	1	1/2	1	1/2
C2	2	1	2	2	2	2	2
C3	1	1/2	1	1	1	1	1
C4	1	1/3	1/2	1	1/2	1	1/2
C5	1	1/2	1	1	1	1	1
C6	1	1/3	1/2	1	1/2	1	1/2
C7	1	1/2	1	1	1	1	1

Source: Prepared by the authors, 2025.

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