Urban solar potential for vehicle integrated photovoltaics

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Abstract

Integrating solar photovoltaics in electric vehicles can reduce operating costs and extend the driving range. It is particularly appropriate for urban mobility due to the relatively short typical daily travels of urban vehicles. However, shadowing cast by buildings will reduce the solar irradiation falling on the vehicle, reducing its PV generation. This study assesses the solar potential of onboard solar for roads and urban parking using data in a geographical information system for the case study of Lisbon. Results show that annual losses due to shadowing may reach 25% for roads and over 50% for urban parking spaces. Nevertheless, despite these losses, the annual solar extended range for onboard solar vehicles is between 10 and 18 km/day/kWp, thus significantly reducing charging needs.

Keywords

Vehicle integrated photovoltaic; urban environment; GIS.

1. INTRODUCTION

Vehicle integrated photovoltaics (ViPV) is a concept that refers to the integration of a photovoltaic (PV) system on the roof, and sometimes the hood or even the trunk or the sides of an electric vehicle. The harvested solar energy can contribute to vehicle motion, reducing the frequency of grid charging.

Most of the literature discussing the integration of PV technology on vehicles has focused on providing additional power to auxiliary systems to reduce deep discharges of service electrical batteries, for example in emergency vehicles [1] or buses [2], or for support heating, ventilation, air conditioning units and other not so common power-consuming auxiliary electronic components [3][4]. Solar-to-vehicle (S2V) systems were proposed to recharge EV using solar arrays located at commuters' worksites [5][6] or, in the case of solar-powered EV, taking advantage of parking idling periods [7]. Vehicle integrated PV in commercial trucks has been explored [8][9] mostly for applications such as refrigeration [10][11].

Only recently a first demonstration of the use of PV for electric engines in commercial passenger vehicles was made, following earlier Audi models with solar roofs, in 2010 Toyota issued the Solar-Prius, a plug-in hybrid vehicle with a roof-top mounted 180 W PV module [12], useful to battery charging during long parking periods but not so much on road. Even more recently, many automobile manufacturers have been announcing vehicle concepts where solar contributes to its motion (Tesla [13], Hyundai [14], Lightyear [15], Fisker Karma [16], Hanergy [17], Sono Motors [17], and Stella Lux [19]).

The opportunity for the deployment of onboard solar vehicles comes from the continuous increasing efficiencies of PV solar cells leading to higher energy generation densities at lower costs [20], thus making the technology more suitable than ever to be integrated into the limited space offered by the non-occupied vehicles surfaces [21]. Considering the state-of-art of highly efficient solar cells, above 30%, and an available surface of 3 m^2, it has been estimated that onboard solar could supply up to 70% [22] of the vehicle's energy demand for optimal insolation conditions. However, those would hardly occur, especially in the urban environment [23], the leading market for electric vehicles.

This work explores the effect of shadows cast by buildings onto roads and parking spaces. Although car surfaces (such as the car roof or hood) are often curved [24][25], the analysis can be simplified by considering them horizontal. Solar irradiance is higher around noon when solar elevation is higher. Since shading will be higher when the sun is lower in the sky (early morning and late afternoon) the most convenient time for solar charging in the urban environment will be around noon, when irradiance is peaking and there are fewer shadows. At those times, individual passenger cars are expected to be (mostly) parked, either at home or at work [26]. Thus, for this category of vehicles, the most relevant assessment is that of parking spaces.

On the other hand, service vehicles, bus transport and other public transport modes such as car-sharing, ride-hailing or taxiing services, are expected to be driving throughout the day, when irradiance levels are higher and shading lower. For this category of vehicles it is important to assess the solar potential of roads.

In the literature, the issue of urban shading on PV potential in vehicles has only been addressed with simple trigonometric approaches and average values. Lodi et al [27] have used the height-width ratio to estimate the time fraction when the vehicle is shadowed by the near obstacle. Considering typical values for the widths of the road (8 m) and the car (2 m), and the height of the obstacles (7.5 m) and the car (1.5 m), and assuming that the car is parked at the edges of a north-south road, they have estimated that the vehicles would be in the shadow 44% of the time. They have assumed that vehicles driving in urban settings would receive a similar level of irradiance. In their study, these shadowing times were attributed to the earlier and later hours of the day leading to a 42% loss of solar irradiation throughout the year.

Carr et al [28] have developed a Vehicle Irradiance Test System for high-frequency measurement of solar irradiance on the roof of a vehicle, conducting measurements for about 20 weeks in the Netherlands. Extrapolating driving patterns and shading events to different locations and considering different charging/discharging strategies and vehicle specifications, they were able to show that, in favourable conditions, VIPV could provide 40% of the required energy, over 5000 km/year. Araki et al [29] have also reported on one year of onboard pyranometer data, in Miyazaki, Japan. These measurements were fit to a linear shading model, yielding an average shading height of 8.6° in the direction along the road and 15.2^o in the direction orthogonal to the road. Both measurement campaigns were conducted in a mostly non-urban environment.

In the present work, the effect of shading is estimated considering detailed 3D modelling of a whole urban area and the shadowing of all buildings onto roads. The following section describes the methods used to assess the urban solar potential for onboard solar for vehicles on roads and urban parking spaces for the case study of the city of Lisbon, Portugal. Section 3 presents the model results, discussing limitations and what they imply for onboard solar vehicles in the urban environment. Section 4 wraps up with the main conclusions of the work.

2. METHODS

All calculations refer to the city of Lisbon, Portugal, which has favourable conditions for solar energy harvesting with average yearly irradiation of 1.8 MWh/m^2/year. Peak solar height (at solar noon) varies between 74^o in summer and 27^o in wintertime.

The methodology of the present work uses two datasets of geographical information systems (GIS) to assess the solar potential. The first dataset includes municipal parking sites and the road network. Both sets are freely available: parking sites through the city hall open data portal [30] and the roads through the Open Street Maps platform [31]. The second dataset includes a Digital Surface Model (DSM) obtained by LiDAR (Light Detection And Ranging) describing the altimetry of the city with high detail (i.e. 1 m^2) [32].

For large spatial scales, computing radiation and accounting for obstructions to sunlight can only be performed using computational modelling of the physical context [33]. In these situations, solar availability is usually modelled in a GIS, using a DSM that describes the urban environment.

Following the methodology proposed by Santos et al. [34], the ArcGIS Area Solar Radiation numeric model was selected to perform the analysis for the city of Lisbon. Using the city's DSM, a detailed estimation of the solar energy was obtained since the shadows cast by surrounding buildings and topography were calculated for each location in the area. The calculation was performed for the DSM, hence the ground inclination is taken into account (i.e. the solar irradiation on a tilted road will be that of an inclined surface) but neglecting the height of the vehicles. This simplification is expected to lead to an underestimation of the solar potential below 5% for the typical urban environment. Local monthly atmospheric diffusion and transmissivity coefficients were considered.

Since locations under trees are always shaded, the initial set of parking sites was purged of spaces under vegetation before the calculation of the solar potential. To that purpose, the vegetation map was obtained using the spectral information available in an orthophoto mosaic, with 0.50 m^2 of spatial resolution. Through an object-oriented classification, the city's tree coverage was obtained and used to remove unsuitable parking sites from the original dataset [35]. This operation eliminated data points corresponding to about 10% of the whole parking dataset. However, this area was taken into account in the assessment of the solar potential (assumed to be totally shaded at all times).

Following the methodologic framework (Fig. 1), a solar map was produced for each month. For the calculation details refer to [36]. Then, all 12 maps were summed up and the annual solar radiation at the surface in Wh/m^2 was calculated for the whole city area. The final solar radiation maps for the roads and the suitable parking sites were obtained by overlaying the GIS data with the previous annual solar map. The urban parking spaces data set was also analysed with an hourly resolution for the summer and winter solstice.

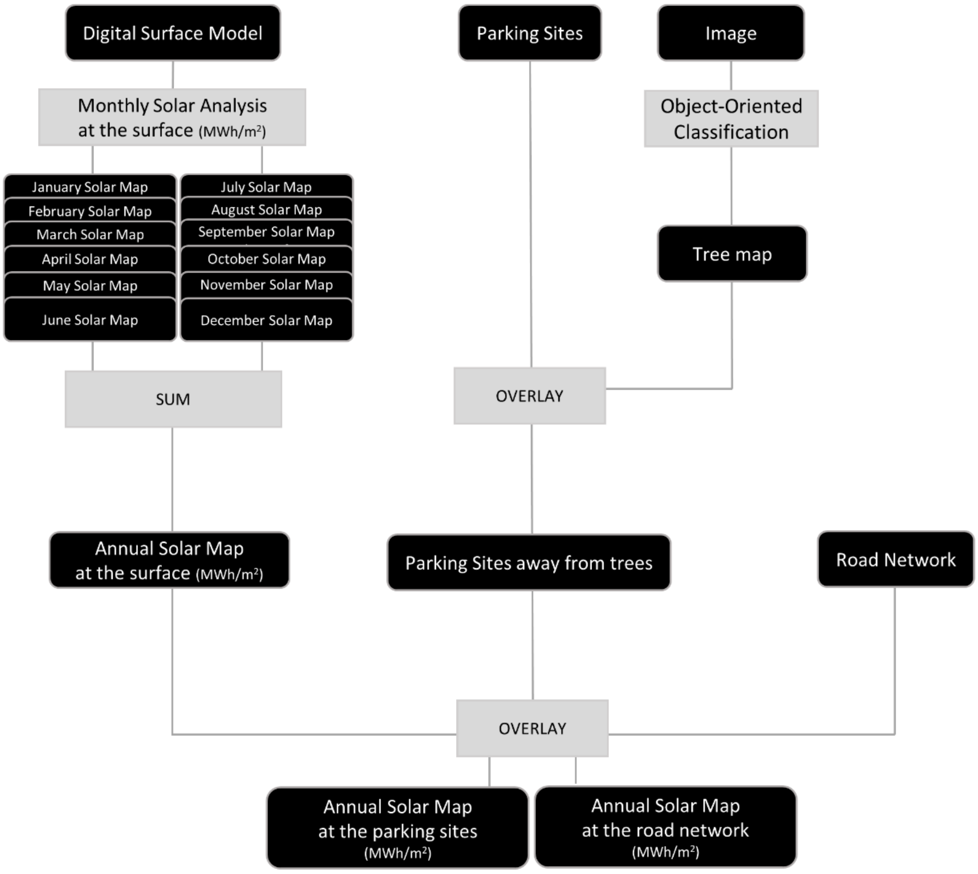

Fig. 1 – Methodology for solar potential assessment

For the analysis, the city area was divided into two different subareas, henceforward referred to as Central and Residential areas; the parking data is only available for the central area. The central area is, in general, characterized by a denser urban layout, with higher buildings and narrower roads, whilst the residential area has, in general, wider open spaces and less compact neighbourhoods. Nevertheless, there are some low-density areas in the central area and some compact areas in the residential area.

3. RESULTS

The impact of shadowing on the yearly solar potential of roads, or the solar potential of driving onboard solar vehicles in the city of Lisbon, is shown in fig. 2. One can observe a wide variability in solar potential across town, with no relevant shadowing along many main roads and residential areas but significant irradiation losses in the more compact areas.

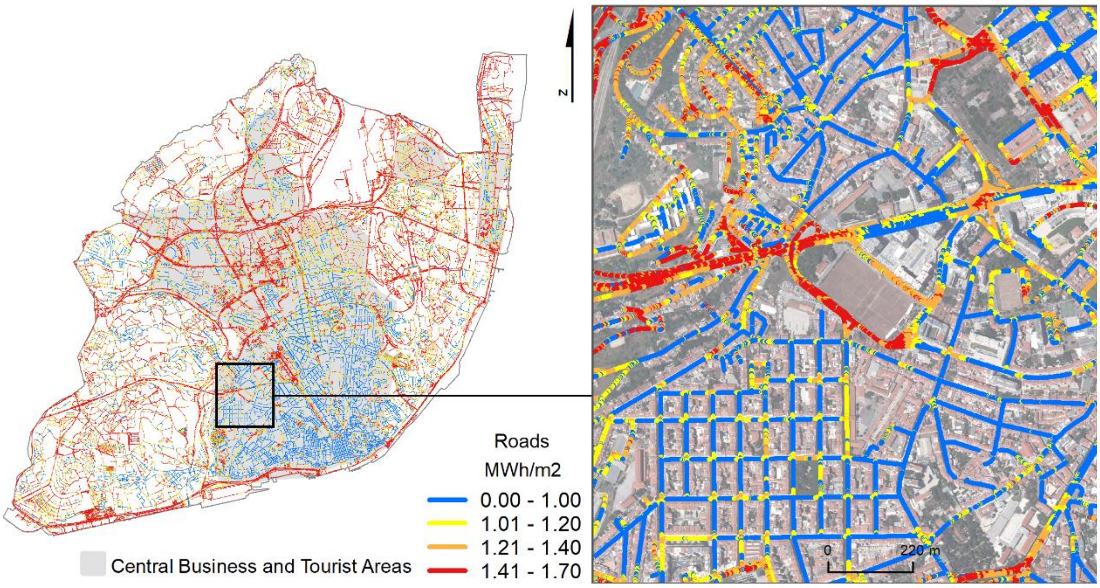

Fig. 2 – Yearly solar irradiation on roads in the city of Lisbon (left). Inset (right) illustrates high solar potential on main roads and modest solar potential in compact areas.

Figure 3 presents the distribution of daily solar irradiation for the central and residential areas for December and June. As expected, and for both areas, irradiation is higher in summer and shadowing more relevant in December. The effect of the denser morphology in the central area is decreasing irradiation (higher shading levels) for about 8% and 12% of the locations, for summer and winter, respectively. The relative decrease in irradiation is much more severe in winter (about 60%, on average) than in summer (about 20% in summer).

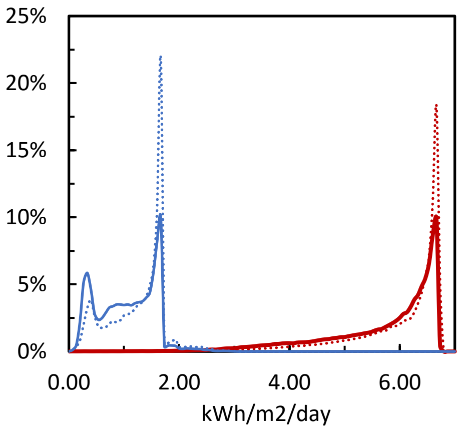

Fig. 3 – Solar irradiation histograms for December (blue) and June (red) in the central (solid line) and residential (dotted line) areas.

The solar potential of urban parking spaces is lower than that of the roads in the central area (fig. 4), mostly because they are often located along the sidewalks, hence more prone to shadowing from neighbouring buildings than the middle of the road. One may also note that parking spaces on the north side of east-west roads feature higher solar potential, due to less sunshine obstruction from neighbouring buildings.

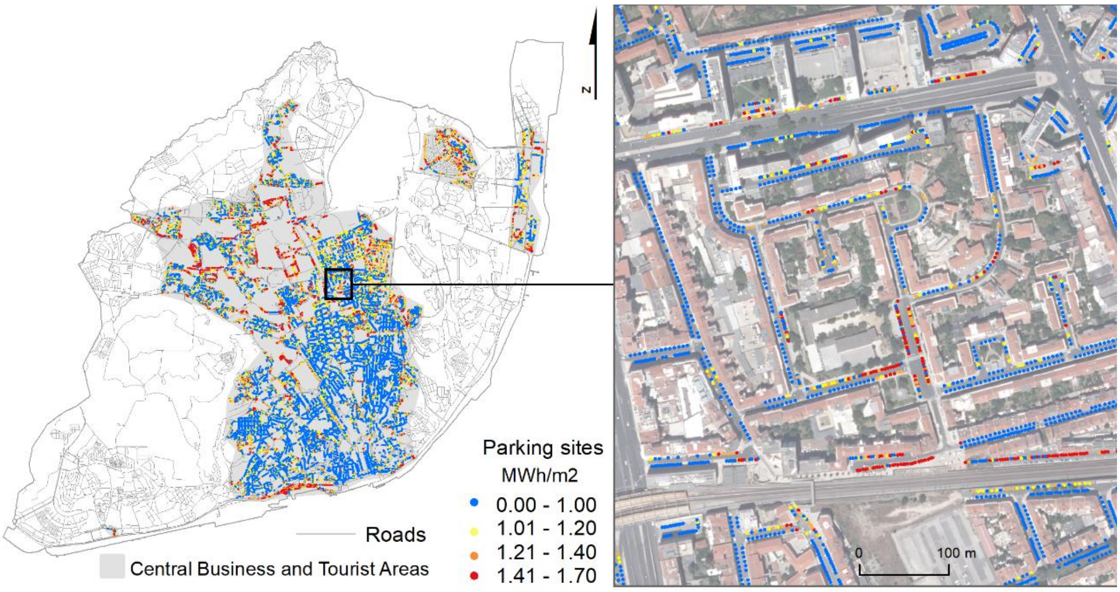

Fig. 4 – Yearly solar irradiation on urban parking spaces in the central area (left). Inset (right) illustrates higher solar potential on parking spaces on the north side of east-west roads, which are less affected by buildings' shadows during the day.

It is also interesting to explore the hourly effect of shadowing. Figure 5 shows the model results for a winter and a summer day for urban parking spaces. The red marker shows the median value for all parking places whilst the error bars indicate percentiles 25% and 75%. We can observe that the summer day reaches peak power above 800 W/m^2 at noon, with no relevant shading. At earlier and later hours of the day there are shading events in some areas, which leads to a wider dispersion of available solar power from almost no shading to almost no irradiance. In the winter, shown with the blue marker, when solar elevation is lower throughout the day, shadowing from buildings has a much stronger impact on the available irradiance at all times of the day.

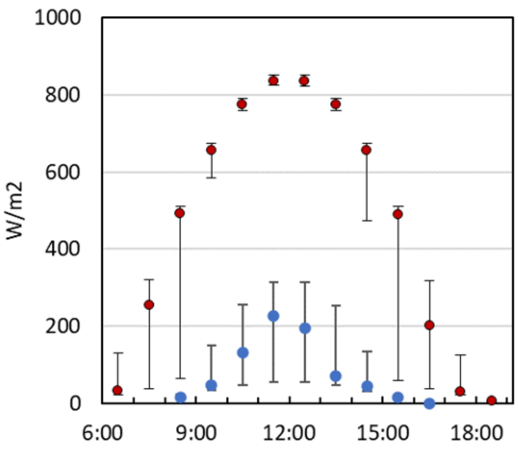

Fig. 5 – Hourly solar irradiance for parking spaces for a day in December (blue) and in June (red). Error bars indicate 25% and 75% percentiles.

The median irradiation losses are presented for the various cases for all months of the year in Table 1. We can observe that the annual median irradiation loss is twice as large for the urban parking, with about half of the irradiation being lost due to shadowing. For roads, irradiation loss for median locations is about 25%, slightly higher for the central area, with higher building density. Shadowing is much more significant in the winter months (over 80% irradiation loss for urban parking, about 50% for roads) than in the summer when the irradiation loss for roads is below 10%. For urban parking, even in summer, irradiation losses for median locations are above 20%.

Table 1. Median irradiation loss for urban parking, central and residential area, for all months of the year and annual average (grey background).

	J	F	M	A	M	J	J	A	S	O	N	D	Y
Urban parking	80%	67%	57%	31%	23%	23%	28%	36%	47%	70%	78%	82%	52%
City centre	51%	39%	28%	15%	10%	7%	8%	13%	21%	36%	49%	54%	28%
Residential area	47%	36%	24%	12%	7%	1%	5%	9%	18%	31%	45%	49%	24%

When the irradiation loss distribution (top and bottom quartile) is considered, as shown in fig. 6, one can also observe that the variability of shadowing in the urban parking areas is much wider than in road areas. In winter, for the worst quartile, irradiation losses for roads are around 60% (blue and orange in Fig. 6) but reach 90% in urban parking spaces (grey). In the summer months, the worst quartile irradiation losses for roads are still below 20%, whilst for urban parking, losses reach 50%.

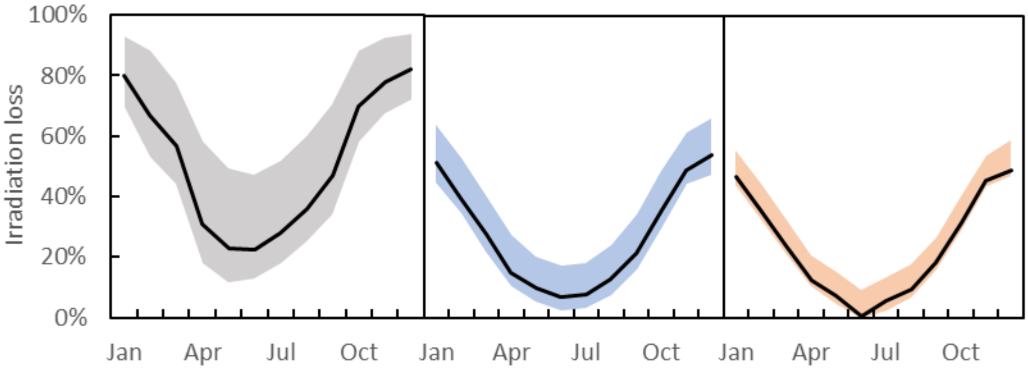

Fig. 6 – Monthly irradiation losses due to shadowing for urban parking spaces (grey), central (blue) and residential (orange) roads. The solid black line is median; coloured areas correspond to 25% and 75% percentiles.

Assuming that, on average, an electric car consumes 13 kWh/100 km (current state-of-the-art [20]) and it can hold about 1 kWp of installed photovoltaic power [37], one can estimate the extended daily driving range (EDR) for onboard solar vehicles. Conservatively, we have also considered an extra 25% loss [23] to take into account other losses due to the curvature of the PV module, mismatch [38], partial shading [29] or transformation losses. This simplified estimation does not consider battery saturation which could lead to an overestimation of EDR in the summer months. For the case of urban parking spaces, we have also assumed that 20% of parking events occur in underground or indoor parking facilities [26]. The results are presented in fig. 7.

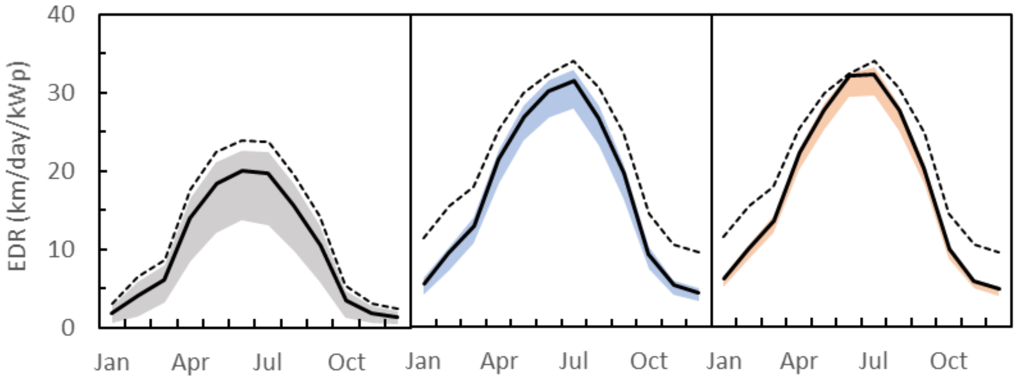

Fig. 7 – Monthly Extended Driving Range (EDR) due to onboard solar for urban parking spaces (grey), central (blue) and residential (orange) roads. The solid black line is the median and the dashed line is the unshaded EDR; coloured areas correspond to 25% and 75% percentiles.

For the urban parking spaces, the annual average extended driving range for median locations is about 10 km/day/kWp, lower than the 17 km/day/kWp for roads in the central area, and 18 km/day/kWp in the residential area. In the summer, the extended driving range is about 20 km/day/kWp for urban parking and above 30 km/day/kWp for the roads. In winter, onboard solar adds less than 2 km/day/kWp to the driving range, compared to 5 km/day/kWp for roads. These results point out that while onboard solar can contribute to significantly reduce the charging needs from the grid, especially in the summer months, the limited resource available during the winter does not allow reducing the battery capacity without risking the vehicle's autonomy.

The variability observed for the irradiation losses in urban parking is also reflected in the estimated solar extended driving range. In the summer, a favourable parking space may yield 22 km/day/kWp whilst a location in the bottom quartile will yield less than 15 km/day/kWp. The effect of the driver's preference for a favourable parking space may be numerically described by the ratio between the EDR for the top quartile and the median. For urban parking, this ratio varies between 1.13 and 1.57, for summer and winter, respectively, with an annual value of 1.2, meaning that choosing a favourable parking space can increase the solar driving range by 20%. This information could be passed on to electric vehicle drivers looking for a parking spot, who benefit of the solar exposure to gain additional miles of autonomy during the day. This variability is less pronounced for roads.

Since the typical vehicle kilometres travelled (VKT) in the city of Lisbon is about 30 km/day [39], assuming that commuters park their cars in a median urban parking space, onboard solar can reduce annual charging needs by about 33%. Of course, if the vehicle is parked in a suburban open area without relevant shadowing then irradiation losses could be ignored, leading to an annual solar fraction of about 60%.

On the other hand, public transport and service vehicles driving at all hours of the day, with typical daily vehicle kilometres travelled in the range of 100 to 200 km/day [33], are expected to reduce operating cost by 9 to 18% due to onboard solar. The difference between the central and residential area is not very significant.

This analysis refers to the case study of Lisbon, with favourable solar resource and, at a latitude of 38° N, relatively high solar heights throughout most of the year. There are of course many other cities worldwide with higher irradiation, such as in California, Chile, or Australia. For locations with less sunshine or at higher latitude, the extended driving range with onboard solar will be somewhat lower. On the other hand, Lisbon is a rather compact city. Other urban areas with lower building density and/or wider roads, will have higher extended driving ranges than those presented in this work.

4. CONCLUSIONS

Irradiation losses due to shadowing in urban environments have a relevant impact on the solar potential of vehicle integrated photovoltaics. For the case study of Lisbon, and neglecting the height of the vehicles, which can represent a 5% underestimation of the solar potential, it is shown that shadows from buildings halves the solar resource available at urban parking areas and reduces it by a factor of 24 to 28% in urban roads, depending on the building density. This impact is more significant in the winter months, when the solar extended driving range is between 2 and 5 km/day/kWp for urban parking and roads, respectively, if assuming a consumption of 13 kWh/100 km. These low values suggest that onboard solar does not enable the reduction of battery capacity without limiting the vehicle's driving autonomy.

Nevertheless, onboard solar can significantly contribute to reducing the charging needs from the grid throughout the year, about 33% for cars that spend most of the day parked in an urban area (assuming VKT of 30 km/day) and 9 to 18% for public transport and service vehicles (assuming VKT of 100-200 km/day).

It was also observed that, for urban parking, a preference for a sunny parking space can increase the solar driving range by about 20%. This enhancement can only be realized in an early phase of deployment of onboard solar vehicles when the demand for sunny parking places is not very significant.

Overall, these results show that onboard solar would significantly reduce annual charging needs, with increased convenience for the user and reduction of operational costs, further enhancing large scale adoption of electric vehicles and thus contributing to the decarbonization of the urban mobility.

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