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Dynamic 3D Solar Irradiation Modelling for Vehicle-Integrated Photovoltaics. High-Resolution Route-Based Assessment of Electric Bus Fleets Using CityGML and Distributed PostGIS Processing

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Abstract

This study presents a scalable framework for estimating solar energy yield from vehicle-integrated photovoltaics (VIPV) on electric buses in dynamic urban environments. It combines semantic 3D CityGML models, distributed PostGIS/Citus processing, CAMS solar data, and high-resolution GTFS trajectories. Direct, diffuse, and reflected radiation are calculated through ray-casting and geometry-based methods, enabling surface-specific assessment of urban shading and reflection. The framework is coupled with the VECTO vehicle energy model to evaluate PV yield against energy consumption. Results show that urban shading can reduce irradiation by more than 20%, while VIPV can cover approximately 2.8–4.1% of annual energy demand for typical electric bus operations. Prior validation using vehicle-mounted sensors confirmed that the 3D approach outperforms conventional 2.5D DSM methods. The distributed architecture supports fleet-scale simulations and integration into CityGML digital twins through Dynamizer, providing a transferable tool for sustainable mobility planning.

1. Introduction

1.1 Challenges in Solar Modelling for Moving Vehicles

Modelling solar irradiation for moving vehicles presents a unique set of challenges that distinguishes it from conventional stationary PV systems. Vehicle motion continuously changes both position and orientation, which directly affects the solar incidence on the surfaces. Unlike fixed installations, these dynamic trajectories require precise spatial tracking and orientation modelling. Temporal variability further increases the complexity, as solar position, irradiance, and atmospheric conditions fluctuate continuously, making fine temporal resolution essential to capture accurate exposure patterns. Additionally, urban environments introduce complex shading effects from buildings, trees, and other obstacles, which are highly time-dependent and necessitate 3D spatial modelling. Finally, fleet-scale simulations must manage millions of spatiotemporal observations, demanding highly efficient computation and scalable processing architectures to handle the data volume without compromising performance.

1.2 Research Contribution

This work presents a novel framework for dynamic solar irradiation modelling tailored for electric vehicle fleets. The methodology introduces high-resolution segmentation of vehicle trajectories, enabling precise calculation of orientation-dependent solar incidence along entire routes. By integrating detailed 3D urban geometry with a scalable distributed computational architecture, the framework can efficiently simulate fleet-wide energy yield while accounting for complex shading effects. The approach captures both spatial and temporal dynamics of solar exposure, providing a realistic assessment of photovoltaic potential for moving vehicles. Validation against empirical measurements demonstrates the reliability and accuracy of the model, highlighting its applicability for planning and optimizing vehicle-integrated photovoltaic systems in urban contexts (Pera et al., 2024).

1.3 Related Work

Solar irradiation modelling has been extensively studied in the context of urban environments and building-integrated photovoltaics (BIPV). Early approaches relied on raster-based digital surface models (DSM), while more recent developments utilize semantically rich 3D city models such as CityGML. These enable surface-specific irradiation estimation, including roof and facade analysis, and improved representation of shading effects.

The added value of CityGML over DSM-based representations is significant for VIPV applications. DSM-based approaches encode urban geometry as a single continuous raster surface, preventing disambiguation of semantic surface types (e.g., roof, facade, ground) and introducing resampling artefacts that degrade accuracy at sub-metre scales. In contrast, CityGML encodes surfaces as typed polygonal objects, enabling: (i) selective use of building roofs and facades for reflection analysis while excluding irrelevant ground clutter; (ii) surface-specific normal vectors without interpolation; (iii) direct assignment of albedo per semantic surface type; and (iv) storage of per-surface simulation results suitable for digital twin integration. Prior validation work confirmed that a 3D CityGML-based simulation approach showed better agreement with vehicle-mounted irradiance sensor measurements than a 2.5D DSM-based model along the same route and under identical radiation inputs, with residual underestimation primarily attributed to local albedo effects and GPS positional mismatch (Pera et al., 2024).

Comparative studies of solar simulation tools demonstrate that vector-based approaches using CityGML provide higher accuracy and flexibility, particularly for complex urban geometries (Giannelli et al., 2022). Furthermore, the integration of temporal dynamics into semantic 3D city models has been explored through the concept of Dynamizers (Chaturvedi et al., 2017). Dynamizers are CityGML constructs that attach time-varying attribute values to specific city objects — for instance, associating a time-series of irradiation values or energy surplus with a building facade or a moving vehicle object. In the context of this framework, per-segment irradiation results and trip-level energy contributions could be written back into CityGML as `DynamizerType` elements linked to the relevant surface geometry, producing self-contained digital twin artefacts that co-locate geometry, semantics, and temporal energy data. While the full round-trip embedding of simulation outputs into CityGML is identified as a direction for future implementation, the framework produces outputs structured to be compatible with this approach. Recent work also highlights limitations of traditional DSM-based approaches, particularly in capturing facade irradiation and temporal shading, motivating extensions of the CityGML data model for energy applications (Casisirano and Claridades, 2026).

In parallel, research on Vehicle-Integrated Photovoltaics (VIPV) has emerged as a growing field. Unlike stationary PV systems, VIPV requires modelling of irradiation under continuously changing orientation and environmental conditions. Experimental studies demonstrate that solar irradiance on vehicle surfaces is highly variable due to motion, curvature of surfaces, and stochastic shading effects (Araki et al., 2020). These studies emphasize that conventional PV modelling approaches cannot be directly transferred to mobile applications.

Recent advances in VIPV modelling incorporate GIS-based methods and remote sensing data to estimate solar irradiation along vehicle trajectories. For example, GIS-based frameworks using satellite-derived irradiance data and shading analysis have shown promising accuracy, with errors as low as 3–7% under clear-sky conditions (Bunme et al., 2026). Similarly, dynamic GIS-based 3D simulation approaches integrating GTFS data and driving cycles have been proposed to assess VIPV potential in urban public transport systems, highlighting the importance of combining realistic trajectories with detailed spatial modelling (Pera et al., 2025). LiDAR-based approaches further enable detailed modelling of urban shading and have been validated using real-world trip measurements (Sovetkin et al., 2023).

A key challenge identified across studies is the accurate representation of dynamic shading in urban environments. Image-based methods and ray-tracing approaches have been proposed to address this issue, highlighting the importance of high-resolution spatial and temporal data (Núñez et al., 2023). Additionally, recent validation studies emphasize the role of reflected irradiance and urban albedo in influencing VIPV performance (Macías et al., 2024).

Despite these advances, existing approaches typically suffer from one or more limitations:

- limited temporal resolution (e.g., hourly or coarse intervals),
- simplified or static vehicle trajectories,
- lack of integration with detailed 3D urban models,
- insufficient scalability for fleet-level simulations.

This work addresses these gaps by combining high-resolution temporal solar data, semantically rich 3D city models, and distributed geospatial processing to enable dynamic, large-scale simulation of solar irradiation for moving vehicle fleets.

2. Data Sources and System Architecture

2.1 3D City Model

For accurate representation of urban geometry, the framework relies on a semantically rich 3D city model of Luxembourg in CityGML format. CityGML is an international standard by the Open Geospatial Consortium (OGC) for storing virtual 3D representations of cities. It encodes terrain, building shapes, surface semantics (e.g., walls, roofs, setbacks), and multiple levels of detail, supporting sophisticated spatial analysis beyond simple visualization (Yao et al., 2018). The Luxembourg model used in this study represents a Level of Detail 2 (LoD2) and includes detailed building geometries with roof, wall, and footprint surfaces, enabling precise extraction of surface normals and geometric properties required for incident solar angle computations. Such 3D models can be managed and processed in relational spatial databases via the open-source 3D City Database (3DCityDB) toolkit, which implements the CityGML schema for efficient storage, indexing and retrieval (Yao et al., 2018).

2.2 Bus Trajectories

Public transport trajectories are derived from timetabled schedule data conforming to the General Transit Feed Specification (GTFS). GTFS is a widely adopted open format for public transportation schedules and associated geographic data including stop locations, routes, and trip timing information. In the context of this study, GTFS feeds from Luxembourg's public transport system are processed to generate continuous spatial trajectories for bus lines, which are then segmented at high spatial resolution (10 meter hyper-segments) to produce fine-grained observations along each route suitable for dynamic irradiation modelling. Luxembourg's GTFS data is freely available through national open data portals, ensuring reproducibility and integration with other mobility applications (OpenOV GTFS Feeds for Luxembourg Public Transport, 2025).

2.3 Solar Radiation Data

Solar radiation inputs are provided by the Copernicus Atmosphere Monitoring Service (CAMS), a core component of the European Union's Copernicus Earth observation programme implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Copernicus Atmosphere Monitoring Service (CAMS) Overview, 2026). CAMS delivers quality-controlled, consistent datasets of atmospheric composition and surface solar radiation at global and regional scales, derived from a combination of satellite observations, ground measurements, and model assimilation. The solar radiation service within CAMS offers time-series of surface irradiance components including global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) for both clear-sky and observed (all-sky) conditions (CAMS Solar Radiation Time-Series Dataset, 2025). These time-series are available at fine temporal resolutions (e.g., 1 minute) and can be interpolated across spatial grids, making them suitable for high-resolution solar exposure assessments along dynamic trajectories. By integrating CAMS irradiance data, the modelling framework captures both the temporal evolution of solar angles throughout the day and the influence of atmospheric conditions, without requiring on-site sensors at each location.

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2.4 Spatial Database and Processing Infrastructure

The spatial database infrastructure is implemented using PostgreSQL (PostgreSQL Global Development Group, 2026), extended with spatial support through PostGIS (Committee, 2026) and distributed execution via Citus (Citus Data / Microsoft, 2026). All spatial datasets, including the imported CityGML model and derived trajectory geometries, are stored and indexed in a spatially enabled PostgreSQL/PostGIS database. To handle the computational demands of large scale dynamic modelling, particularly when simulating hundreds or thousands of trajectories with minute-level irradiation resolution, the database is extended with the Citus distributed processing extension. This architecture allows data to be partitioned across multiple worker nodes, enabling parallel execution of spatial joins, temporal matching with solar radiation data, and 3D shading computations, thereby providing scalable performance suitable for fleet-wide simulations.

To contextualise the data volumes that motivate this distributed approach: GTFS data for a single high-frequency bus line in Luxembourg yields more than 41,000 annual trips (Pera et al., 2024). At the 10-metre hyper-segment resolution used in this framework, each 18 km route produces approximately 1,800 trajectory segments per trip, amounting to over 74 million segment-level records per line per year. Each segment is then matched against CAMS solar irradiance, the CityGML building geometries, and the 3D ray-casting computation, resulting in tens of millions of spatial-temporal join operations for a single bus line. Extending this to multiple concurrent lines and a full annual simulation cycle produces a workload that rapidly saturates single-node PostGIS processing; the Citus extension addresses this by partitioning both data shards and query execution across worker nodes, enabling linear scaling with the number of nodes.

2.5 System Architecture

The core of the modelling framework is implemented on a distributed spatial database infrastructure using PostgreSQL/PostGIS extended with the Citus distributed processing extension. The system architecture, illustrated in Figure 1, is designed to handle the computational demands of fleet-scale, high-resolution solar irradiation simulations along dynamic vehicle trajectories.

The architecture consists of a **coordinator node** and multiple **worker nodes**. The coordinator node is responsible for query planning, task distribution, and aggregation of results. Worker nodes store distributed portions of the spatial datasets and execute computationally intensive operations in parallel, including spatial joins between vehicle trajectories and urban surfaces, 3D ray casting for shading assessment, and irradiation calculations on vehicle-integrated photovoltaic surfaces.

Input datasets, namely the GTFS-based bus trajectories, the CityGML 3D urban model, and CAMS solar irradiation time-series, are preprocessed and partitioned across the worker nodes. Trajectory segmentation, geometric transformations, and indexing of 3D surfaces are performed as part of this preprocessing to ensure that subsequent spatial and temporal computations are efficient and scalable. Each worker node independently evaluates solar exposure for its assigned spatial partition, taking into account both direct solar irradiance and shading effects from surrounding buildings and vegetation.

Intermediate results from the worker nodes are then transmitted back to the coordinator, which aggregates the data to produce fleet-scale energy estimates. This distributed approach allows the system to handle millions of spatial-temporal observations, providing high-fidelity results at fine temporal and spatial resolution without incurring prohibitive computational costs. By leveraging the parallelization capabilities of Citus, the framework can scale linearly with the number of worker nodes, making it suitable for large urban environments and multiple bus lines operating simultaneously.

3. Dynamic Solar Irradiation Modelling

3.1 Trajectory Segmentation

To capture the dynamic interaction between vehicle movement and solar irradiation, each bus route is discretized into short segments with a nominal length of approximately $10\,\mathrm{m}$. This high-resolution segmentation ensures that changes in vehicle position and orientation are accurately represented, which is critical for computing time-dependent solar exposure and shading effects in urban environments.

For each hyper-segment, a set of attributes is calculated to support subsequent irradiation and shading analyses:

- **Position** (x, y, z)**:** The three-dimensional coordinates of the segment start point are recorded. The z coordinate incorporates both the ground elevation from a digital terrain model (DTM) and the vehicle height, providing a realistic representation of the sensor plane on the vehicle roof.
- **Timestamp and CAMS data:** The temporal location of the segment is derived from scheduled start and end times. Accurate timestamps allow alignment with high-frequency solar irradiation data (e.g., 1-minute CAMS data) and account for variations in solar position and intensity throughout the day. CAMS is used to represent the unshaded part of irradiation on the vehicle roof.
- **Speed and time to pass segment:** The average speed for the segment is estimated from the ratio of segment length to scheduled travel time, enabling calculation of exposure duration for each portion of the trajectory. This information is critical for integrating irradiance over time to compute energy yield along moving routes.

By discretizing trajectories in this manner, the methodology allows fine-grained assessment of solar energy availability for each vehicle along its route. The approach balances computational efficiency with the spatial and temporal resolution needed to capture rapid changes in shading and irradiance, ensuring that the model can accurately reflect realistic urban operating conditions. Furthermore, the segment-level attributes provide a flexible foundation for coupling with distributed spatial computations, allowing parallel processing across multiple worker nodes in the PostGIS/Citus architecture.

3.2 Irradiation Computations

In the current implementation the vehicle roof is modelled as a planar surface defined by its total PV area ($3.5\,\mathrm{kWp}$, covering approximately 80% of the available roof surface), its geographic position derived from the trajectory, and its orientation (tilt and azimuth) computed from the route heading. Detailed

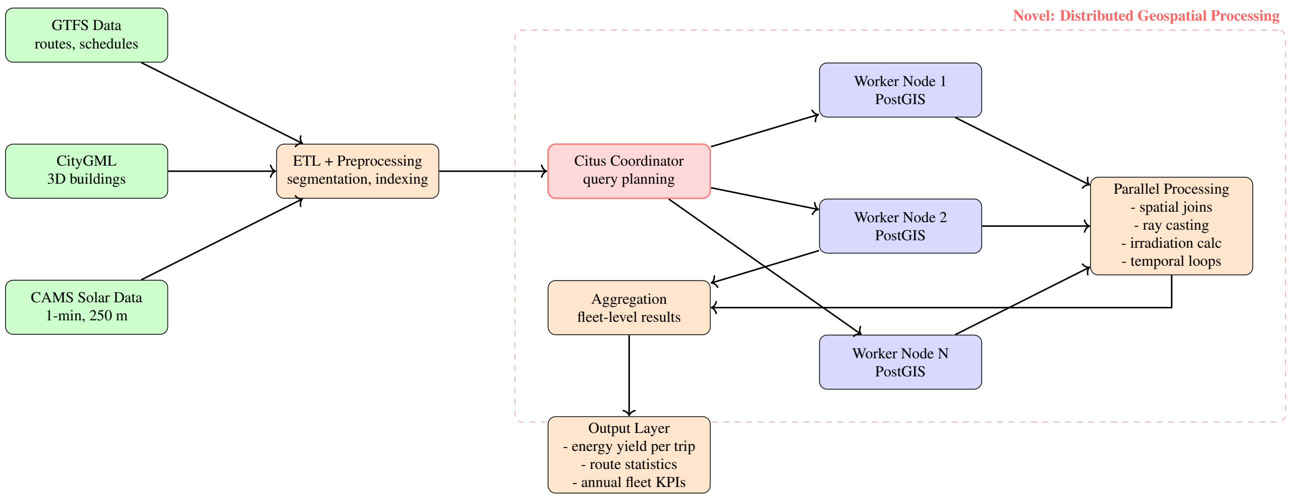

Figure 1. System architecture for distributed solar irradiation modelling using PostGIS and Citus. Input datasets (GTFS, CityGML, CAMS) are preprocessed and distributed across worker nodes, where spatial and temporal computations are executed in parallel. Results are aggregated at the coordinator level to produce fleet-scale energy estimates.

3D vehicle surface meshes — accounting for roof curvature, HVAC equipment, or structural discontinuities — are not incorporated. This simplification provides sufficient accuracy for fleet-scale energy accounting while keeping computational demands tractable, and is identified as a direction for future refinement.

The global horizontal irradiance (GHI) is obtained directly from the CAMS dataset and is not derived from surface-based calculations. For each trajectory segment, the direct component of solar radiation is evaluated by performing a line-of-sight analysis between the vehicle roof and the sun position. If this ray intersects with surrounding objects such as buildings or vegetation, the direct irradiance is considered fully obstructed.

In such cases, only the diffuse horizontal irradiance (DHI), retrieved from CAMS for the corresponding spatio-temporal location, contributes to the incident radiation on the vehicle surface. Independently of the direct visibility condition, an additional reflected component is computed by analysing nearby urban surfaces. These surrounding structures may reflect solar radiation toward the vehicle, and their contribution is estimated based on their spatial configuration and reflective properties.

The total incident irradiation on the vehicle roof is thus composed of (i) the direct component under unobstructed conditions, (ii) the diffuse component derived from CAMS, and (iii) a locally computed reflected component from the urban environment.

3.2.1 Diffuse Irradiation Diffuse radiation is derived directly from the CAMS dataset as diffuse horizontal irradiance (DHI) at the corresponding spatio-temporal position of each trajectory segment. In contrast to the direct component, diffuse radiation is assumed to be available regardless of obstruction conditions, as it represents solar radiation scattered by the atmosphere.

To account for the orientation of the vehicle roof, an isotropic sky model is applied, distributing the diffuse irradiance uniformly across the hemisphere:

$$I_{diffuse} = DHI \cdot \frac{1+\cos(\theta)}{2} \quad (1)$$

where θ denotes the tilt angle of the surface. This formulation ensures that even in fully shaded conditions—where direct radiation is blocked—the surface continues to receive a physically consistent baseline irradiation contribution. Consequently, the diffuse component represents the dominant source of solar input in dense urban environments with frequent shading.

The isotropic sky model was selected for its direct compatibility with the DHI product delivered by CAMS, which provides a single integrated diffuse flux value without directional decomposition. More advanced anisotropic models such as Hay-Davies or Perez require circumsolar radiance and horizon brightness coefficients that are not available from CAMS at this temporal and spatial resolution (Pera et al., 2024). While the isotropic assumption may underestimate diffuse irradiance under low sun-angle conditions — where circumsolar concentration and horizon brightening become relevant — it provides a physically consistent and computationally tractable baseline appropriate for fleet-scale simulation. Future work incorporating directional sky radiance products could extend the model to anisotropic formulations with improved accuracy under such conditions.

3.2.2 Reflected Irradiation In addition to atmospheric scattering, indirect radiation originating from the urban environment is explicitly considered. Surrounding buildings and ground surfaces may reflect incoming solar radiation toward the vehicle roof, thereby contributing to the total received energy.

For each trajectory segment, the local neighborhood is analysed using ray-based visibility queries within the 3D city model. Only surfaces that are visible from the vehicle roof are considered as potential contributors. The reflected irradiance is computed as:

$$I_{reflected} = \sum_i \rho_i \cdot I_i \cdot F_{i\to\text{vehicle}} \quad (2)$$

where ρ_i represents the effective reflectance (albedo) of surface i, I_i its incident irradiance (derived from CAMS-based components), and $F_{i\to\text{vehicle}}$ a geometric weighting factor describing the spatial relationship between the reflecting surface and the vehicle segment.

This formulation enables the incorporation of localized urban effects, such as strong reflections from building facades or bright ground materials, which are particularly relevant in narrow street canyons.

3.2.3 Total Irradiation The total irradiation incident on the vehicle roof is defined as the combination of three components:

$$I_{total} = I_{direct}^{shaded} + I_{diffuse} + I_{reflected} \tag{3}$$

The direct component is conditionally included based on the outcome of the ray-casting visibility analysis, while the diffuse component is always present as provided by CAMS. The reflected component is computed independently from the surrounding 3D geometry.

This modelling approach as shown in Figure 2 ensures a consistent integration of atmospheric radiation data with local urban effects. By combining spatio-temporally matched CAMS inputs, explicit shading evaluation, and geometry-based reflection modelling, the framework captures the highly dynamic irradiation conditions experienced by moving vehicles. When executed within the distributed PostGIS/Citus environment, these computations can be efficiently scaled to fleet-level simulations covering extensive temporal and spatial domains.

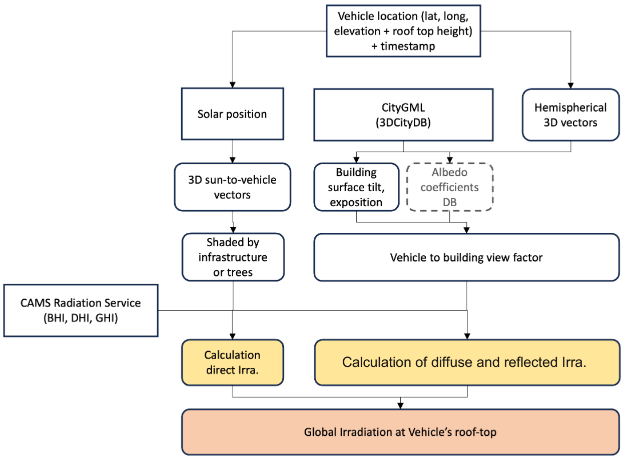

Figure 2. Workflow for distributed dynamic solar irradiation modelling. CAMS provides radiation components, direct irradiation is determined via ray casting, diffuse radiation is continuously applied, and reflections are computed from the urban environment. The distributed PostGIS/Citus architecture enables scalable fleet-level simulations.

4. Fleet-Scale Simulation

While the irradiation model provides detailed estimates of solar energy incident on vehicle rooftops, a full assessment requires modeling how this energy interacts with the vehicle. For this, the framework integrates the Vehicle Energy Consumption Calculation Tool (VECTO) (Commission, 2026), the European standard for assessing energy use and CO_2 emissions in heavy-duty vehicles. VECTO allows the direct use of GTFS-derived driving cycles, ensuring reproducible and comparable results aligned with European standards.

Input data include the already used CAMS irradiance products, CityGML files, GTFS feeds, PV specifications, and vehicle catalogs. GTFS routes are converted into geospatial trajectories, from which a Driving-Cycle Generator produces 2-second resolution time series of speeds, stops, and gradients. These feed two branches: (i) irradiation and PV yield calculations, and (ii) vehicle energy consumption via VECTO, accounting for rolling resistance, aerodynamic drag, e-axle characteristics, regenerative braking, auxiliaries, and battery state-of-charge evolution.

The resulting workflow shown in Figure 3 combines geospatial analysis, radiative transfer modelling, and vehicle physics in a modular environment. This approach not only estimates annual photovoltaic yield but also evaluates operational impacts of VIPV, such as reduced charging frequency, peak demand mitigation, and potential battery-life effects. Its scalability and reliance on widely available GTFS data make it directly relevant for transport operators and policymakers assessing the techno-economic feasibility of vehicle-integrated photovoltaics.

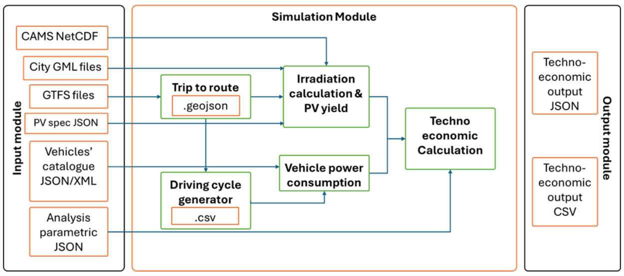

Figure 3. Combined workflow which combines geospatial analysis, radiative transfer modelling, and vehicle physics in a modular environment.

An interactive web-based interface was developed to facilitate exploration and scenario analysis of vehicle-integrated photovoltaic (VIPV) performance at both trip and fleet levels. The interface allows users to configure PV system characteristics, including technology type (e.g., c-Si), installed area size, and system losses, thereby enabling flexible assessment of different technological setups. Bus operations can be selected by route and direction, while departure time is interactively adjusted using a slider to analyse temporal variability in solar conditions. Additional vehicle parameters, such as auxiliary load and state-of-charge constraints, can also be specified.

Simulation results are computed dynamically and presented through multiple coordinated visualizations. These include monthly energy yield distributions, high-resolution temporal irradiation patterns, spatial representations of routes with segment-level energy contributions, and time-series plots of driving cycles and battery state-of-charge evolution. This interactive environment enables users to intuitively explore the interplay between solar availability, vehicle operation, and energy consumption, supporting scenario-based evaluation and decision-making while maintaining consistency with the underlying high-resolution modelling framework.

5. Results and Discussion

The developed framework was applied to a high-frequency bus corridor in southern Luxembourg as an illustrative case for fleet-scale VIPV assessment. This example demonstrates how dense urban morphology, frequent service, and regular operational schedules influence rooftop photovoltaic potential and energy contributions across a fleet.

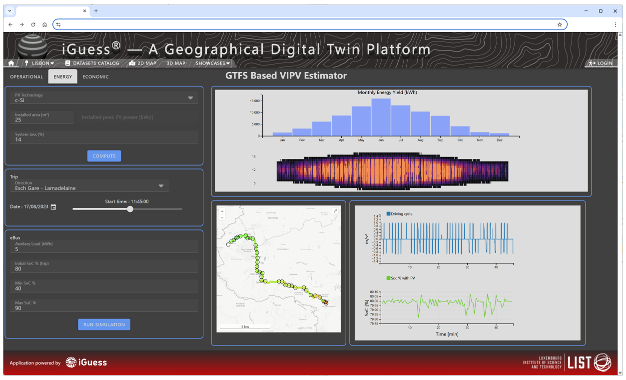

Figure 4. An interactive web-based interface was developed to facilitate exploration and scenario analysis of VIPV performance.

5.1 Irradiation and Shadowing Effects

Simulations combining CAMS radiation data and 3D CityGML models indicate that the annual clear-sky irradiation on a standard bus rooftop reaches approximately 1409 kWh/kWp, while real-sky conditions reduce this to 944 kWh/kWp, a 33% decrease. Figure 5 shows that urban shadowing patterns contributes to significant losses (20–21%), underscoring the necessity of accounting for building geometry and orientation. Simplified models ignoring 3D shading would overestimate yield by over 20%, potentially misleading planning and investment decisions.

The 250 m spatial resolution of the CAMS radiation grid introduces a smoothing effect that is most pronounced at transitions between dense urban corridors and open suburban road segments. Within a single CAMS grid cell, the modelled irradiance reflects spatially averaged atmospheric conditions, while the 3D shading model resolves local geometry at segment level. For the routes considered here — spanning both dense urban and peri-urban sections — this decoupling between coarse atmospheric input and fine geometric shading is acceptable; however, it represents a practical constraint in areas with sharp spatial gradients in cloud cover or aerosol loading.

These simulation results are consistent with prior validation work in which the same 3D CityGML-based irradiation modelling approach was evaluated against vehicle-mounted silicon irradiance sensors logging at 30-second intervals across Luxembourg road networks. That study demonstrated statistically significant agreement between modelled and measured irradiance, with the 3D approach outperforming a 2.5D DSM-based model under identical route and radiation conditions; residual underestimation was attributed primarily to local albedo variability and GPS positional mismatch (Pera et al., 2024).

5.2 Energy Balance and Fleet Impact

For a representative 12 m electric bus (eCitaro K, 330 kWh battery, 2 × 125 kW motors), typical one-way energy demand is $23 - 24$ kWh, corresponding to a 7% state-of-charge depletion. Rooftop PV modules of 3.5 kWp with a 75% performance ratio supply 2.8–4.1% of annual energy demand, avoiding up to 98–146 charging cycles per year depending on irradiation conditions (see Figure 6). While modest in absolute terms, these contributions reduce charging frequency, mitigate peak demand, and can positively affect battery longevity, particularly during summer months.

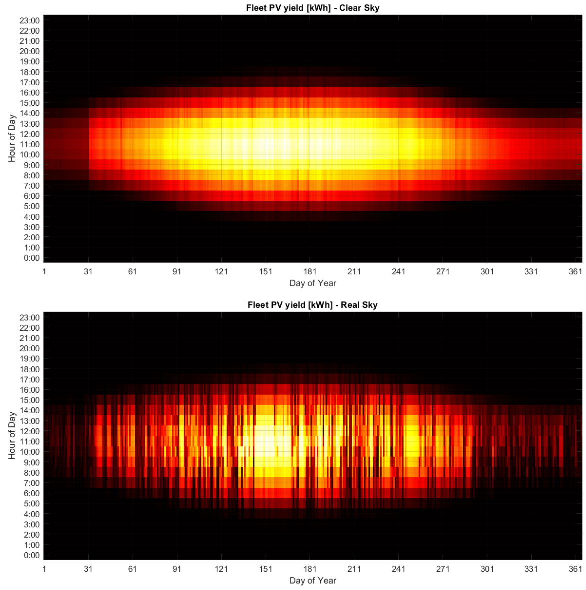

Figure 5. Annual irradiation distribution for a city bus line in Luxembourg under clear-sky (top) and real-sky bottom), with shadowing losses.

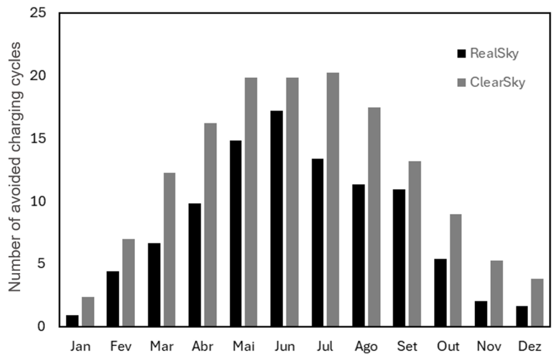

Figure 6. Annual avoided charging cycles (20–80% SoC) under clear-sky and real-sky conditions. Totals: 146 cycles (clear-sky), 98 cycles (real-sky), 707 MWh fleet demand.

5.3 Techno-Economic Insights

Assuming system costs of 1.5 €/Wp and an electricity tariff of 0.21 €/kWh, simple payback is estimated between 7–10 years under favorable conditions. Although VIPV does not drastically reduce infrastructure requirements due to limited contribution to total energy demand, the operational benefits at the fleet scale, including distributed generation and reduced reliance on grid power, are significant.

The results also highlight the critical role of urban morphology: shading, albedo, and building façades significantly affect irradiation patterns. Incorporating GTFS-derived driving cycles ensures that energy demand and PV contributions are evaluated under realistic operational conditions. Remaining uncertainties relate to passenger load dynamics, auxiliary power variations, and fine-scale albedo effects, which can be addressed in future work through automated urban datasets and improved modelling of vehicle surfaces.

5.4 Implications for Solar-Enabled Electric Mobility

The results confirm that VIPV provides a meaningful, albeit modest, contribution to the fleet energy balance. While insufficient to eliminate charging infrastructure requirements, the 2.8–4.1% annual yield yields tangible operational benefits — reduced charging frequency, extended battery lifetime, and partial support of auxiliary loads — particularly under favorable seasonal conditions.

Urban morphology and route characteristics play a decisive role in achievable yields. Dynamic shading, suboptimal vehicle orientation, and limited rooftop area inherently constrain energy capture, with dense urban canyons reducing irradiation by up to 50% as reported in previous studies (Hoth et al., 2024). Our simulations confirm these effects, showing that open suburban segments or elevated roads receive substantially higher solar irradiance than dense city corridors. The explicit modeling of building façades, albedo, and shadowing highlights the importance of route-level evaluation rather than relying on average assumptions.

Integrating GTFS-derived driving cycles ensures that both energy demand and PV contributions reflect realistic operational patterns, enhancing the relevance of results for transport operators and decision makers. Remaining uncertainties, such as passenger load variations, auxiliary power fluctuations, and fine-scale albedo effects, indicate opportunities for further refinement. Future work should focus on improving vehicle surface modeling, incorporating automated urban albedo datasets, and accounting for dynamic auxiliary loads, all of which can increase the accuracy of fleet-scale VIPV assessments while maintaining computational efficiency.

Compared to existing approaches in the literature, the present framework distinguishes itself through the joint integration of operational trajectories, semantically typed 3D urban geometry, distributed spatial processing, and vehicle energy modelling. GIS-based irradiance estimation methods (Bunme et al., 2026) establish solar exposure along road networks but do not couple them with vehicle energy modelling or realistic driving cycles. LiDAR-based approaches (Sovetkin et al., 2023) enable high-fidelity shading but are computationally intensive and difficult to scale to fleet-level annual simulations. The Berlin VIPV case study (Hoth et al., 2024) provides operational context for fleet-level energy estimates and reports shading losses of up to 50% in dense urban canyons; our results for Luxembourg (20–21% urban shading loss) are lower, consistent with differences in urban density and route morphology between the two cities. Image-based shade detection methods (Núñez et al., 2023) offer high spatial resolution for individual vehicles but are not scalable to multi-line fleet simulations. The role of local albedo and building facade reflections, highlighted by (Macías et al., 2024) and confirmed in our earlier measurement campaigns (Pera et al., 2024), is explicitly captured in this framework through the geometry-based reflected irradiance component. The use of semantically typed CityGML surfaces rather than raster DSMs enables surface-selective shading and reflection modelling that integrates naturally with urban digital twin infrastructure — an approach that, to our knowledge, has not previously been demonstrated at fleet scale for VIPV applications.

6. Conclusion

This study presents a scalable, high-resolution framework for dynamic solar irradiation modelling on moving vehicles. By integrating 3D city models, distributed geospatial processing via PostGIS/Citus, and high-frequency CAMS solar data, the approach enables realistic estimation of solar potential for electric bus fleets and other vehicle types. Millions of trajectory segments can be simulated efficiently, supporting integration into urban digital twins for real-time energy estimation, scenario-based route planning, and coupling with traffic, weather, and energy systems. Time-dependent attributes in CityGML — specifically through the Dynamizer mechanism (Chaturvedi et al., 2017) — allow per-surface simulation outputs such as irradiation time-series or trip-level energy surplus to be embedded directly within city object representations, enabling a unified digital twin artefact in which geometry, semantics, and temporal energy data are co-located and accessible for real-time route energy estimation or urban-scale energy planning.

While demonstrating strong performance and scalability, several limitations remain. Gridded solar data may not fully capture local cloud dynamics, vegetation shading is only partially represented, and vehicle roofs are simplified. Multiple reflections and urban canyon effects are also simplified. Despite these constraints, the framework provides a robust and scalable assessment of fleet-wide solar energy potential, delivering operational insights for VIPV deployment.

Future research should enhance physical realism and operational relevance, including improved vehicle surface geometries, integration of high-resolution weather data, coupling with energy management systems, and extension to multimodal fleets and heavy-duty trucks. Incorporating techno-economic assessments and combining physics-based simulations with data-driven approaches, such as generative solar models, can reduce computational costs while maintaining predictive accuracy.

Overall, the framework lays the foundation for integrated energy-mobility systems, demonstrating that vehicle-integrated photovoltaics can meaningfully contribute to urban mobility energy supply. Distributed computation allows fleet-scale evaluation, and integration with digital twins supports both operational insights and strategic planning, providing a transferable and scalable methodology for assessing VIPV potential across cities.

Key Takeaways. The framework demonstrates that vehicle-integrated photovoltaics can meaningfully contribute to urban mobility energy supply, that distributed computation allows fleet-scale evaluation, and that integration with digital twins enables both operational insights and strategic planning. Even with current limitations in data and geometry, the approach provides transferable, reproducible, and scalable methodology for evaluating VIPV potential across cities.

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