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Enhancing Electric Vehicle Autonomy With Solar Energy: A Case Study of the "Takai Urban" in Northern Chile

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Abstract. The global transition towards electromobility presents unique challenges, particularly in regions with limited infrastructure. In Northern Chile, the sparse distribution of charging stations, with distances often exceeding 100 km, complicates the widespread adoption of electric vehicles (EVs). This study investigates the potential of enhancing the autonomy of the "Takai Urban", a solar-assisted battery EV through the integration of Zebra IBC solar cells, leveraging the region's high solar irradiance. Initially, the Takai Urban EV had a maximum range of 72.8 km per charge. Through virtual modelling and simulations, which incorporated GPS and meteorological data along a typical 43.3 km route in Antofagasta city, we examined the impact of solar integration on vehicle performance. The simulations indicated that with the strategic placement of high-efficiency solar cells, the vehicle efficiency increases from 10.88 km/kWh to 12.32 km/kWh, a relative improvement of 13.3%$_{rel}$ for this specific testing route. Furthermore, the vehicle's range could be extended by approximately 41.3%$_{rel}$, achieving a new maximum of 102.9 km per charge. This approach not only demonstrates the potential for solar-assisted EVs in regions like Northern Chile but also underscores the broader implications for sustainable mobility in similar environments globally. The results highlight the potential for practical enhancements in EV designs using solar technologies, focusing on efficiency improvements and sustainable mobility solutions.

Keywords: Battery Electric Vehicles, Solar Integration, Zebra Solar Cells, Vehicle Autonomy, Northern Chile.

1. Introduction

The shift to electromobility represents a commitment to sustainable energy, essential in the transportation sector for reducing greenhouse gas emissions and transforming energy infrastructure for ecological resilience. In the realm of transportation, battery-powered vehicles (BEV) are gaining global adoption to reduce CO_2 emissions. As the economies transition toward electrified transportation, photovoltaic (PV) generated electricity and other renewable energy sources play a crucial role in providing a low CO_2 emission power [1]. The decentralized nature of PV electricity generation opens new possibilities for charging BEVs, including charging zones powered by PV systems (either grid connected or isolated), or even directly harnessing on-board PV panels converting the BEV into a PV-powered BEV. In this matter, ongoing research explores the direct mounting of photovoltaic cells on vehicles, also known as vehicle integrated photovoltaics (ViPV), the development of solar-powered recharging stations, and the use of solar energy for producing hydrogen to power fuel cells. This works focuses on the challenges and opportunities of the PV solar cells integration in BEVs, with the aim of helping the transportation sector to increase the BEV range without the need of larger batteries, and to avoid congesting the utility electric grid.

The adoption of EVs faces challenges like insufficient charging infrastructure, especially in regions like Northern Chile where charging stations are sparsely located, as illustrated in **Figure 1**. This way, it is anticipated that solar-powered BEVs will be able to commute between long-distance cities diminishing the driver's range anxiety.

Figure 1. *Distances between main cities in Northern Chile between Tocopilla and Copiapó.*

In Europe, Sono Motors and Lightyear led the manufacturing of PV-powered vehicles until 2021. Sono Motors' "Sion" model incorporated lightweight photovoltaic modules that were at least 20% lighter than their metal body counterparts at its time and were able to generate 1208 W under standard test conditions (STC). Sono Motors projected that its vehicle could travel up to 34 km/day in Munich, Germany, using only solar energy, which translates to 5800 km/year. Lightyear's "Lightyear One" model was designed to be extremely lightweight, with photovoltaic modules spread over 5 m^2, whose power rating were 215 W/m² at STC, providing up to 70 km/day. In addition, CEA-INES has developed a prototype vehicle equipped with 1.3 m^2 c-Si photovoltaic modules [1], with a nominal power of 206 W, estimating a range of 1600-2000 km at Le Bourget du Lac, France.

According to the IEA PV-PS [2], in Japan, Toyota and Nissan have engineered prototypes of PV-powered passenger vehicles using high-efficiency III-V multijunction solar cells, with support from NEDO, and have initiated testing. The PV capacity of Toyota's PV-powered vehicle, the Prius-HEV, is 860 Wp, while Nissan's PV-powered vehicle, the e-NV200, has a capacity of 1150 Wp. It's worth noting that both vehicles are commercial passenger vehicles, suggesting that the III-V multijunction solar cells can be installed on standard passenger vehicles without compromising their aesthetic appeal.

Our study addresses these challenges by exploring the integration of Zebra solar cells [3] onto the "Takai Urban", a battery-powered electric vehicle with integrated photovoltaics (BEViPV), potentially increasing its range, and reducing reliance on charging stations [4],[5].

2. Methodology

The methodology adopted in this study was crafted to theoretically estimate the "Takai Urban" performance upon integration of solar cells. The solar PV contribution, the vehicle autonomy, its battery state of charge (SoC), and projection of the photovoltaic integration impact on the efficiency and autonomy of the BEViPV are of main interest. As depicted in **Figure 2**, this approach merges empirical data with computational simulations to estimate the BEViPV performance. The former comprehend the definition of a testing route, its specifications (elevation profile, traffic signs, etc.), the solar irradiance and ambient temperature collection along this route, solar cells specifications (current-voltage and geometry characteristics) and their arrangement to build up PV panels to be in the "Takai Urban" integrated, and the specifications of this vehicle (battery capacity, original range, etc.). The latter focuses on the vehicle battery energy and the PV potential assessments, being the first achieved by using the SUMO software [6] with inputs such as the performance of the BEV without solar contribution, the road network of Antofagasta, and the testing route specifications. The PV potential is assessed by a Python code based on the single-diode model to simulate PV performance using the solar irradiance, the cell temperature, and the GPS data over the testing route collected.

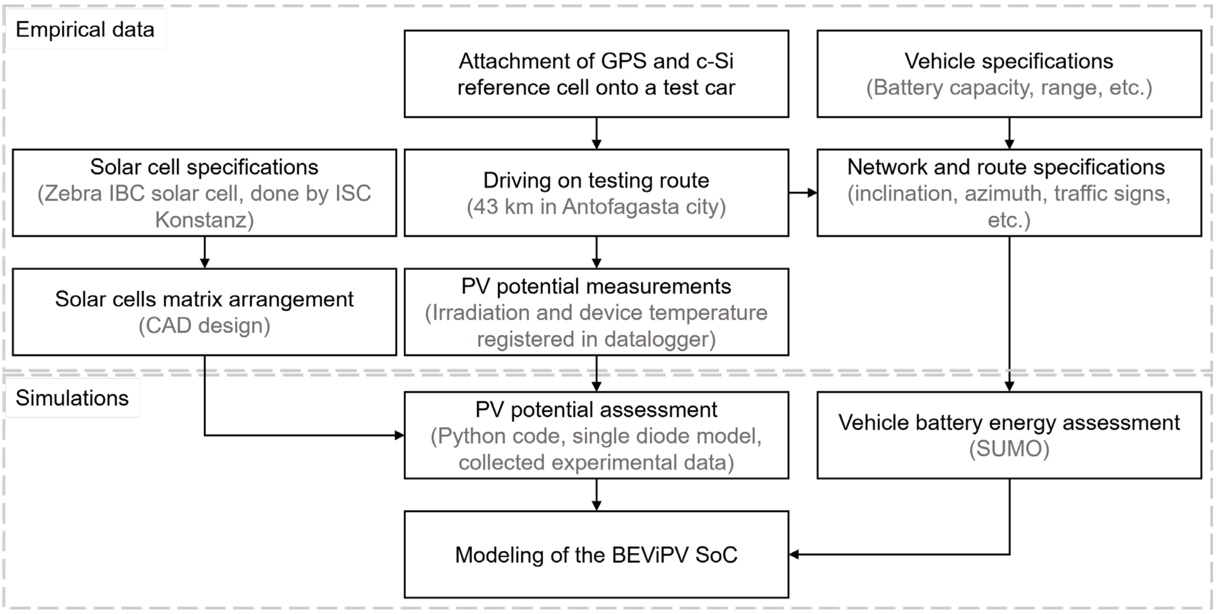

Figure 2. *Block diagram of the methodology to assess the PV contribution to the BEV.*

2.1 Solar panel design

The main goals of our design are: 1) to maximize the area usage for solar cells on top of the vehicle, 2) to reduce the Joule heating loss caused by current flow, 3) to reduce the optical loss due to metal contacts. Hence the solar cell area must be as small as possible with all its contacts on its backside. The all-backside contact cells allows one to create modules with a smaller packing ratio if compared to the traditional front-to-back contact solar cells, since the gap within cells can be smaller. This way, the BEViPV under development uses the Zebra cells, an interdigitated back contact (IBC) solar cells developed by ISC Konstanz [3], distinguished by their efficiencies exceeding 24% and open circuit voltages above 700 mV.

Using CAD software, we designed a solar panel for the "Takai Urban" model using a variant of the Zebra cells cut by half, with the result displayed in the **Figure 3**. The result involved distributing 400 half-cells on the roof and hood of the vehicle, forming eight panels each of 50 half-cells all in series connected, achieving the parameters of the photovoltaic array summarized in the **Table 1**. A bypass diode is included in each 10 cells, as shown in the figure at the side of each panel. The latter is connected to a DC-DC converter with maximum power point tracker (MPPT) algorithm to boost the total voltage output of the panel.

The panels are designed to be encapsulated by epoxy resin and fiberglass as reinforcing material, hence their weight is calculated approx. 3.03 kg/panel, where 8.2% corresponds to the solar cells, 44.9% to the epoxy resin, and 46.9% to the fiberglass reinforcing sheet. The eight panels this way sum up 24.22 kg, 7.5% lighter than the sum of the originals roof and hood without solar (14.8 kg and 11.4 kg, respectively). This does not include the panels' anchoring mechanism, which needs to be carefully assessed in future work.

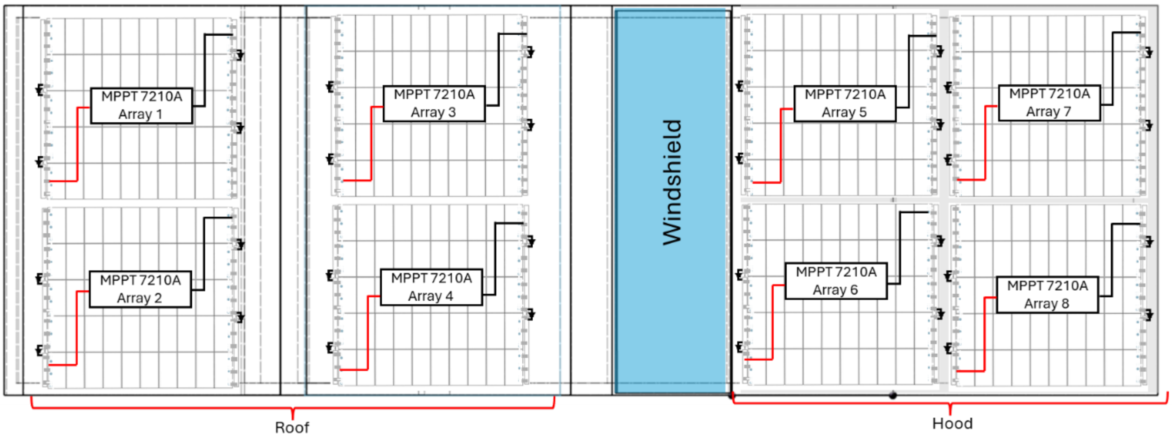

Figure 3. *PV modules based on Zebra cells attached to the "Takai Urban" vehicle.*

Table 1. *Technical specifications of the photovoltaic array. Power performance a STC (1000 W/m^2, 25 ºC, AM1.5)*

Electrical specification	Cell	Panel	PV System
Nominal power P_{NOM} [W]	2.86	143.00	1144.0
Open circuit voltage V_{OC} [V]	0.690	34.50	34.5
Short circuit current Isc [A]	5.24	5.24	41.9
Voltage at Pmax V_{MPP} [V]	0.584	29.20	29.2
Current at Pmax I_{MPP} [A]	4.91	4.91	39.2
Weight [g]	4.96	3028	24224

2.2 Data collection of irradiance and temperature

A photovoltaic c-Si reference cell was mounted on the roof of a test vehicle, as shown in **Figure 4**, for a relivable measurement in the predefined 43.3 km route, which is presented in **Figure 5**. The reference cell is mounted onto the car roof by means of neodymium magnets, with previous validation tests to confirm there is no interference from the mounting method in the solar irradiance record. Irradiance and temperature data were continuously recorded during the journey using a CR6 datalogger from Campbell Scientific. Data was collected every second and later analyzed by a Python code, which allows one for assessing the solar panels' performance under variable environmental conditions, integrating the data into our simulations to assess the performance as depicted in the route map.

Figure 4. *PV reference cell mounted onto the test car.*

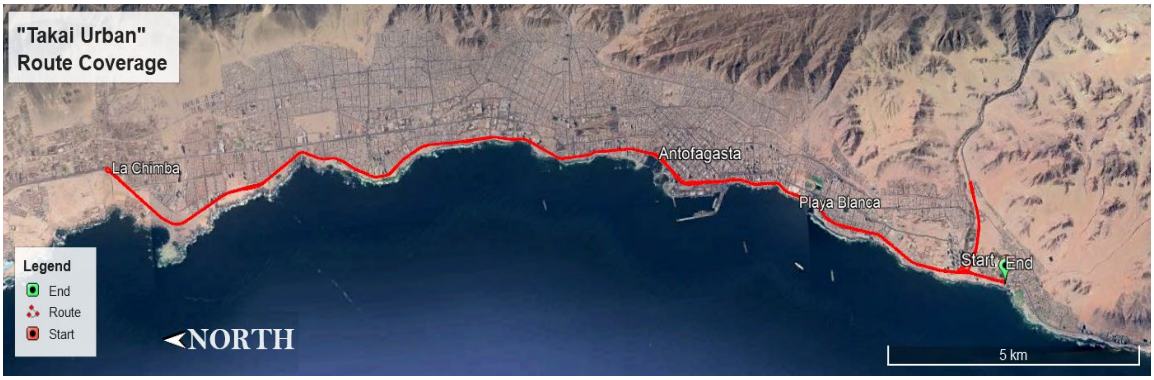

Figure 5. *"Takai Urban" BEViPV 43.3 km testing route map.*

2.3 Vehicle trajectory simulation

To analyze the behavior of the "Takai Urban" BEViPV under realistic traffic conditions we employed the SUMO (Simulation of Urban MObility) software, an advanced tool that allows one for detailed simulation of urban traffic and vehicle mobility [4]. The software was configured to replicate a specific pre-defined 43.3 km route within the city of Antofagasta (shown in **Figure 5**), integrating data on traffic and road infrastructure.

The specific parameters of the "Takai Urban", shown in **Table 2**, were set up in SUMO to reflect its characteristics and performance. The maximum speed (maxSpeed) is the top speed that the vehicle can reach, while the minimum gap (minGap) represents the minimum distance it maintains from other vehicles on the road. The air drag coefficient (airDragCoefficient) measures the vehicle’s aerodynamic resistance and the front surface area (frontSurfaceArea) affects this resistance. The vehicle mass (vehicleMass) is crucial for dynamics calculations and the battery capacity (device.battery.capacity) determines the vehicle's range. The maximum power (maximumPower) indicates the highest power output the vehicle's motor can produce. The propulsion efficiency (propulsionEfficiency) reflects the efficiency with which the battery's energy is converted into motion. All these six last variables were experimentally determined [7].

Table 2. *Summary of the parameters used in the simulation.*

Parameter	Value
Vehicle Type ID	Takai_v1
Minimum Gap (minGap)	3.00 m
Maximum Speed (maxSpeed)	16.67 m/s
Vehicle Class (vClass)	evehicle
Air Drag Coefficient (airDragCoefficient)	0.32
Front Surface Area (frontSurfaceArea)	1.7 m²
Vehicle Mass (vehicleMass)	850 kg
Battery Capacity (device.battery.capacity)	6.68 kWh
Maximum Power (maximumPower)	8.00 kW
Propulsion Efficiency (propulsionEfficiency)	0.9
Rolling Drag Coefficient (rollDragCoefficient)	0.017
Stopping Threshold (stoppingThreshold)	0.1

Using the data generated by SUMO, the battery discharge profile of the “Takai Urban” for the pre-defined test route was simulated. The simulation output includes energy consumption, traveled distance, vehicle speed, and other relevant indicators, establishing a baseline for the vehicle's autonomy without solar assistance, allowing for comparisons with scenarios where solar panels are active.

2.4 PV potential assessment and modeling of SoC

To model the energy generation of solar panels, we developed a Python code based on the single-diode model [8]. Our code uses real-time solar irradiance and cell temperature data, measured by the crystalline silicon (c-Si) reference cell installed on the test vehicle, as mentioned in section 2.2. The simulation code incorporates specific parameters of the Zebra solar cells, such as short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), and efficiency at the maximum power point (I_{MPP} and V_{MPP}). Key parameters like thermal voltage and reverse saturation current are adjusted based on the measured cell temperature, assuming the PV panels will reach similar operational temperatures once mounted in the vehicle. For this, the temperature coefficients for P_{MPP} (−0.29 %/K), I_{SC} (0.046 %/K) and V_{OC} (−0.246 %/K) are used.

The Python code simulates the energy generation for the array of panels configured as described in section 2.1, integrating solar generation into the battery discharge profile, showing how the solar panels affect the BEViPV energy profile. The discharge profile of the battery is generated by SUMO, providing a foundation for calculating the impact of solar harvesting on vehicle autonomy. The solar harvesting is combined with the vehicle behavior (calculated by SUMO) through the iterative process shown in equation (1), which updates the SoC of the battery at each t moment, where $SoC_{(t)}$ is the state of charge at time t, $P_{\mathrm{gen}(t)}$ is the generated power of the solar panels at time t, Δt is the time between measurements, and $C_{\mathrm{Bat\_total}}$ is the total capacity of the battery. The power loss of the MPPT DC-DC converter is included in the $P_{\mathrm{gen}(t)}$ calculation (its efficiency ranges between 0.85–0.90).

$$\mathrm{SoC}_{(\mathrm{t})} = \mathrm{SoC}_{(\mathrm{t}-1)} + \frac{\mathrm{P}_{\mathrm{gen(t)}} \cdot \Delta \mathrm{t}}{\mathrm{C}_{\mathrm{Bat\_total}}} \qquad (1)$$

3. Results and discussions

The results evidenced in **Figure 6** show that the BEV arrives with 40.81% of SoC, meaning that it requires 59.19% of the total battery capacity to travel along the 43.3 km predefined test route (**Figure 5**). If the solar cells are embedded in the BEV, it allows a consumption of 41.87% of the battery, which turns in ~17% of extra SoC at the arrival. Furthermore, on the one hand, the results return that the total energy consumed by the BEV from the battery along the testing route is calculated to be 4.02 kWh, which means a BEV performance of 10.88 km/kWh (without solar contribution). On the other hand the BEViPV consumes 3.55 kWh, meaning a performance of 12.32 km/kWh, a gain of 13.3%$_{\mathrm{rel}}$ in favor of the BEViPV over the BEV, which emphasizes the unique solar context of Northern Chile.

Figure 6 also displays how the cell temperature decreases as the vehicle advances. This decline in temperature is likely influenced by vehicle speed, as higher speeds promote forced convection, improving thermal dissipation and reducing losses. Consequently, efficiency losses due to cell temperature rapidly dropped from over 12% to 4-6%. It is crucial to consider that the actual performance of integrated solar panels on vehicles may vary under real-world operational conditions. Factors such as variability in solar irradiation, surrounding shades, wind speed, ambient temperature, and cell mismatch losses are critical aspects that could affect the efficacy of the BEViPV system once implemented.

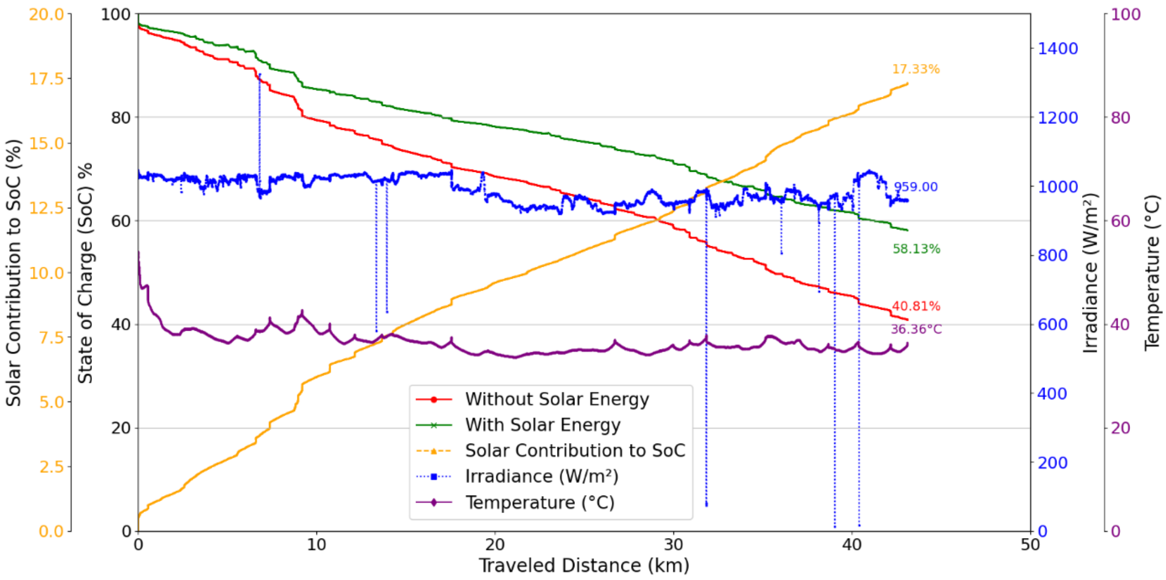

Figure 6. *Battery discharge calculation along the testing route.*

4. Conclusions

This study assesses the potential of enhancing the autonomy of the "Takai Urban" BEViPV by incorporating Zebra IBC solar cells. The designed PV panels cover most of the hood and roof area, and it has been calculated that their material composition does not add weight to the vehicle. Furthermore, simulation results indicate that the integration of half-cells significantly extends the vehicle's range, as evidenced by a remaining SoC of 58.13% after a 43.3 km journey, compared to a 40.81% SoC without solar assistance. This equates to an approx. 17% SoC increase upon arrival, demonstrating a significant improvement in vehicle efficiency from 10.88 km/kWh to 12.32 km/kWh, which corresponds to a relative improvement of 13.3%$_{rel}$ for this specific testing route. Consequently, when driving the vehicle on the same route but long enough to fully discharge the battery, its range extends from 72.8 km (without solar) to 102.9 km, reflecting a relative improvement of 41.3%$_{rel}$ by using half-size Zebra cells.

Extending the results to analyze a hypothetical terrestrial BEV with 34 kWh battery capacity and a WLTP estimated range of 200 km (efficiency of 5.88 km/kWh), this BEV will finish a trip from Antofagasta to Tocopilla cities with a 6.5% SoC without solar assistance and would not complete the journey from Antofagasta to Taltal. However, with the efficiency gain from integrating solar cells, the BEV would arrive with a SoC of 40.6%, alleviating the driver's range anxiety. Furthermore, the route to Taltal would be achievable with solar assistance, arriving with 33.1% SoC at destination. These findings highlight the potential of solar integration to substantially extend the range of electric vehicles and reduce their dependency on the grid, thus promoting a more sustainable and efficient mode of urban mobility.

Although the high solar irradiance in Northern Chile offers a unique advantage for the deployment of ViPVs, it is crucial to acknowledge that the real-world performance of integrated solar panels may vary due to factors such as variability in solar irradiance, surrounding shade, environmental effects, and efficiency losses. Future research should therefore focus not only on validating these simulation results through empirical testing but also on addressing the practical challenges of integrating solar panels into vehicle designs.

Data availability statement

The data that supports the findings of this study are available from the corresponding author, [F.C.G.], upon reasonable request.

Author contributions

This study was conceptualized, directed, and supervised by J.R.A. as the principal investigator. J.R.A., F.C.G. and S.R.R. designed the experiments. F.C.G. did the investigation, data curation and visualization. J.R.A., F.C.G. and S.R.R. discussed the results. D.O. provided resources as instrumentation for the data collection and E.F. led the funding acquisition. The manuscript draft was initially written by F.C.G. and commented on by all authors. All authors read, reviewed, and edited the final manuscript.

Competing interests

The authors declare no competing interests.

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