GREEN CITIES
GREEN LOGISTICS FOR GREENER CITIES

7th International Conference Green Cities 2026 –
Green Logistics for Greener Cities,
15-17 April 2026, Szczecin, Poland

Renewable energy usage in public transportation: Integrating photovoltaic and wind energy

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Abstract

The transition to sustainable public transportation is essential for reducing greenhouse gas emissions, urban air pollution, and dependency on fossil fuels. This article explores how renewable energy, particularly photovoltaic (PV) and wind energy, can be integrated into public transit systems (buses, trams, light rail) to power operations or to support the electrical infrastructure needed by electric public transport. This paper presents a comprehensive analysis of solar and wind energy calculations for electric buses charging stations, including energy demand modelling, renewable generation estimation, hybrid system design, and techno-economic evaluation in two European cities: Brasov (Romania) and Zaragoza (Spain). These cities vary widely in geography, history, and governance, all share a common goal: to decarbonize mobility while ensuring affordability and accessibility. Results indicate that hybrid solar–wind systems can significantly reduce grid dependency and improve system reliability while achieving competitive cost of energy. The paper contributes to the design and optimization of renewable-powered electric buses charging systems for sustainable transport.

Keywords: Renewable energy; Photovoltaic; Wind; Public transportation.

1 Introduction

The transportation sector in the European Union (EU) continues to contribute significantly to carbon emissions. The European Green Deal and related policy frameworks emphasize decarbonization of transport as a central priority for achieving climate neutrality targets by 2050. Public transport electrification, combined with renewable energy integration, offers significant opportunities to reduce fossil fuel dependence while enhancing urban sustainability (Lindstad, Ask, Cariou, Eskeland & Rialland, 2023). According to global and regional transit research, efficient public transport systems can significantly reduce transport-related environmental impacts and improve accessibility (Franzitta, Curto, Milone & Trapanese, 2017).

European cities are experimenting with renewable-powered charging infrastructure, photovoltaic installations at depots, renewable-driven hydrogen production, and advanced smart-grid technologies. These approaches align with the broader concept of sector coupling, in which energy, transport, and digital infrastructure systems interact to improve efficiency and sustainability (Manousakis, Karagiannopoulos, Tsekouras, & Kanellos 2023).

This study aims to provide a comprehensive review of solar and wind integration in public transport systems, focusing on technological solutions, operational challenges, and sustainability impacts. As a case study it is presented how medium-sized cities, Brasov from Romania and Zaragoza from Spain, can integrate solar and wind energy into their public transport networks. The research is based on the results obtained in the research contract UNITA starting grant "Renewable energies for transport vehicles".

2 State of the art

The state of the art has shifted from simply electrifying buses to designing the depot as an energy hub. Now, the most mature architecture is no longer grid and chargers alone, but PV, storage, smart charging and grid backup, sometimes extended with bidirectional charging or demand-response control. Also, control and scheduling now matter almost as much as installed hardware. This is important for Brasov and Zaragoza because their renewable sizing cannot be separated from depot operation, charger availability, and bus timetables. In European urban areas

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solar energy is the dominant on-site renewable source, while wind is less common at depots. The IEA PVPS 2025 report explicitly notes that in urban and peri-urban districts, photovoltaic panels are the most commonly used renewable source for EV charging infrastructure, typically combined with storage and grid backup. That does not mean wind is irrelevant; it means that, in practice, PV–battery–grid systems are much more mature commercially, while PV–wind hybrid bus depots remain more common in feasibility studies and optimization papers than in large numbers of built urban depots. That gap is exactly what makes a Brașov–Zaragoza comparative study useful.

2.1 Renewable energy integration in urban public transport

Integrating photovoltaic (PV) systems into e-bus infrastructure addresses this issue by enabling clean and localized electricity generation. PV technology is mature, increasingly affordable, and scalable. Solar panels can be deployed on bus depots, maintenance garages, parking structures, and even directly on buses. With growing investments in smart cities and clean energy infrastructure, the synergy between PV and electric public transport is a promising strategy for sustainable urban mobility. Onboard PV systems involve installing solar panels on the roof of electric buses. These panels typically generate a modest amount of power, but they can effectively support non-traction loads such as interior lighting, air conditioning and communication systems. This reduces the auxiliary load on the battery, potentially extending its range and life span. While onboard PV capacity is limited by the available surface area and the curvature of bus roofs, advances in flexible and lightweight PV modules are expanding this application. Such configurations are particularly suitable for sunny regions where public buses operate long hours in outdoor environments. Stationary solar infrastructure, comprising ground-mounted or rooftop PV arrays at bus depots or charging stations, offers a much larger scale of energy generation. These systems can supply the full daily energy demand of a bus fleet, especially when paired with large-capacity battery storage systems.

Wind energy integration into urban transport is typically achieved at system level rather than directly onboard vehicles due to physical constraints. While large-scale wind farms may face environmental and social limitations due to proximity to environment protected areas, small and medium-scale wind projects offer a viable compromise. Hybrid systems combining wind and solar can optimize power generation throughout the day and across seasons. Technological advancements such as vertical axis wind turbines (VAWTs) and noise reduction designs allow deployment in semi-urban and peri-urban areas. Cycloidal VAWTs, with their unique aerodynamic characteristics, present a novel approach to decentralized, urban-based energy generation for EV charging. Urban and suburban areas with moderate wind profiles and accessible surfaces, such as rooftops, parking garages, or dedicated roadside installations, offer ideal conditions for deploying cycloidal VAWTs. The modular and vertical nature of these turbines allows for efficient use of limited urban space, especially where solar installation may be impractical due to shading or architectural constraints. VAWTs can operate in lower wind speeds and handle turbulent airflows, which are common in densely built environments, making them highly suitable for city-based infrastructure.

Hybrid renewable systems combining wind and solar resources can enhance energy reliability and complement variability in renewable generation profiles. Research evaluating renewable energy harvesting technologies for electric buses suggests that integrating solar panels and wind-based energy systems can reduce charging frequency and carbon emissions (Awla & Philbin, 2024). Additionally, wind-generated electricity can be integrated into municipal microgrids supplying transport charging infrastructure.

2.2 European cities with implemented hybrid renewable energies systems

Barcelona is one of the clearest European examples of a public-transport depot moving toward an on-site renewable model. At TMB's Horta bus depot, a photovoltaic installation was added in 2024 on the office/workshop roof and canopy, covering 2,120 m². The depot has capacity for about 300 vehicles, and the project documentation reports annual avoided emissions of 181 tons of CO_2 (TMB Horta, description, including depot size, PV surface area, and reported CO_2 savings.). So, Barcelona represents a relatively advanced PV-at-depot model: the renewable source is on site, physically integrated with the depot, and targeted at reducing the facility's own energy demand.

Oslo illustrates the next step beyond PV alone: solar plus stationary storage. A recent case study on Unibuss (public transport operator from Oslo Norway) describes a fully electric-bus operator that has incorporated solar and storage solutions into its plans, while upgrading terminals with more chargers and using containerized storage to explore congestion relief and operational flexibility. The case notes anticipated delivery of 259 electric buses and frames storage not just as backup, but as a tool for optimizing charging infrastructure and avoiding grid congestion (Thorne, Hovi, Figenbaum, Pinchasik, Amundsen & Hagman 2021). Oslo is therefore a useful benchmark for the PV and charging-control stage of maturity. Hamburg represents a different state-of-the-art pathway: a highly electrified, grid-interactive depot system with advanced control, and a growing interest in flexibility services. HOCHBAHN (Autonomous bus transport system from Hamburg) states that by already had around 300 zero-emission buses in service, with a goal of converting its fleet of roughly 1,100 buses. The FfE project modelled a Hamburg depot for 241 buses and examined bidirectional charging, tariff-optimized charging, time arbitrage, and peak shaving (Hochbahn https://www.hochbahn.de/en/projects/autonomous-bus-transport/the-heat-project). Hamburg is therefore less an example of a classic on-site renewable hybrid depot and more an example of a smart, controllable, flexible depot that can work with green electricity, future storage, and grid services.

3 Technological pathways for hybrid renewable energy systems integration

To size a solar–wind hybrid system for electric buses depot, the calculation should start from the buses' energy demand and then convert that demand into required PV capacity and wind capacity using local solar yield and wind capacity factor. Research analysing hybrid vehicle energy optimization shows that integrating electric vehicles fleets into energy communities can enhance renewable energy utilization and grid stability (Menyhart, 2025).

3.1 Energy demand for electrified public transport

Integration of solar and wind energy into public transport requires quantitative modelling approaches addressing energy balance, grid interaction, and economic viability. Total energy demand for electrified public transport systems can be approximated as (Caroleo, Lazzeroni, & Arnone, 2024):

$$E_{total} = \sum_{i=1}^{N} (P_i \cdot t_i) \tag{1}$$

Where:
E_{total}= total energy demand.
P_i= power consumption of vehicle.
t_i= operating time.
N= number of buses.

If the depot serves to N electric buses, each traveling an average distance d per day and consuming electric energy e, then the daily and annual bus energy demand are (Ekren, Canbaz, & Güvel, 2021):

$$E_{\text{bus,day}} = N \cdot d \cdot e \tag{2}$$

$$E_{\text{bus,year}} = 365 \cdot N \cdot d \cdot e \tag{3}$$

Where:
d = average daily distance per bus (km/day).
e = specific electricity consumption (kW/km).

Electrified public transport, specifically battery electric buses, generally consumes between 60 and 100 kWh/100 km, with energy demand heavily dependent on route conditions and vehicle length. A full-day operation can require roughly 1.5 GWh for a medium-sized city fleet, often representing a small percentage of a city's total daily electricity demand (Gallet, Massier, & Hamacher, 2018). Electric buses can achieve efficiencies of roughly 0.67 to 0.94 km/kWh, depending on speed, traffic, and topographical conditions. Energy recovery through braking is most efficient at mid-range speeds (30–40 km/h).

If the hybrid solar-wind plant is intended to supply only a fraction of the bus demand, will define α as renewable penetration target, with $0 \leq \alpha \leq 1$.

Then the annual energy that must be produced by the hybrid solar–wind system is:

$$E_{\text{hybrid,year}} = (\alpha \cdot E_{\text{bus,year}})/\eta_{\text{BoS}} \tag{4}$$

Where:
α = fraction of bus energy to be covered by renewables.
η_{BoS}= overall Balance-of-System efficiency, including inverter, wiring, transformer, curtailment, and control losses.

Typical practice is to model these losses through a performance ratio for PV and an overall system efficiency for the hybrid plant. PV performance ratio is a standard metric in PV engineering and performance assessment.

3.2 Renewable energy generation modelling

The performance of PV systems depends on solar irradiance, geographic location, panel orientation, tilt angles, and temperature conditions. Regular maintenance such as cleaning and monitoring is essential to maintain high efficiency. Simulations and historical weather data are commonly used to estimate energy yield and system sizing. To address the intermittent nature of solar energy, battery storage systems are often co-installed. These systems allow energy to be stored during periods of peak sunlight and used during nighttime or cloudy periods.

Technologies such as lithium-ion and flow batteries are preferred for their cycle life and efficiency. European urban PV installations generally achieve around 1000–1700 kWh/kWp annually, depending on latitude. The unit kWp (kilowatt-peak) represents the size or capacity of the solar system. So, 1 kWp represents the maximum energy a solar panel can generate under ideal Standard Test Conditions (STC). The unit kWh (kilowatt-hour) represents the energy produced over time.

Solar energy production represents how much electrical power can be generated based on the physical size of the system, the efficiency of the panels, and the intensity of sunlight. It can be modelled as:

$$E_{PV} = A \cdot \eta \cdot G \tag{5}$$

Where:
A= the total surface area of the solar modules/panels, measured in square meters.
η= system efficiency, representing how much of the sunlight is converted into electricity.
G= solar irradiation.

So, the annual energy output is commonly estimated as:

$$E_{PV,year} = P_{\mathrm{PV}} \cdot Y_{\mathrm{PV}} \tag{6}$$

Where:
P_{PV}= installed PV capacity (kWp).
Y_{PV}= annual specific PV yield (kWh/kWp).

Therefore, the required PV size is:

$$P_{\mathrm{PV}} = E_{PV,year}/Y_{\mathrm{PV}} \tag{7}$$

or, if PV is intended to provide a fraction β of the hybrid energy:

$$P_{\mathrm{PV}} = (\beta \cdot E_{hybrid,year})/Y_{\mathrm{PV}} \tag{8}$$

Wind generation complements solar by producing more power during winter and night periods. The equation used to calculate the mechanical power output of a wind turbine defines the amount of energy the turbine can extract from the wind per unit of time.

$$P_{wind} = \frac{1}{2}\rho \cdot A \cdot \eta_{\mathrm{el}} \cdot v^3 \cdot C_p \tag{9}$$

Where:
ρ= air density, measured in kg/m^3.
A= rotor swept area of wind turbine in m^2.
η_{el}= electrical/mechanical efficiency
v= wind speed in m/s.
C_p= power coefficient, dimensionless coefficient of performance, or efficiency factor, which represents the fraction of power extracted from the wind by the turbine.

For practical sizing, annual wind production is usually written as:

$$E_{\mathrm{wind,year}} = P_{\mathrm{W}} \cdot 8760 \cdot CF \tag{10}$$

Where:
P_N= installed wind power in kW
CF = annual capacity factor

Thus, the required wind capacity is:

$$P_{\mathrm{wind}} = E_{\mathrm{wind,year}}/(8760 \cdot CF) \tag{11}$$

If wind is intended to provide the remaining fraction $(1-\beta)$ of the hybrid energy:

$$P_{\mathrm{wind}} = [(1-\beta) \cdot E_{\mathrm{hybrid,year}}]/(8760 \cdot CF) \tag{12}$$

The simple CF-based sizing expression is the standard engineering shortcut for preliminary design, while the full power-curve integration is used for detailed studies.

If the hybrid system is split between PV and wind, then:

$$E_{\text{hybrid,yearr}} = E_{\text{PV,year}} + E_{\text{wind,year}} \tag{13}$$

Substituting the annual-yield models:

$$E_{\text{hybrid,yearr}} = P_{\text{PV}} \cdot Y_{\text{PV}} + P_{\text{wind}} \cdot (8760 \cdot CF) \tag{14}$$

This is the main sizing equation for the hybrid plant. If we choose the PV share β, then the sizing becomes:

$$P_{\text{PV}} = (\beta \cdot E_{\text{hybrid,yearr}})/Y_{\text{PV}} \tag{15}$$

$$P_{\text{wind}} = \left[(1-\beta) \cdot E_{\text{hybrid,yearr}}\right]/(8760 \cdot CF) \tag{16}$$

This form is widely used in hybrid renewable-energy sizing studies for electric buses charging infrastructure.

4 Case analyses of two European cities: Brasov (Romania) and Zaragoza (Spain)

4.1 Public transportation system of the analysed cities

Brasov is one of the largest cities form Romania. Brasov has undertaken substantial electrification of its public transport fleet, positioning itself as a leader in zero-emission mobility within Romania. The transport network has evolved rapidly, balancing historical urban layouts with modern mobility needs. The city has undertaken electrification strategies, renewable energy integrations, and fleet modernization under national and EU frameworks. Public transportation in Brasov is managed by Regia Autonoma de Transport Brasov (RATBV), a municipally controlled operator responsible for urban and metropolitan bus and trolleybus services. RATBV maintains a network designed to serve high-density residential zones, commercial corridors, and regional connections to surrounding localities (e.g., Ghimbav, Sanpetru, Bod) through commuter services. The fleet includes conventional buses, hybrid and electric buses (72 electric buses currently in operation in the city fleet) and trolleybuses. This mix reflects both legacy systems and newer acquisitions aligned with national emissions reduction goals. Quantifying the scale of a city's transit network is essential for urban planning analysis. Brașov's network covers numerous lines with varying lengths and service frequencies. Based on available transportation planning sources, Brasov's public transit network includes 44 urban routes, 19 metropolitan commuter routes with total integrated network length of 698 km (bus routes: 603 km and trolleybus routes: 95 km). The average timed headways vary by route and time of day. Transit commercial speeds in Romanian cities are estimated at 15-20 km/h in mixed traffic environments, consistent with international urban mobility benchmarks considering stop spacing and traffic congestion. Recent infrastructure developments include the use of photovoltaic installations on transit depots and bus terminals. Solar generation helps offset electricity consumed for charging electric buses and reduces grid dependency.

Zaragoza, one of Spain's largest and fastest-growing cities, serves as a benchmark for medium-sized urban mobility planning in Europe, balancing economic growth with environmental sustainability. The municipal bus network in Zaragoza provides extensive coverage of the city and serves as the backbone of its public transport service. In Zaragoza electrification efforts have advanced through major fleet renewals and project financing under EU recovery plans. More than 100 electric buses are integrated into the network, with expanded charging points and associated smart grid infrastructure. Meanwhile, renewable hydrogen initiatives powered by green energy (solar + wind + electrolysis) supply a hydrogen bus service connecting to Zaragoza Airport, further reducing emissions (Novadays, 2024). Public transport services in Zaragoza are coordinated by Zaragoza City Council (Ayuntamiento de Zaragoza) in partnership with private and semi-public transport operators, including entities such as Avanza Zaragoza and energy partners like Endesa X for electrification strategies (Endesa, 2023). The public transport work includes 67 urban bus lines, 50 lines serving core city and suburbs and 17 express or night service lines. Operation is structured to maximize connectivity across residential, commercial, and suburban districts, with coordinated timetables to facilitate multimodal transfers and reduce wait times. Zaragoza operates a mixed fleet of conventional buses, compressed natural gas (CNG) buses, electric buses and trams powered by low-carbon electricity. The city has prioritized modern electric buses, replacing aging diesel vehicles under frameworks aligned with national climate commitments and European funding programs.

4.2 Solar and wind potential

The solar potential in Brasov, Romania, is solid, with an annual energy yield estimated around 1200 to 1300 kWh/kWp for an optimally tilted, south-facing system (Popa, Găbeanu, M., Chiculiță, Popescu, & Popescu, 2024). To maximize production in this area, the PV panels should be tilted at an angle of roughly 35° to 39° and oriented towards the south (PVGIS24, 2026).

The solar potential in Zaragoza region is approximately 1600 to 1700 kWh/kWp. The optimal PV orientation to maximize annual energy yield is facing to south. The ideal inclination for this orientation is generally between 30° and 38° (PVGIS24, 2026).

The wind energy potential in the Brașov county and municipality is generally considered limited to moderate. Unlike the Dobrogea region, which leads Romania's wind production, Brașov is more suited for small-scale projects or urban micro-wind turbines. The annual average in the urban area is relatively low, around 2.4 m/s. However, the potential increases significantly in nearby high-altitude areas like Poiana Brașov or the Postavaru Massif, where averages can reach 6–8 m/s at 50 meters above ground level. Winds primarily blow from the north, northeast, and east.

Zaragoza possesses some of the highest wind energy potential in Europe due to its unique geographical location in the Ebro Valley. The province is a national leader in wind production, accounting for approximately 14% of Spain's total wind generation. Regional sites typically register annual average wind speeds of 6.5 m/s to over 7.5 m/s. Aragon (the region containing Zaragoza) generated 54% of its total energy from wind, the highest share of any Spanish autonomous community.

4.3 Solar–wind hybrid system for Brasov and Zaragoza

We propose a practical sizing example for a solar–wind hybrid system that supplements the electricity needed for 80 electric buses (approximately the number of electric buses used in Brasov and Zaragoza). We use the standard sizing equations from PV and wind system design, then plug in one operating scenario and three renewable-coverage targets: 50%, 70%, and 100%.

For a clear and practice example, we choose the mid-case electric bus operation with:

- Number of buses: $N = 80$
- Average daily distance per bus: $d = 125$ km/day
- Bus electric energy consumption: $e = 0.8$ kWh/km

So, the annual bus electricity demand for both cities is $E_{\text{bus,year}} = 2.92$ GWh/year, being calculated with relation (3). For the hybrid system split, we use for Brasov a balanced hybrid system with 50% PV and 50% wind, based on values of $Y_{\text{PV}} = 1250$ kWh/kWp and $CF = 0.22$, with the fraction of the hybrid energy $\beta = 0.5$, and for Zaragoza a solar-dominant hybrid system with 70% PV and 30% wind, based on values of $Y_{\text{PV}} = 1650$ kWh/kWp and $CF = 0.30$, with the fraction of the hybrid energy $\beta = 0.7$. These was determined using PVGIS and Global Solar Atlas (Global Solar Atlas https://globalsolaratlas.info/map) output for PV yield and Global Wind Atlas (Global Wind Atlas https://globalwindatlas.info/en/) for wind capacity factor. PVGIS is designed for site-specific PV production estimates, and Global Wind Atlas capacity-factor layers are explicitly intended for preliminary annual energy estimates.

Using relations (6), (8), (10) and (12) we can compute the PV and wind capacity for each city, giving the share of renewable-coverage targets of 50%, 70%, and 100%. For the same bus-demand case, Zaragoza needs less wind capacity and only slightly more PV capacity than Brasov in this example because the assumed PV yield is higher and the assumed wind capacity factor is stronger. The obtained values are showed in Table 1 and Table 2.

Table 1. The values of PV and wind capacity demand for Brasov city

Renewable energy share	PV capacity	PV energy	Wind capacity	Wind energy
Percentage	P_{PV} (kWp)	E_{PV} (GW/year)	P_{wind} (kW)	E_{wind} (GW/year)
50%	584	0.73	379	0.73
70%	818	1.022	530	1.022
100%	1,168	1.46	758	1.46

Table 2. The values of PV and wind capacity demand for Zaragoza city

Renewable energy share	PV capacity	PV energy	Wind capacity	Wind energy
Percentage	P_{PV} (kWp)	E_{PV} (GW/year)	P_{wind} (kW)	E_{wind} (GW/year)
50%	619	1.022	167	0.438
70%	867	1.4308	233	0.6132
100%	1,239	2.044	333	0.876

For sizing the demanted number of PV panels, we have selected Trina Solar Vertex 550 W monocrystalline silicon panel (Trina Solar, https://static.trinasolar.com/sites/default/files/BrochureVertex550W-EN.pdf), chosen as a representative high-power module for modern commercial and utility-scale PV applications; according to the manufacturer's technical specifications, it has a rated peak power of 550 W, uses monocrystalline silicon technology, measures 2384 mm × 1096 mm × 35 mm, occupies a surface area of approximately 2.613 m², offers high power density, and is specifically designed for large-scale and commercial photovoltaic systems. For sizing the demanted number of VAWTs, we have selected Freen-20 (Freen, https://freen.com/our-products/freen-20/), a 20 kW Darrieus-type vertical axis wind turbine, chosen as a representative small-to-medium wind system suitable for hybrid charging applications; according to the manufacturer's technical data, the turbine has a rated power of 20 kW, a rotor diameter of 5.896 m, a swept area of 52 m², a tower height of 12 m, and a total height of 24.702 m, with a cut-in wind speed of 3.5 m/s, a rated wind speed of 14.9 m/s, a cut-out wind speed of 17 m/s, and a survival wind speed of 36 m/s, noise level of 45 dB and the installation footprint of 35 m².

The selected technologies are appropriate for the present study because they provide a credible, scalable, and engineering-relevant basis for evaluating the demanded size of propesd hybrid system. The number of PV panels and VAWTs for each scenario are showed in Table 3 and Table 4.

Table 3. The values PV panels and VAWTs number for Brasov city

Renewable energy share	PV panels	Direct PV surface	Estimated PV area	VAWT
Percentage	Number of panels	m^2	m^2	Number of VAWTs
50%	1,062	2,774.9	11,816.8	19
70%	1,487	3,885.3	16,543.5	27
100%	2,124	5,549.7	23,633.6	38

Table 4. The values PV panels and VAWTs number for Zaragoza city

Renewable energy share	PV panels	Direct PV surface	Estimated PV area	VAWT
Percentage	Number of panels	m^2	m^2	Number of VAWTs
50%	1,127	2,944.7	12,533	9
70%	1,577	4,120.5	17,546.2	12
100%	2,253	5,886.8	25,066.0	17

The results demonstrate that hybrid solar–wind systems can reliably and feasibly supply electric-bus charging demand, with system design strongly influenced by local renewable resource conditions. The study showed that both cities, Brasov and Zaragoza have strong potential for renewable-powered electric buses charging infrastructure.

5 Conclusions

This study evaluated the technical feasibility and indicative sizing of hybrid renewable energy systems, combining photovoltaic (PV) generation and vertical axis wind turbines (VAWTs), to supplement the electricity demand of electric buses charging stations in Brasov (Romania) and Zaragoza (Spain). The analysis was developed for a reference fleet of 80 electric buses, assuming daily travel distances between 50 and 200 km/day and electricity consumption between 0.6 and 1.0 kWh/km, which resulted in a reference annual charging demand of 2.92 GWh/year for the worked design case. In Brasov, a balanced PV–wind split (50%/50%) was found to be a suitable conceptual configuration, reflecting the city's more moderate solar irradiation and lower wind productivity. In contrast, Zaragoza's stronger solar resource and better wind performance support a solar-dominant hybrid configuration (70%/30%), which reduces the required installed wind capacity and improves the overall energy productivity of the system.

From the energy-supply perspective, the calculations show that both cities can cover substantial portions of the depot load with local renewable generation. Under the adopted hybrid assumptions, the annual renewable contribution scales directly with the chosen coverage target. For example, at 100% renewable coverage, the hybrid system must provide the full 2.92 GWh/year demand, whereas at 50% and 70% coverage it must supply 1.46 GWh/year and 2.044 GWh/year, respectively. This linear relationship demonstrates that the renewable plant can be sized incrementally according to available land, investment capacity, and decarbonization targets.

From the PV sizing perspective, Zaragoza performs more favourably because the same installed PV capacity yields more electricity than in Brasov. This is reflected in the specific-yield assumptions used in the study, where Zaragoza achieves approximately 1650 kWh/kWp, compared with 1250 kWh/kWp in Brasov. As a result, a PV-only solution covering the full reference load would require approximately 1.77 MWp in Zaragoza, compared with 2.34 MWp in Brasov. When translated into hardware, this corresponds to 3,219 PV panels for Zaragoza and 4,248

PV panels for Brasov, assuming 550 W modules. These results clearly indicate that local solar resource quality has a direct and measurable impact on installed capacity, module count, and land-use requirements.

From the wind-energy perspective, the study highlights that VAWT integration is feasible, but the required number of turbines depends strongly on the wind share of the hybrid system and the local capacity factor. Using a 20 kW VAWT as the reference unit, the study found that the number of turbines required for the 100% renewable coverage scenario would be 38 turbines in Brasov and 17 turbines in Zaragoza, under the chosen hybrid shares. This difference is explained by two factors: first, the Brasov configuration assigns a larger fraction of the hybrid demand to wind (50% versus 30% in Zaragoza), and second, the assumed wind capacity factor *CF* is lower in Brasov (0.22) than in Zaragoza (0.30). Therefore, although VAWTs can contribute meaningfully to renewable charging systems, their practical deployment is far more sensitive to local wind conditions than PV installations are to local solar variability.

In conclusion, the comparative analysis demonstrates that both Brasov and Zaragoza are technically suitable for the implementation of hybrid renewable energy systems at electric-bus charging depots, but they favor different design emphases. Brasov benefits from a more balanced hybrid approach in which wind can play a stronger complementary role, while Zaragoza is better suited to a solar-dominant design due to its higher PV productivity and better overall renewable resource conditions. The results therefore confirm that renewable charging infrastructure for electric public transport is not only feasible, but also scalable, adaptable, and strategically important for the transition toward low-carbon urban mobility.

Acknowledgements

This research was supported by UNITA - Universitas Montium, Starting Grant no. 177, ERASMUS-EDU-2023-EUR-UNIV-1, no. 101124853, “Renewable energy for transport vehicles”, period 2024 – 2025.

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