SUN-POWERED WHEELS: PV CHARGERS FOR SHARED E-SCOOTERS TO MITIGATE URBAN CO_2 EMISSIONS

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Abstract. Shared scooters have the potential to be environmentally friendly; however, current data demonstrate that shared e-scooters produce additional 239.9 tonnes of CO_2 in Riga. The lifespan of the scooters and the operations involved in charging their batteries play a critical role in determining the total net CO_2 emissions. Utilizing locally produced photovoltaic (PV) energy to eliminate the need to move scooters (or swappable batteries) for charging by providing continuous charge top-ups, would be a significant step towards sustainability of shared electric scooters. In this study we have analysed the possibility of generating enough energy on-site to provide chargers with PV energy based on data from 3 million scooter trips from the 2021-2022, to determine the energy requirements. Using solar energy data from Riga over the past seven years and a Monte Carlo simulation, the minimum requirements for scooter charging stations were determined to ensure adequate energy provision without grid connection. The analysis demonstrated that using just 0.2 m^2 of PV panels combined with energy storage system, it was possible to provide enough solar energy to ensure continuous charging of 98% of electric scooters for most of the season. Still, the solar radiance in Latvia is insufficient to generate enough energy for worst-case scenarios during early springs and late autumns. Despite challenges, introducing this system in Latvia would significantly reduce CO_2 emissions. However, PV chargers are best suited for regions with consistent solar energy, such as Portugal and Los Angeles, California, where they can operate smoothly all year round.

Keywords: e-scooter CO_2 emissions, photovoltaic (PV) charging, renewable energy in transport, shared scooters, micromobility.

Introduction

The aim of this article is to evaluate the technical feasibility of the e-scooter charger docks with local PV generation in Latvia.

The implementation of dockless mobility systems, encompassing traditional bicycles, e-bikes, and electric scooters, was rapidly adopted in the United States by 2017 [1]. Dockless electric scooters, in particular, surged in popularity, amassing 38.5 million rides in their inaugural year of 2018, the level which station-based bicycles reached over a decade [2]. Similarly, after shared electric scooter introduction in Riga, Latvia in 2019, their popularity grew exponentially: in 2019 there were around 100 scooters [3], by 2021 there were 1750 providing 750 thousand rides [4] – an achievement that was tripled by the next year [5]. While causing increasing concerns regarding the safety of the electric scooters sharing the pavements with pedestrians[6], this popularity of electric scooters presented an opportunity to support sustainability efforts by incorporating these vehicles into the urban transportation framework [7].

The initial research in the environmental effect of the scooters, however, was discouraging. It was found that the emissions from manufacturing the scooters and the process of relocating them for charging substantially exceeded the emissions from the energy used to operate the scooters themselves [8]. Hollingsworth et al. estimated lifecycle emissions of 141 g CO_2 per passenger-kilometre (ppkm) for two-year-old e-scooters [9], the 2020 ITF analysis ranged scooter emissions from 29 to 508 g CO_2 ppkm, averaging 106 g CO_2 ppkm [10]. When compared to traditional internal combustion engine (ICE) cars, which are estimated to emit between 160 to 208 gCO_2 pkm [10; 11], electric scooters perform favourably; they are on par with those from battery electric vehicles (BEVs), currently emitting between 111 $gCO_2 \cdot km^{-1}$ (EU average) to 176 (India) [12]. However, these emissions are greater than those of ICE buses, which range from 52 to 91 gCO2 ppkm [10; 13]. In Riga, Rubenis et al. estimated scooter emissions to be 221g CO_2 ppkm [14], noting however that more research is necessary in the future with data over a longer time period to establish scooter lifetime with more confidence.

Using green energy just for battery charging would have a minor effect, as studies agree that energy for operation accounts for less than 5% of CO_2 emissions [15]. Lack of the research regarding scooter charging and rebalancing has been noted, considering the substantial influence these aspects have on environmental sustainability [16]. Kazmaier et al. reported that electric scooters could reduce CO_2

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emissions to as low as 46 gCO_2 ppkm by adopting e-scooters with swappable batteries, as the scooter transport adds 12% or 20 gCO_2 ppkm [17]. Fitting scooter charging stations with solar power energy would be a solution that has well been adapted in docked bicycle industry – for years many docking stations have been fitted with solar PV panels, although quite often without analysing the required amounts of the energy required, which has led to their inoperability in cloudy days [18]. Analysis by Li et al. has shown that on average of 24% downtime has been marked and doubling the PV panel size could reduce most stations' downtime by 55% [19]. However, there has been almost no research focusing specifically on scooter PV charging on-site. In a 2022 Singapore study, Zhu et al. proposed a solar charging system for 24-67% of the total number of e-scooters, requiring 1–3 square meters of PV panels per station, which would be capable of supporting nearly all e-scooter trips and reducing charging-related trips by 98% [20].

2024 research by Rubenis et al. calculated that charging operations add 17.15 g CO_2 in Riga, and moving to charging docks with locally produced PV energy could hypothetically reduce total CO_2 emissions from the electric scooter fleet in Riga by nearly 35% or 51 tonnes CO_2 annually [5]. This article will examine the feasibility of the on-site generated PV energy for scooter charging in Riga, and determine the technical parameters required for such a system.

Materials and methods

To evaluate the technical viability of the on-site PV generation, the energy requirements for the scooters were compared with energy availability from the solar radiation.

The energy requirements are determined by the scooter trip characteristics and scooter technical parameters. Scooter trip characteristics for Riga were obtained by logging trip data from main charger operator application programming interface (APIs). For purposes of determination of individual scooter trip history, a database of scooter IDs were logged. To establish the trip characteristics and energy requirements, data from 3.9 million scooter trips over the two-year period for two seasons in 2021 and 2022 were analysed.

As the data available from API does not show the actual energy consumptions, but the remaining battery SoC, the energy consumption needed to be calculated from that:

$$E_{SC,n} = \frac{\left(SoC_{n+1} - SoC_n\right) \cdot V_{SC}}{100}, \quad (1)$$

where n – number of trips;
$E_{SC,n}$ – energy used by scooter during the trip n, Wh;
SoC – battery state of charge at the beginning of the trip n and n+1, %;
V_{SC} – battery capacity for the scooter, Wh.

The energy demands of electric scooters are influenced by daily travel distances and the scooter energy consumption per journey. An examination of data from 2021 and 2022 reveals significant fluctuations in daily travel distances and charging frequencies. In 2022, the average daily travel distance of scooters declined by 50%, from 12 km in the previous year to 6 km. Notably, the most common daily distance travelled was only 2 km, accounting for 12% of all scooter days, as depicted in (Fig. 1).

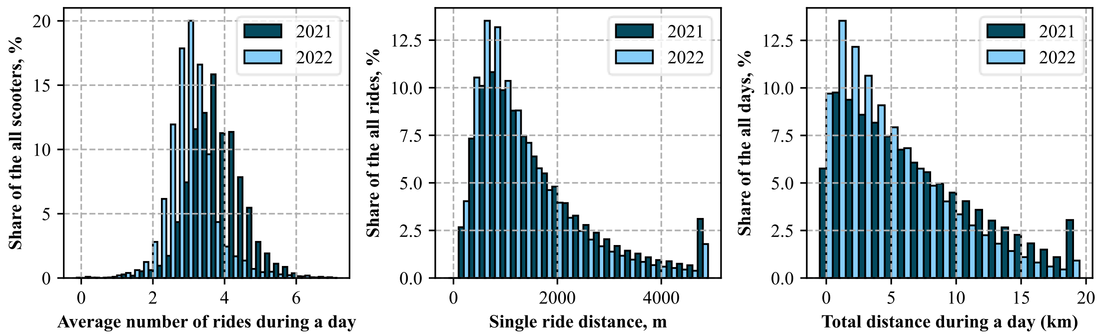

Fig. 1. **Distribution of average number or rides, trip distance and scooter daily distance**

This reduction can be attributed to a decrease in both the average number of daily scooter rides, from 3.8 to 3.0, and the average journey distance, which fell from 1.7 km in 2021 to 1.5 km in 2022.

Reduced energy consumption due to shorter rides has led to a marked increase in the number of scooter rides undertaken between charging, with the median rising from 5 rides in 2021 to 10 rides in 2022 and the average rising from 6.7 trips per charge in 2021 to 9.5 trips in 2022. This is also reflected in increase of the duration between charging (Fig. 2).

Furthermore, the state of charge (SoC) distribution for scooters exhibits an almost linear pattern within the 40-90% range, indicating a consistent charging behaviour where scooters are typically retrieved for recharging once they reach 30% remaining battery life and are charged to between 90-100%. Interestingly, the SoC data suggests a shift in charging practices between the two years: in 2021, scooters were generally charged to 90% and removed from circulation at 30% remaining battery, whereas in 2022 the policy appears to have changed, with scooters being charged to their full 100% capacity, and some remaining available for use even with only 20% of their battery life remaining.

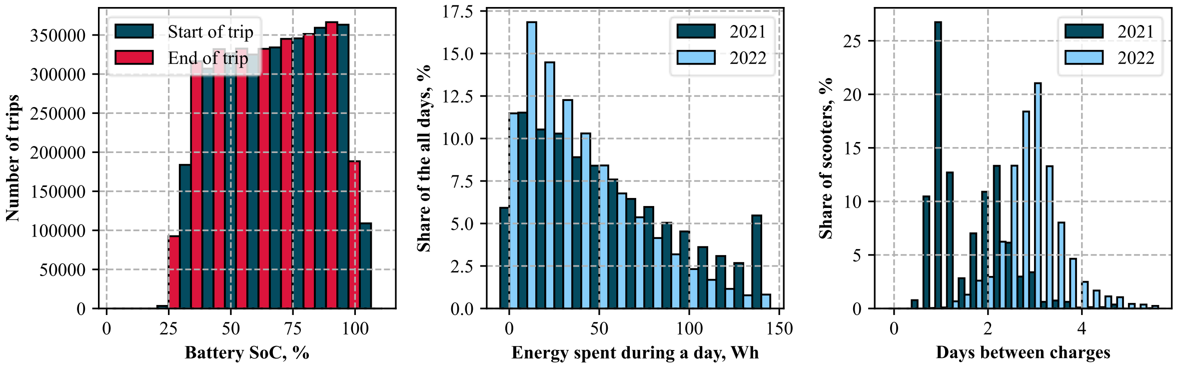

Fig. 2. **Shared scooter battery state of charge (SoC) and energy consumption distribution**

The majority of journeys consumed between 2.5% to 5% of the scooter battery capacity. Based on API data, the battery capacity of the scooters ranges from 200 to 280 watt-hours (Wh). Consequently, this means that a typical trip results in a discharge of approximately 5 to 10 watt-hours from the battery.

Scooter energy consumption per km (Fig. 3) is dependent of many variables: riders' weight, trip incline and the quality of the road surface are significantly impacting the variability of energy consumption. Different riding speeds, stop-and-go patterns, and route choices can also contribute to the observed heavier tails in the distribution. Scooter energy consumption in Riga ranges between 2.5 to 12.5 $W \cdot km^{-1}$, with mean 8.5 $W \cdot km^{-1}$, median 7.8 and standard deviation 3.0 $W \cdot km^{-1}$. There are slight differences between 2021 and 2022, however they are not significant. The energy consumption distribution has a kurtosis of 1.3 showing a higher propensity for extreme values compared to a normal distribution, with a skew of 1.1 demonstrating slight skewness towards higher energy consumption.

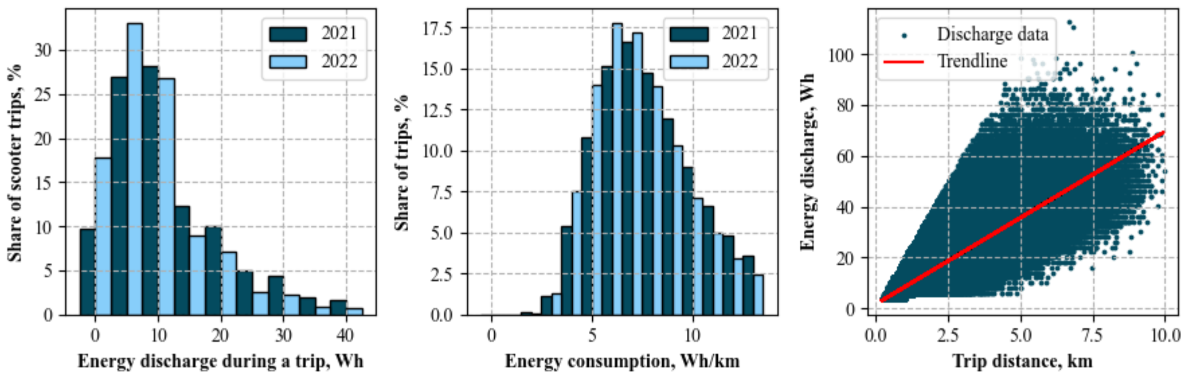

Fig. 3. **Distribution of energy consumption and value depending on scooter trip distance**

Determining the function for energy consumption depending on the scooter trip statistics was carried out using SciPy optimization software package. Linear correlation between the trip distance and energy discharge was most accurate (2), demonstrating R^2 value of 0.75.

$$E_{SC,n} = \quad 6.786 \cdot s + 1.7, \tag{2}$$

where s – distance of the trip, km.

Knowing these parameters Monte-Carlo simulation can be used to generate the trips for various energy consumption scenarios.

Solar radiation data from the Latvian Environment, Geology and Meteorology Centre information system [21] was used to develop the function for predicted amounts of PV energy for the testing site. Data for 7 years 2015-2022 was analysed with an hourly resolution to develop an expected PV energy production scenario.

The data from the Riga Meteorologic Station was used. The station is located in Riga, the capital of Latvia, in Northern Europe, with latitude: 56º 56' 45.60" N and longitude: 24º 06' 21.20" E.

The climate of Latvia is characterized by an annual average air temperature of +6.8 ºC. Urban heat islands, particularly in Riga, exhibit the highest annual average air temperature at +8.0 ºC. Latvia enjoys an average annual sunshine duration of 1700-2000 hours, peaking in July with approximately 300 hours of sunlight. Contrastingly, December experiences the least amount of sunlight, averaging to about 25 hours, which translates to less than an hour of sunshine per day [22], which significantly hampers the PV energy availability during winter months.

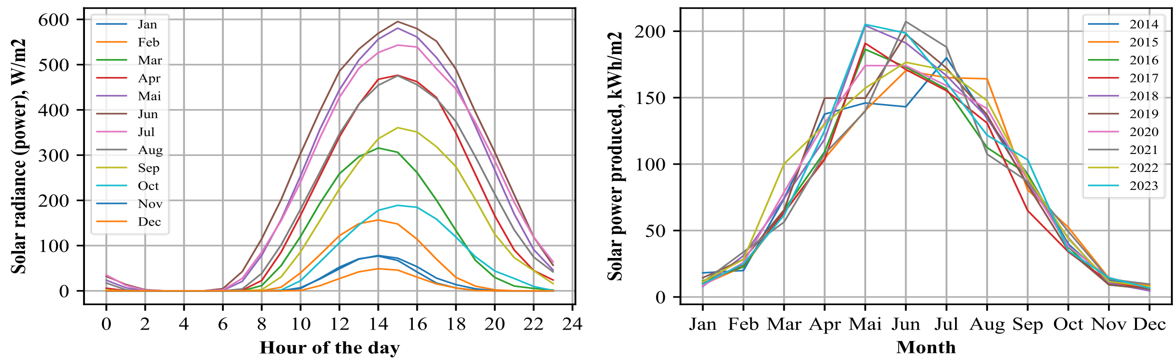

Fig. 4. **Solar radiation and energy in Latvia, 2014-2023**

To simulate the available solar energy for modelling purposes, the Gaussian (normal) distribution curves of the annual solar energy were obtained (Fig. 5).

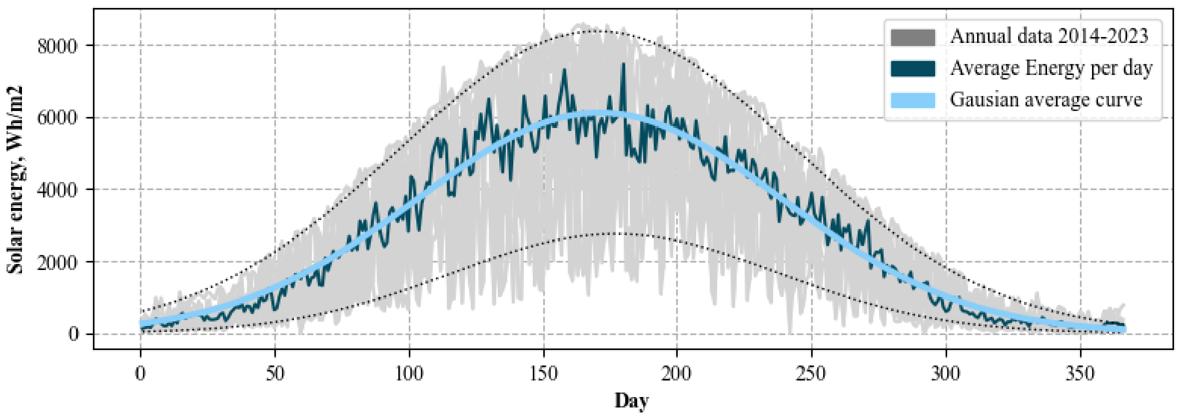

Fig. 5. **Gaussian solar energy distribution curves in Latvia by day**

The fitting of a Gaussian (normal) distribution curve to the average solar radiance data in Latvia over the last decade (2014-2023) was accomplished utilizing the SciPy optimization software package. The derived parameters characterizing the curve include the mean (μ), standing at 177.048, the amplitude (A), at 2756.264, and the standard deviation (σ), which is 60.656, representing the central tendency, peak height, and data spread, respectively.

$$G_{PV,t} = A \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}} = 2756.264 \cdot e^{-\frac{(t-177.049)^2}{-2\cdot(60.656)^2}} , \quad (3)$$

where t – day of the year;
$G_{PV,t}$ – sum of solar radiance energy during the day t, $kWh \cdot m^{-2}$;
A – amplitude, which scales the height of the curve;
μ – mean, which locates the centre of the peak;
σ – standard deviation, which controls the width of the bell curve.

Similarly, the maximum and minimum curves were determined, and the parameters were: μ =170.355, A = 8379.754, σ = 74.087 and μ =177.049, A = 2756.264 and σ = 60.656 respectively.

To obtain the actual energy produced, the theoretical solar radiance must be adjusted for solar panel area and efficiency:

$$E_{PV,t} = G_{PV,t} \cdot a \cdot \eta , \quad (4)$$

where $E_{PV,t}$ – solar energy on the day t, kWh;
a – solar panel area, m^2;
η – coefficient of solar panel efficacy.

A Monte Carlo simulation was carried out to generate PV energy availability for each day, selecting a value between minimum and maximum curves. The power generation scenario assumed generic solar cells with 10% and 20% efficiency.

Two energy use scenarios were further analysed, to evaluate the suitability of locally installed PV generation. In the first scenario, the simple comparison between the energy generated and energy required was carried out.

$$R_t = \frac{\sum_{n=1}^{N} \left\{ E_{PV,t} > E_{SC,n} \right\}}{N} , \quad (5)$$

where R_t – share (ratio) of the scooters where PV energy is sufficient to cover the energy spent during the day of the year t;
N – total number of scooters.

For comparative purposes, an alternative model was conceptualized in which scooter chargers are equipped with 0.2 m^2 PV cells operating at 20% efficiency, coupled with an energy storage capacity of 200 Wh. This system is governed by a hierarchy of operational priorities:

1. maximize the charging of the scooter battery using solar energy;
2. store any surplus energy in the charger battery reserve;
3. in cases where the scooter battery is not fully charged, supplement the charging using the stored energy from the charger battery.

Results and discussion

The first results were obtained using a simple comparison between the energy required for scooter charging and PV energy available. The two levels of PV panel efficiency were used: 10% and 20%.

Our findings indicate that within Latvia's latitudinal range, a PV array spanning at least 2 m^2 is necessary to fully charge each scooter throughout the operating season from April to November, assuming the PV efficiency of 10%. Should the PV efficiency be doubled to 20%, the requisite area for the PV panels would be halved to 1 m^2, which still is excessively large for PV panels installed on standalone scooter charging stations.

Nevertheless, the integration of an auxiliary energy storage system alongside the deployment of energy management algorithms can markedly enhance the system's performance without expanding the PV panel area. Through a simulation based on scooter usage and solar radiation data from 2022 and utilizing a 0.2 m^2 PV area with 20% efficiency, we achieved a significant increase in the proportion of days with faultless scooter operation. Specifically, the rate of days where the simulated scooter battery level remained above 0 kWh rose from 40% when solely reliant on PV charging, to 98% with the use of a 200Wh energy storage in the charging station and an optimized energy flow algorithm (Fig. 7).

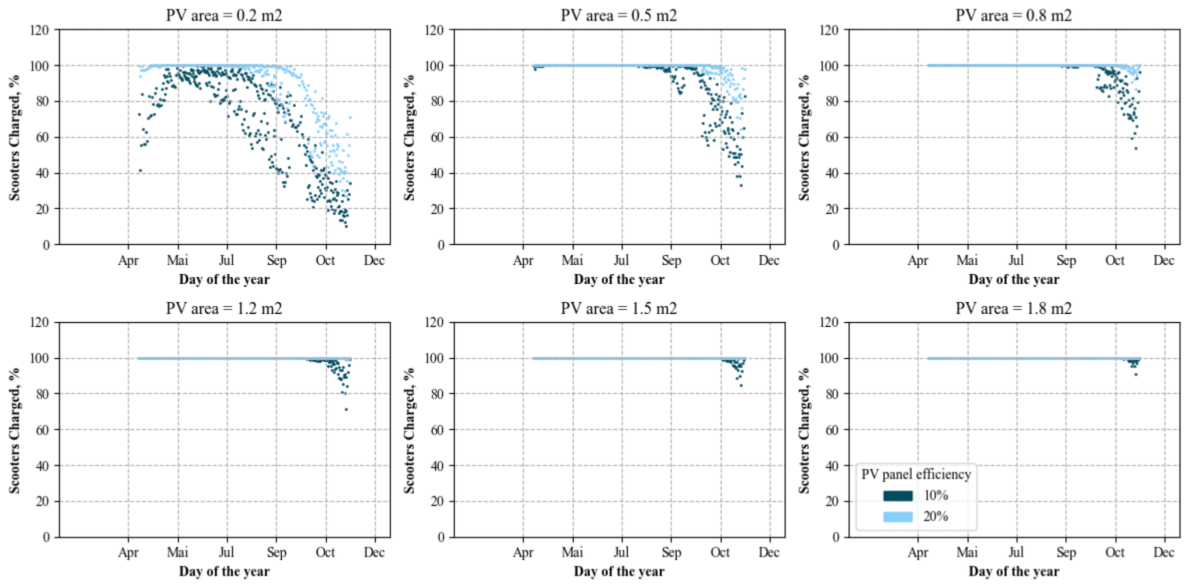

Fig. 6. **Share of scooters, which could be fully charged with PV generated energy without storage and charging optimisation**

Despite these improvements, it was not possible to eliminate charging failures. Beginning from the latter half of October, the rate of charging failures began to rise incrementally, reaching a peak of 20% by mid-November, coinciding with the close of the scooter season. This rate, however, was substantially lower compared to the scenario without optimization measures, where the failure rate occasionally surged to 90%.

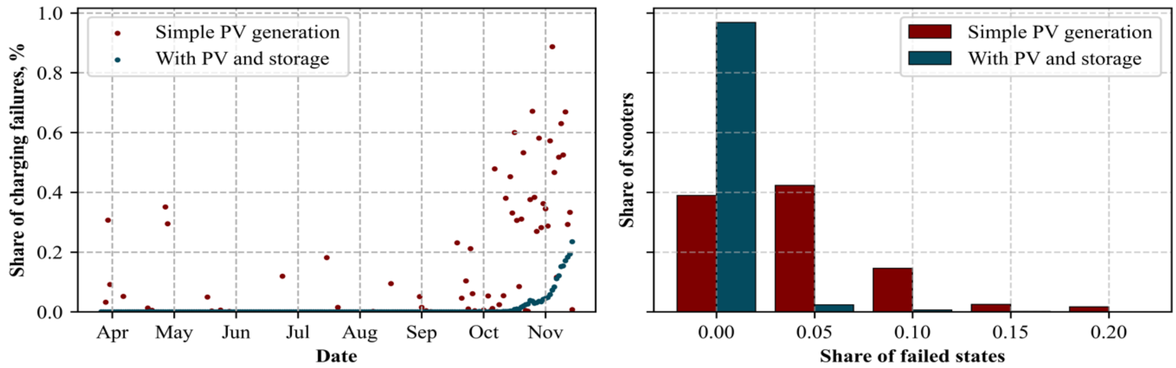

Fig. 7. **Modelled share of scooter charging failures in 2022** (PV area: 0.2m^2, efficiency: 0.2)

The challenge stems from the inadequate solar radiation in Latvia during spring and autumn, which fails to meet the energy demands of the scooters. This shortfall becomes apparent when examining the battery levels of individual scooters (Fig. 8), where the generated PV energy begins to trail behind the required levels as early as September 29th [A]. Initially, this deficit is compensated for by the gradual depletion of the charger energy storage, but by November 1st, this measure is no longer sufficient [B]. Were it not for the extended period during which the scooter was parked, from November 1st to 4th [C], the decline in scooter battery levels, which commenced on November 11th [D], would have been precipitated by approximately a week, resulting in a system failure [E] around November 10th rather than November 18th.

While the system would ultimately fail in Latvia, it would still be usable for most of the scooter season, falling back to current scooter manual charging only during the early spring and late autumn, which still would help bring down the CO_2 emissions significantly.

These findings are different to those of Zhu et al, who found that 1-3m^2 area for charger stations was required to cover almost all the scooter trips in Singapore [20]. Singapore study assumed much fewer but larger PV charging stations without energy storage, and that scooters would return to the nearest station when their battery level is below a certain SoC threshold – 3.75%. This would mean that in other times the scooters would stand unused. In our model, the scooters would be parked on any of smaller local PV charging stations after almost each ride, to maximise the charging time. This difference in approach might be explained by differences in the charger use and in solar power availability – in Singapore, the daily average solar irradiation is 5532 Wh·m^{-2} a day; the amount which Riga can reach during the few summer months only.

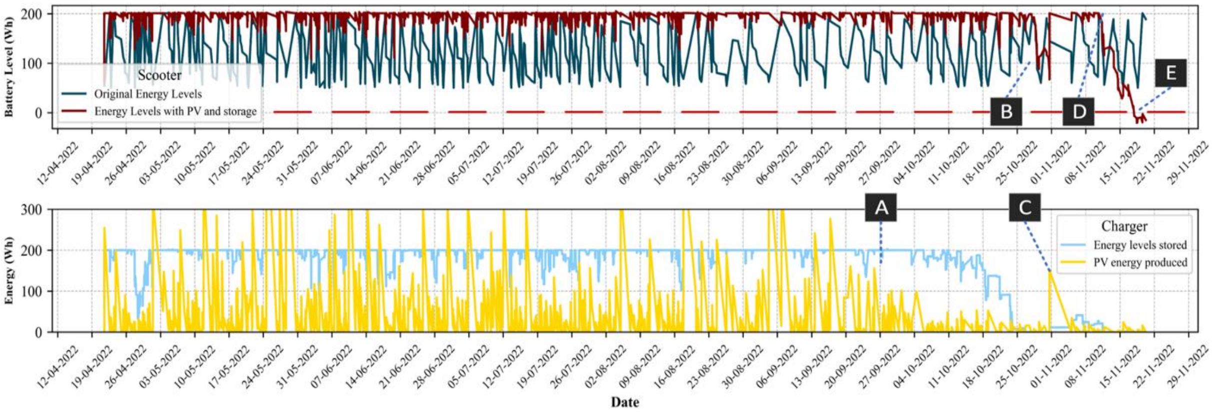

Fig. 8. **Modelled individual scooter charging** (year: 2022, PV area: 0.2m^2, efficiency: 0.2)

Additionally, a system of this nature would be feasible year-round in regions with higher levels of solar radiation. For instance, the solar radiation in cities such as Lisbon, Portugal, and Los Angeles, USA, is sufficient to meet the minimum energy requirements throughout the entire year (Fig. 9). This demonstrates the potential for broader applicability of such a system in geographies that are favoured with more abundant sunlight.

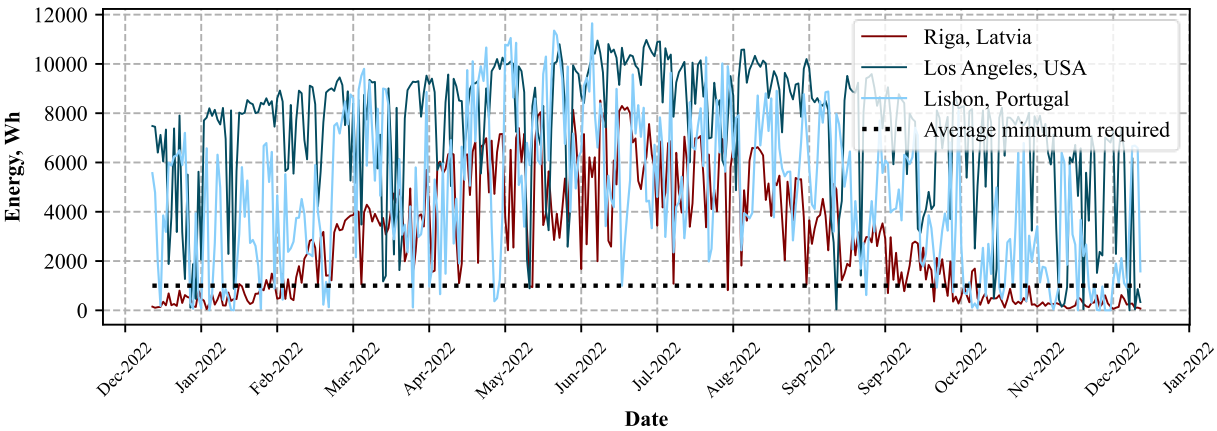

Fig. 9. **Solar radiation in various countries vs the minimum requirements**

Although not the primary focus of this research, operational issues, and CO2 emissions from such a PV charging infrastructure should be briefly touched upon to fully assess the system's feasibility.

Several approaches how to build such a system for locally produced PV scooter charging could be possible, which would affect the system efficiency and CO_2 emissions. They cannot be exactly determined at this point; however, it is possible to consider the main aspects. The efficiency of the system could be compromised by several factors, starting from PV panel degradation over time, with median losses in the 0.5-0.6% per year range [23], to temporary efficiency loss due to the soiling of surfaces, which can be restored by cleaning the panel surfaces.

CO_2 of the PV charging infrastructure should be added to the total CO_2 emissions. The lifetime emissions from PV module amount range from 115.04 to 201.4 kgCO_2·m^{-2} depending on their technology [24]. The panel lifespan is typically guaranteed for 25 years, although some systems have operated successfully for over 30 years. [25]. Assuming a reduced lifespan of 10 years, the 0.2 m² PV panels for a charger would contribute 2.3 to 4.0 kg of CO_2 annually, or 1.8 to 3.2 gCO_2·km^{-1}, based on an annual scooter ride distance of 1250 km [5].

The CO2 emissions range for the batteries used in energy storage is broader, varying from 38 to 356 $kgCO_2 \cdot kWh^{-1}$ [26]. Disregarding the worst performers, this would come to 7.6 $kgCO_2$ per charging station. Battery lifespan is influenced by numerous factors, including the charging parameters, state of charge, C-rate, or temperature [27]. We will assume a battery lifespan of 8 years, the warranty period for electric vehicles offered by most manufacturers [28]. Furthermore, for EVs a battery is considered to have reached its end of life when it degrades to 80% of its initial capacity -- a standard not typically applied to storage batteries. Even under this assumption, the battery would contribute an additional 0.8 $gCO_2 \cdot km^{-1}$, bringing the total scooter charging infrastructure CO_2 emissions to 3.6-4.0 $gCO_2 \cdot km^{-1}$, or less than a quarter of the emissions currently generated from relocating shared electric scooters for charging.

Conclusions

1. Implementing photovoltaic panels locally for the generation of green energy has the potential to reduce carbon dioxide emissions from the electric scooter fleet in Riga by an impressive 51 tonnes of CO_2 each year.
2. A model utilizing 0.2 m^2 PV cells with 20% efficiency – calibrated with data from 3.1 million scooter trips in Riga and historical solar radiation records – indicates that, by integrating a 200 Wh energy storage system at charging stations and employing an optimized energy flow algorithm, it is possible to power 98% of all scooter days in Riga using PV energy. Without these enhancements, PV energy would only suffice for 40% of the days.
3. While the system can sustain seamless operations for most of the year in Latvia, the country's limited solar radiation during the spring and autumn months proves insufficient for meeting the scooter energy needs. As a result, system failures are more likely before April and after October.
4. Despite these seasonal challenges, the adoption of such a system in Latvia would still markedly contribute to the reduction of CO2 emissions. The operation of PV chargers would be most effective in regions with more stable solar energy resources: e.g. locations such as Portugal in the EU and Los Angeles in California would enable the PV system to function without interruptions throughout the year.

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Author contributions

Conceptualization, methodology, software, data curation, original draft preparation A.R.; review and editing, L.A.; project administration, funding acquisition, M.G. All authors have read and agreed to the published version of the manuscript.

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