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Photovoltaic Electric Scooter Charger Dock for the Development of Sustainable Mobility in Urban Environments

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ABSTRACT Means and modes of transport in urban environments are changing. The emergence of new means of personal transport, such as e-scooters or e-bikes, combined with new concepts such as ‘vehicle sharing’ are changing urban transport. A greater social awareness of the harmful effects of polluting gases is leading to the adoption of new e-mobility solutions. A sustainable e-scooter recharging dock has been designed, built, and put into operation in a small town north of the city of Valencia (Spain). In the proposed novel solution, a stand-alone PV system is built for the free recharge of e-scooters using an original system that supports new sustainable means of transport. The design of the PV system considers the size limitations of the equipment, where a single PV module must generate the energy needed to recharge the e-scooters. A battery is used to store the energy and adjust power generation and consumption profiles. A commercial electronic converter adjusts the various electrical characteristics of generation, storage, and consumption. As a result of the system analysis, the surplus autonomy provided for the e-scooter recharging dock is calculated. Potential stakeholders in the use of the proposed system and their reasons for adopting this sustainable solution are identified. Experimental results of the first months of operation are included and these demonstrate the correct operation of the proposed system.


INDEX TERMS E-scooter charger dock, photovoltaic energy, sustainable mobility, e-mobility solutions, stand-alone photovoltaic system.

I. INTRODUCTION

The fight against climate change is one of the most important challenges we face. The transport sector accounts for 24% of global CO₂ emissions, 29% of global energy demand, and 65% of the world total oil consumption [1]. Mobility problems are the result of numerous situations, among which the following can be highlighted: deterioration of air quality, mainly in urban areas [2], [3]; deterioration in health and life quality with reference to traffic noise [2]; traffic congestion, with the loss of productive time and its economic repercussion [4]–[6]; urban space destined to infrastructure for the circulation and parking of vehicles [4]; limited and expensive parking spaces [2]; long commuting distances that favour

the use of the private vehicles; and seasonal concentration of tourism that results in oversized infrastructure. Changes in the transport sector must start in the cities with boosts for e-mobility transport systems powered by renewable electricity [7], [8]. The establishment and operation of e-mobility services and infrastructures for electric vehicles (EV) that focus on the use of internet of things (IoT) solutions in the management of charging stations is currently an important issue [9]–[11]. The technical challenges for achieving a greater penetration of e-mobility solutions are explained in [12].

There is little literature on the use of electric scooters (e-scooter) in urban environments as a new element in micro mobility, but there are studies that show the e-scooter’s ability to replace the conventional private vehicles in short urban trajectories [6], [13]. Several reasons explain the increase in

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the number of e-scooters in cities [8]. E-scooters represent a cheap and independent mobility system with easy parking, and can often share lanes initially intended only for bicycles [14]. The use of e-scooters in urban routes increasingly enables the use of other means of public transport (metro, bus, train, etc.), strengthening intermodality, as well as reducing the use of private vehicles [15].

Shared mobility is now a new means of transport [13], [15]. In 2018, Spain was home to the largest implementation of moped scooter-sharing services – with 35 % of the total world fleet [2]. Sharing has spread to many types of vehicles and free-floating scooter sharing could help improve the situations previously identified, and move us towards a more sustainable urban mobility. Most of the advantages identified in [16] for e-bikes also are valid for e-scooters. Some common disadvantages of free-floating floats, like the battery recharging and the relocation trips, are analysed in [6], [17].

Different types of scooters can be distinguished: scooters with a seat, also known as moped scooter or motorbikes, like the one described in [18] with a motor maximum power of 1.5 kW; light-moped or regular mopeds, with maximum legal speeds of 25 km/h and 45 km/h respectively [14], kick-style scooters [2] with maximum powers ranging from 250 W to 2 kW; bicycle-style electric scooters [19]; and mobility scooters for older people with walking difficulties [20]. All these, with the exception of mobility scooters, can be classified as powered two-wheelers (PTW) vehicles [21], and can use different types of energy sources: gasoline; liquefied petroleum gas (LPG); electricity from batteries; etc. Gasoline scooters present the same impacts as other conventional mobility solutions (air pollution, noise pollution, and traffic accidents), and [14] discusses how regulating PTWs is an important issue for environmental management in urban areas.

Cost reductions in new clean transport technologies and new international agreements can lead to substantial reductions in greenhouse gas (GHG) emissions, overcoming the barriers identified in [22]. More environmentally-friendly urban means of transport include light electric vehicles (LEV), such as electric scooters and bikes [23], also known as light electric powered two-wheelers (LePTWs). These LePTW offer new urban smart mobility scenarios that reduce dependence on conventional combustion vehicles, while reducing noise and air pollution and traffic congestion [2], [19]. The use of this type of personal LePTW is widely accepted in an increasingly environmentally aware society, and their main uses are described in [24]. The environmental benefits are clear when the energy requirements of e-cars and e-scooters are compared when only one passenger is traveling: an e-car requires an average of 240 Wh/km, while an e-scooter requires an average of 12 Wh/km (20 times less of energy).

An e-scooter is an LePTW driven by an electric motor powered by a rechargeable battery and with a power converter controlling the flow of power between them [25], [26]. Several studies deal with the different types of motors that can

be used for e-scooters [25], [27], [28]. Lithium-ion batteries are commonly used in e-scooters [12], [19]. The battery is usually recharged by plugging the charger (an AC/DC power converter) into a standard wall outlet at home or the office. Following recommendations to extend battery life, the optimal charging time is about two hours for LePTWs [19]. Typical distances covered by e-scooters range between 20 km to 25 km, depending on the battery capacity, the hilliness of the route, the weight of the driver, and the riding style. All these new electric mobility resources are quick for urban journeys of up to 10 km, according to the German Federal Environmental Agency [15], [29]. A study performed in [30] shows that between 14% and 29% of car trips made in a Spanish city could be walked, or cycled (between 50% and 70%), and so they might also be done on LePTWs.

The autonomy of this type of transport is not very high, but sufficient for most urban trips. Private LePTWs are usually recharged at home or at work; and wireless power transfer systems are under study to simplify the recharging process and avoiding the use of the different types of charging adapters [31]. Charging systems for personal e-mobility devices are insufficient and versatile chargers that can adapt for different voltages and currents must be developed [8]. The recharging of units offered by means of dockless scooter-sharing services, like those described in [32], is done by crowd-sourcing programs in which the company pays individuals to recharge e-scooters at home, using the conventional electricity provided by the power network [33]. The freelance charger assignment problem during e-scooter collection is analysed in [6]; while the full life-cycle environmental impact of e-scooter sharing services is discussed in [15]. Recharging with an off-board charger connected to the grid also produces air contamination due to the electricity mix used in most countries. The deployment of shared e-mobility systems often requires large investments in infrastructure and maintenance, which has so far prevented rapid growth in the use of e-mobility systems [32]. The sharp growth of dockless scooter-sharing services is creating new problems in cities [34]. The use of charging docks, as proposed in this article, or as presented in [35], are one of the solutions to this problem.

The use of environment-friendly alternatives like photovoltaic or wind energies must be heightened to move towards a more sustainable transport sector. A PV module can be used as an energy source to recharge an e-scooter, and thereby reducing the power conversions and improving overall efficiency [26], [36], [37]. The main disadvantages of using a photovoltaic module as a power source to recharge an electronic scooter in a home are as follows: access to the roof; mechanical attachment of the photovoltaic module; system wiring; and the inability to use the scooter during the recharge time. Charging with shared PV systems matches well with temporal activity peaks denoted in [13], where the minimum usage is between 9 am to 5 pm (between the most common weekday commuting hours). The promotion and use of renewable energies in the e-mobility sector includes as an

objective the development of charging facilities in locations popular with tourists, and the creation of parking docks for e-bikes [23], [38].

PV energy today has several advantages (low cost; easily scalable from hundreds of watts to kW; minimal maintenance of installations; and good acceptance by the public) and is the most widely used source of energy for distributed generation in towns and cities. Investments in battery charging infrastructure will be important for the future development of these new personal transport technologies [22]. These distributed refilling facilities are equivalent to the opportunity chargers for e-buses described in [39] and their use could help to:

- Extend the battery life due to opportunity recharges that avoid low states of battery charge.
- Extend the distances covered during daily trips between home recharges.
- Increase the shift from traditional motorized vehicles to new clean transport [23].
- Solve the problem of the lack of parking at destinations [30].

The advantages of distributed refilling facilities provide the base for increasing the number of e-scooter users and for promoting the massive use of this new and sustainable form of transportation, and reducing the number of trips made in cars powered by internal combustion engines [40]. It is also important to note that a decrease in dependence on private vehicles would decongest urban centres [33]. The use of renewable energies in recharging stations, such as the one proposed in this article, is a further step towards achieving more sustainable mobility.

The article is organized as follows. The following section describes the stand-alone PV system proposed for charging e-scooters in urban locations. The expected operation of the proposed system is analysed in the third section, considering the seasonal variations of the location where the system is installed. This is followed by an analysis performed on the data acquired during the first months of operation of the e-scooter recharging dock. The benefits found with the use of the proposed systems, and potential stakeholders interested in the e-scooter recharging dock are detailed before the conclusions.

II. PV-BASED E-SCOOTER RECHARGING DOCK DESCRIPTION

The first unit of the patented PV-based e-scooter recharging dock [41] started its operation in the town of Rafelbuñol (population 8900) and is being supported by the town council (Fig.1). The most important constraints considered in the design of the system are the following:

- Totally autonomous, without the need for connection to the AC grid and with minimal installation costs.
- Fast commissioning, no need for approvals or conformity testing.
- Easy to move around in an urban and inter-urban environment.



FIGURE 1. PV-based e-scooter recharging dock installed near a public park in Rafelbuñol.

- Recharge of several e-scooters simultaneously.
- Allow e-scooters to be blocked during recharging to prevent theft.

The autonomous e-scooter recharging unit is conceived as a stand-alone PV system that includes the following components mounted on a mobile platform: PV module; PWM charge regulator; lead-acid battery; and an inverter. Other electrical (electric protections, electrical panel, power supplies, etc.) and mechanical parts (supporting structure, etc.) are needed in the construction of the e-scooter recharging dock. The use of commercial equipment available on the market enables a faster commercial distribution compared to a proprietary electronic development that must be homologated before commercial use. The charging of the e-scooters is made by connecting the scooter to an AC plug that provides 230 V/50 Hz (equivalent to the rms voltage provided by the power network). The recharging dock is designed for supporting up to six e-scooters connected to six AC sockets. The scooter is blocked and users can use a lock to prevent theft during recharging. The block diagram of the electrical system is described in Fig.2.

Given the size and mobility restrictions, only one PV module of the characteristics indicated in Table 1 is used in the recharging dock [42]. The module has 60 multi-crystalline cells of 6", and its selection has been made following the guidelines of the PWM charge controller manufacturer [43], which suggests a V_{MPP} of between 30 V to 32 V for the PV module.

The PV module is connected to the PWM charge controller that controls the current delivered by the PV module (depending on the battery state of charge). The PWM charge controller is part of the power converter model Axpert VP3K-24, that also includes an inverter [44]. Because the recharging dock is implemented with only one PV module

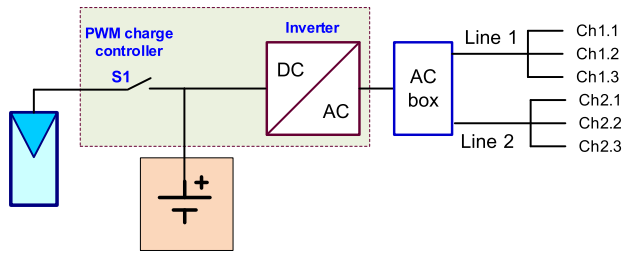


FIGURE 2. Block diagram of the PV-based e-scooter recharging dock.

TABLE 1. PV module characteristics.

$V_{OC}=38.1\text{ V}$	$V_{MPP}=31.1\text{ V}$	$\beta=-0.32\text{ \%}/\text{K}$
$I_{SC}=9.32\text{ A}$	$I_{MPP}=8.84\text{ A}$	$\alpha=+0.05\text{ \%}/\text{K}$
$P_{MPP}=275\text{ W}_{pk}$		$\gamma=-0.41\text{ \%}/\text{K}$
Efficiency=16.8%		NOCT=44 °C

and the temperature coefficient of V_{OC} (β in Table 1), the use of an Axpert converter with an MPPT charge regulator is discarded because two modules would be needed in series to reach an MPPT voltage greater than 30 V (the minimum required for the correct operation of the MPPT charge regulator). The PWM charge controller control unit that manages the battery recharge has four charging stages: bulk; absorption; floating (maintenance); and equalisation. Two 12 V and 60 Ah compact AGM lead-acid batteries are connected in series, providing 24 V and a capacity equal to $C_{10} = 60\text{ Ah}$ [45]. Considering I_{SC} in Table 1 and a peak of irradiance equal to $1200\text{ W}/\text{m}^2$, the maximum charging current during the bulk stage can reach 11.2 A. This value is smaller than the 18 A permitted by the battery [45] and is far from the 50 A supported by the PWM charger included in the Axpert VP3K-24 [44]. The selection of the battery capacity and model has been made considering size restrictions and cost. Battery charging control is performed by the PWM charge regulator default setting and features a low DC cut-off voltage equal to 21 V, a maximum bulk voltage of 28.2 V (that also corresponds to the voltage in the absorption stage), and a voltage equal to 27 V during the floating stage [43].

The inverter provides an AC single-phase supply to the six sockets installed in the e-scooter recharging dock. Two AC lines have been separated, with three sockets each, in order to achieve better protection for the electrical circuit dedicated to recharging the e-scooters. Maximum depth of discharge of the battery is limited to values of around 50%, with a low DC cut-off voltage equal to 21 V in the default setting of the inverter. The typical power demanded by an e-scooter during the recharging can vary between 60 W and 300 W, so with 6 units the maximum power in the output of the inverter can reach 1800 W maintained continuously during time intervals greater than 30 minutes. The inverter unit of the Axpert VP3K-24 has the following specifications:

- Rated output power: 3 kVA
- Maximum output power overload for less than 5 seconds: 150 %

- Maximum output power overload for less than 10 seconds: 105 % to 150 %.

The rated output power of the inverter is greater than the maximum power demanded in the six sockets due to the operating conditions in the interior of the e-scooter recharging dock. High temperatures in summer will reduce the output power capabilities due to the derating behaviour of power converters (that reduce the power output to reduce power dissipation and the temperature in the interior of the power semiconductors). Under these high temperature conditions, the inverter can deliver the 1800 W without problems.

III. SEASONAL ANALYSIS OF THE E-SCOOTER RECHARGING DOCK OPERATION

The first unit of the e-scooter recharging dock has been installed in Rafelbuñol, 15 km north of Valencia (latitude 39.588, longitude -0.323). Irradiation estimated values for a horizontal plane at this location were obtained from [46]. The monthly irradiation values, represented as peak sun hours (PSH in $\text{kWh}/\text{m}^2/\text{month}$), for the years 2015 and 2016 are presented in columns $PSH_{m,2015}$ and $PSH_{m,2016}$ in Table 2. A daily average value is calculated in column $PSH_{day,AV}$ (in $\text{kWh}/\text{m}^2/\text{day}$) with an annual average value equal to 4.79 PSH and a yearly irradiation equal to 1750 PSH (average value for the two years). The daily average value is 4.79 PSH, and the seasonal variations in Valencia are in the range of +61.8 % (June) and -54.1% (December). This significant variation in the PSH during the year produces a large variation in the amount of ampere-hour (Ah) generated by the PV module (Ah_{PV_gen}) with a corresponding effect on the battery state-of-charge.

The value of Ah_{PV_gen} in a day can be estimated by multiplying the number of PSH per day and the current generated by the PV module under STC conditions for the voltages of operation imposed by the PWM charge regulator. The current generated by a PV module (I_{PV}) can be estimated using the simplified model of a photovoltaic detailed in [47]. Using the PV module characteristics shown in Table 1, $C1 = 9.74203 \cdot 10^{-08}$ and $C2 = 0.061941628$. The I-V curves for different irradiances are represented in Fig. 3. The curve for STC conditions ($1000\text{ W}/\text{m}^2$ and $T_{cell} = 25\text{ }^\circ\text{C}$) represents the PV current depending on the conditions imposed by the load.

A PWM charge regulator connects and disconnects the PV module and the battery by means of a controlled power semiconductor. Due to this operation, the voltage of the battery and the PV module will be the same when the switch is on. The equalisation voltage in the PWM charge regulator is equal to 29.2 V, and the inverter low DC cut-off voltage is equal to 21 V (default values configured in the Axpert VP3K-24). Table 3 represents the values of voltage and current in the PV module for STC conditions. During the bulk stage, the charging current corresponds to that generated by the PV module, and this is maintained until reaching a battery voltage of 28.2 V for AGM batteries. This means that at the end of the bulk stage, the PV module current can be in values

TABLE 2. PSH for the location of the e-scooter recharging dock and values of ah and distances obtained with the proposed system.

Month	$PSH_{m,2015}$ (kWh/m ² /day)	$PSH_{m,2016}$ (kWh/m ² /day)	$PSH_{day_{AV}}$ (kWh/m ² /day)	$Ah_{PV_{gen}}$ (Ah)	$D_{rech-dock}$ (km)
Jan	86.33	66.87	2.47	22.6	35.1
Feb	87.68	88.34	3.14	28.8	44.6
Mar	132.6	137.86	4.36	40.0	61.9
Apr	184.06	158.82	5.71	52.3	81.1
May	231.07	190.49	6.80	62.3	96.5
Jun	232.24	232.56	7.75	71.0	109.9
Jul	229.22	226.7	7.35	67.4	104.3
Aug	197.47	215.37	6.66	61.0	94.5
Sep	145.25	156.21	5.02	46.0	71.3
Oct	101.26	105.52	3.34	30.6	47.3
Nov	87.05	70.66	2.63	24.1	37.3
Dec	70.65	65.51	2.20	20.1	31.2

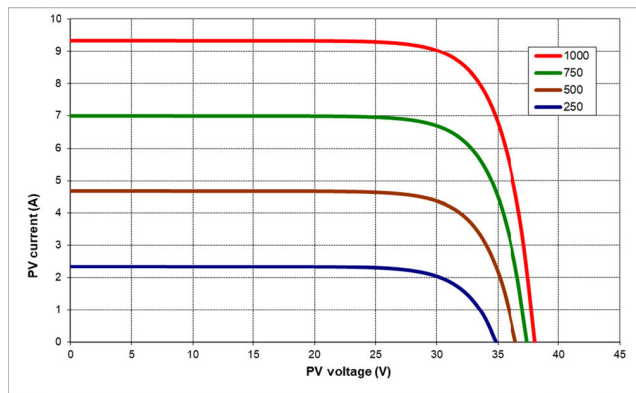


FIGURE 3. I-V curves of the PV module for different irradiances: 250 W/m², 500 W/m², 750 W/m², and 1000 W/m² (rest of parameters in STC conditions).

greater than 9.16 A. The Ah generated by the PV module in an average day of each month are calculated in column $Ah_{PV_{gen}}$ in Table 2 using a PV current value of 9.16 A multiplied by the average daily values of PSH ($PSH_{day_{AV}}$).

The value adopted for the calculation of $Ah_{PV_{gen}}$ is conservative because temperature effects on the current generation have not been considered, in addition to having used the current value at the end of the bulk stage. The climate in the region where the e-scooter recharging dock is under test is hot-summer Mediterranean (Csa) in the Köppen-Geiger climate classification [48]. The temperature coefficient of I_{SC} is equal to +0.05 %/K, equivalent to $\alpha = +4.66$ mA/K, and so a small increase in the PV current can be expected in summer months with respect those shown in Table 3.

The most popular e-scooters used in the region are the Xiaomi Mi Scooter and its Pro version. Mi Scooter has a battery capacity of 280 Wh, an autonomy of 30 km, and so the average energy consumption per kilometre is equal to 9.3 Wh/km [49]. Mi Electric Scooter Pro has a battery capacity of 474 Wh and an autonomy of 45 km, and so consumption is equal to 10.5 Wh/km [50]. The autonomy values are obtained for specific lab test conditions, and so we

TABLE 3. Voltage, current, and power values in the PV module for STC conditions for the voltages of operation of the battery.

$V_{PV_{STC}}$ (V)	$I_{PV_{STC}}$ (A)	$W_{PV_{STC}}$ (W)
21.0	9.31	195.16
21.9	9.31	203.96
22.9	9.31	212.72
23.8	9.30	221.41
24.8	9.29	230.00
25.7	9.27	238.43
26.7	9.25	246.61
27.6	9.21	254.40
28.6	9.16	261.61
29.5	9.07	267.92
30.5	8.95	272.82
31.4	8.77	275.58
32.4	8.49	275.03

can expect an average consumption of 12 Wh/km considering that the region around the e-scooter recharging dock is quite flat. Energy consumption in hilly cities would be higher and should be considered when calculating the extra distances that the system can provide. In these cases, the inclusion of a kinetic energy recovery system (KERS) in the e-scooter is very important to extend the distances that can be travelled without recharging the battery, as well as prolonging battery life.

The peak efficiency of the inverter ($\eta_{inv_{pk}}$) is in the range 90 % to 93 % [44], so a value of 85 % (average performance ratio of the inverter or PR_{inv}) can be used for the calculation of the energy required in the inverter input for covering a distance of 1 km:

$$E_{DC_{in_inverter}} = \frac{E_{AC_{out_inverter}}}{PR_{inverter}} = \frac{12 \frac{Wh}{km}}{0.85} = 14.1 \frac{Wh}{km} \quad (1)$$

Using the nominal battery voltage of 24 V, the equivalent Ah in the DC inverter input can be calculated as follow:

$$Ah_{DC_{in_inverter}} = \frac{E_{DC_{in_inverter}}}{V_{bat_nom}} = \frac{14.1 \frac{Wh}{km}}{24V} = 0.587 \frac{Ah}{km} \quad (2)$$

Battery performance varies depending on charge and discharge profiles. Some 10 % of losses can be considered for the e-scooter recharging dock due to energy generation and consumption profiles coinciding [13]. This means that 0.65 Ah must be approximately produced by the PV module for providing a surplus autonomy of 1 km. The daily estimated distance that the e-scooter recharging dock provides, denoted as $D_{rech-dock}$, is calculated as appears in (3), obtaining the values given in the last row in Table 2.

$$D_{rech-dock} = \frac{Ah_{PV_gen}}{0.65 \frac{Ah}{km}} \quad (3)$$

The daily estimated distances shown in $D_{rech-dock}$ represent the extra trip distance that can be provided to the e-scooters maintaining a balance in the energy stored in the battery. The typical power demand of e-scooter chargers ($P_{e-scooter}$) is less than 100 W (71 W in [49], [50]), with a full charge made in 5 (equivalent to 355 Wh) to 8 hours (equivalent to 568 Wh). Knowing these values, the performance ratio of the e-scooter AC/DC charger ($PR_{charger}$) can be calculated for the two models under study as follows:

$$PR_{charger-Mi} = \frac{E_{in}}{E_{bat}} = \frac{355 Wh}{280 Wh} = 1.26 \quad (4)$$

$$PR_{charger-MiPro} = \frac{568 Wh}{474 Wh} = 1.2 \quad (5)$$

This means that in one half-hour of charging, the surplus autonomy (distance $D_{1/2\ hour}$) provided to the e-scooter in the worst case is equal to 2.35 km.

$$D_{\frac{1}{2}hour} = \left(0.5h \cdot 71 W \cdot \frac{1}{1.26} \right) / 12 \frac{Wh}{km} = 2.35 km \quad (6)$$

Daily average distance presented in [21] is equal to 22.2 km, with an average distance covered in one trip equal to 11.2 km and trip variation from 6.4 km to 19.5 km. The value of 22.2 km is just at the limits of the maximum distance that a typical e-scooter can cover with a fully charged battery. This trip distance will reduce due to ageing effects in the battery, and so the surplus energy provided by the e-scooter recharging dock can be very important to complete daily trips.

Values obtained for $D_{rech-dock}$ in Table 2 show that the seasonal characteristics of the e-scooter recharging dock vary considerably, with a minimum rechargeable distance equal to 31.26 km, for December, and a maximum rechargeable distance equal to 109.9 km for June. The seasonal recharging capabilities fit well with the e-scooter usage, which is more frequently used in good weather than in winter months.

IV. EXPERIMENTAL RESULTS

The first unit of the e-scooter recharging dock is installed in an area where e-scooter traffic is expected and with connections to a bicycle lane. The system includes a small monitoring system that records the battery voltage in 15-minute intervals. Fig. 4 to 6 show the variation of the voltage between terminals of the battery (V_{bat}) and the irradiance from March and May. Irradiance values have been

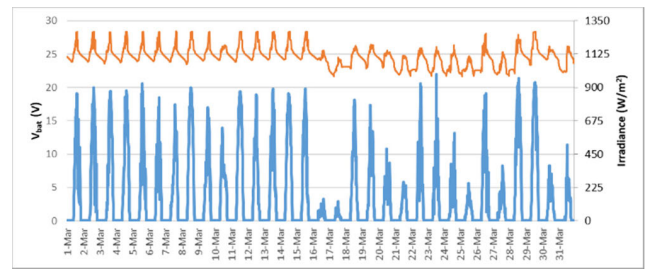


FIGURE 4. Voltage in the battery and irradiance in March.

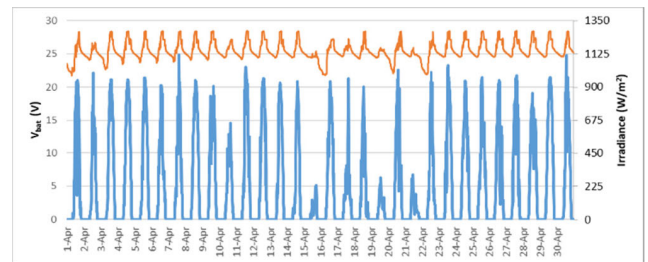


FIGURE 5. Voltage in the battery and irradiance in April.

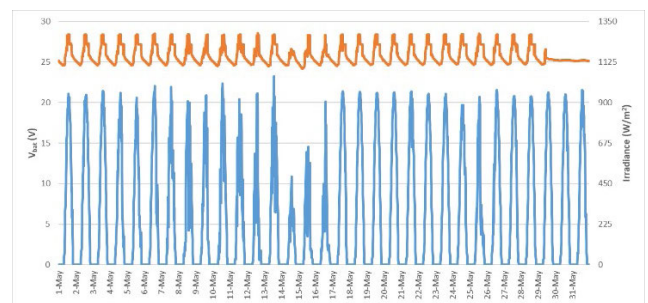


FIGURE 6. Voltage in the battery and irradiance in May.

obtained from the ETSID PV installation described in [51]. Although the irradiance sensor is tilted 20° and is 13 km from the e-scooter recharging dock, the irradiance profile enables sunny days to be distinguished from cloudy days, and so the variations in the battery voltage can be related to irradiance variations.

During sunny days, such as in the beginning of March (from 1 to 9 March), the voltage in the battery exceeds 28.3 V. During the bulk stage, the output current of the PWM charge regulator corresponds to the current generated by the PV module and is maintained until reaching a battery voltage of 28.2 V for AGM batteries. A level of 28.2 V is reached between 1 pm to 3 pm (approximately) during these sunny days. Fig. 7 shows the variations of the voltage in the battery and irradiance on a typical sunny day.

Battery voltage decreases at rate of 120 mV/hour during the night (t_0 to t_1 interval in Fig. 7) due to self-discharge of the battery, the stand-by consumption of the system, and the 7 W LED lights that show the location of the unit during the night, as seen in Fig. 8.

The PV module starts its current generation at dawn (bulk stage) and the battery voltage increases until the end of this



FIGURE 7. Voltage in the battery and irradiance during 8 March.



FIGURE 8. Night view of the e-scooter recharging dock.

charging stage (t_1 in Fig. 7). A flat voltage behaviour around 25.6 V appears from 9:50 to 10:50 (t_2 to t_3 interval). This could be caused by the connection of an e-scooter to the dock. This is followed by a quick increase in the voltage due to the increase in the current generated by high irradiance levels (greater than 800 W/m²). The bulk stage finishes in t_4 , when the battery voltage reaches 28.2 V. From 12:50 to 15:35 (approximately) the voltage in the battery is greater than 28.2 V (t_4 to t_5 interval) and this corresponds to the absorption stage of the battery recharging process. During the absorption stage, the average charging current is controlled to maintain a constant battery voltage equal to 28.2V. The duration of the absorption stage can vary from a minimum of 10 minutes to a maximum of 8 hours, and is set by the charge controller as ten times the duration of the bulk stage. In the float stage, from 15:35 to 16:35 (approximately), the battery voltage is set at 27 V (t_6 to t_7 interval) and the charging current is controlled to maintain this voltage level. A sharp decline is observed at 16:35, and the voltage changes from 27 V to 25.6 V (t_7 to t_8 interval). The voltage level of 25.6 V is fairly constant until the irradiance is very low (around 18:35, in t_9). The voltage of 25.6 V is the same level observed during the morning while an e-scooter recharges its battery. The battery voltage after t_9 then constantly declines in a similar way to night-times.

Fig. 9 represents the main magnitudes in the system during the recharge of an e-scooter for a scenario where there is a balance between the power generated by the PV module and the power demanded by the e-scooter charger. The 71 W demanded by the e-scooter chargers described in [49], [50], appear as 83.5 W in the DC input of the inverter if a

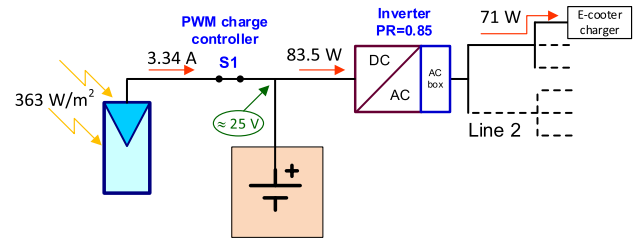


FIGURE 9. Magnitudes during the recharging of an e-scooter with power balance between generation and consumption.

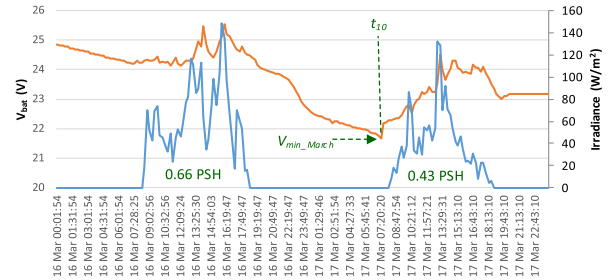


FIGURE 10. Voltage in the battery and irradiance during 16 - 17 March.

$PR_{inv} = 0.85$ is considered. Considering an approximate battery voltage equal to 25 V, the current to be supplied by the PV module is approximately 3.34 A. For battery voltages between 25 V and 26 V the current supplied by the PV module in STC conditions is approximately 9.2 A (as shown in Table 3). Knowing that the current of the PV module is proportional to the irradiance, the value of 3.34 A corresponds to an irradiance level of around 363 W/m², as calculated in (7). The value obtained is quite close to the GI value observed during the t_2 to t_3 interval, in which the battery voltage is fairly constant, and so the battery operates as an energy buffer and fixes the DC operating voltage.

$$\begin{aligned}
 I_{PVGI_x} &= I_{PVGI_{STC}} \cdot \frac{GI_x}{1000 \frac{W}{m^2}} \rightarrow GI_x \\
 &= \frac{3.34A}{9.2A} \cdot 1000 \frac{W}{m^2} = 363 \frac{W}{m^2} \quad (7)
 \end{aligned}$$

The second half of March starts with two cloudy days with less than 1 PSH, as can be seen in Table 4. As is shown in Fig. 10, the battery voltage decreases in t_{10} until 21.67 V, but does not reach the low cut-off DC voltage that is set to 21 V in the default configuration for the Axpert VP3K-24. The PWM charge regulator was working all day in the bulk stage, without reaching the 28.2 V level that corresponds to a change to the absorption stage. In 48 % of the days in March, the PWM charge regulator reached the absorption stage. Maximum and minimum voltages in the battery are detailed in Table 4 for March, the month in which the variations are most pronounced. Maximum and minimum battery voltages were respectively 28.46 V and 21.71 V in April and 28.54 V and 24.16 V in May.

After revision of the V_{bat} values presented in Fig. 4 to 6, it is clear that the operation of the battery is better when daily PSH increases. The inclusion of the monitoring system enables

TABLE 4. Daily PSH measured in the ETSID PV installation described in [48], and maximum and minimum battery voltages for March/2020.

Day	PSH	V _{bat_max}	V _{bat_min}
1	4.58	28.3	23.8
2	4.67	28.3	23.9
3	5.00	28.3	23.6
4	5.20	28.4	23.8
5	4.11	28.3	23.9
6	3.48	28.4	23.9
7	3.79	28.5	23.8
8	6.04	28.4	23.5
9	4.10	28.3	24.0
10	3.27	26.4	24.1
11	5.94	28.4	23.8
12	3.86	28.3	24.1
13	4.82	28.3	24.2
14	5.83	28.3	24.2
15	4.80	28.4	24.2
16	0.66	25.6	22.6
17	0.43	24.5	21.7
18	4.15	26.3	22.8
19	3.85	26.4	22.9
20	2.20	25.6	22.7
21	1.49	24.8	21.8
22	3.41	26.0	22.4
23	3.07	26.1	21.7
24	2.12	26.4	21.7
25	1.14	24.7	21.7
26	4.06	28.1	22.3
27	1.60	25.3	21.7
28	6.34	28.0	22.2
29	6.60	28.4	23.4
30	1.88	26.2	23.6
31	1.52	26.2	22.3

an analysis of the behaviour of the proposed system and the detection of problems in the units, such as the disconnection that appears at the end of May (when the battery voltage stopped following the daily pattern that it had followed during the previous days and a process of smooth discharge was observed). The system shutdown was caused by moving the unit to a location where it was not receiving proper solar radiation. A mobile e-scooter recharging dock makes it possible to find the best location for the system, while at the same time making it possible to modify the urban layout when necessary, such as when maintenance work is required on the streets. The best places for the e-scooter recharging dock is somewhere with good exposure to sunshine throughout the day, free of shadows, while being located near e-scooter routes or user destinations.

V. DISCUSSION

There is an increasing interest in sustainable e-mobility solutions for several reasons: to reduce the use of internal combustion cars; reduce costs associated with daily transport needs; reduce the need for car parking facilities; improve air quality in urban areas; encourage use of public transport by enhancing intermodality; reduce vehicle traffic noise in urban environments; and reduce stress levels generated by high traffic densities in cities. The public sector related to universities, hospitals, and large centrally located workplaces

is sensitive to these benefits. The use of e-mobility solutions in these environments makes it possible to make better use of the infrastructures implemented in cities for bicycles and also benefits public transport by allowing greater intermodality between train, bus, underground. Within the private sector, one of the most important motivations refers to corporate image, where the companies that are seen too concerned about sustainability and participating in the fight against climate change are better perceived by customers and users. Private sector businesses concerned with environmental sustainability include large shopping centres near dense urban areas that have a strong orientation towards the younger public with leisure activities, restaurants, and shops. Other potential stakeholders in the use of recharging stations could be hotels in tourist areas, centres related to sports activities (football or mass sports stadiums), or leisure activities related to tourism: zoos, music halls, bars, restaurants, etc.

The public and private sectors could promote the use of e-mobility solutions by installing distributed e-scooter recharging units. The e-scooter recharging unit analysed in this article is based on the capability of recharging batteries from the energy produced by a PV module when light beams strike PV cells. These units provide a recharging infrastructure solution for small powered e-scooters during daily urban trips, permitting an extension of trip lengths by using a renewable energy source that is well accepted by citizens. The solution of installing e-scooter recharging units based on renewable energies could be considered by town councils when authorising the establishment of e-scooter rental companies, or when licenses are granted for new leisure and shopping areas. The installation of e-scooter recharging units corresponding to a station-based model can be combined with the free-floating model for organising e-scooter distribution in public streets.

The results obtained in the first months of operation of the e-scooter recharging dock demonstrate that it can enhance the use of this new e-mobility solution. From the results obtained in these first three months, several improvements are under consideration for future units of the e-scooter recharging dock (including improvements to the monitoring system, system control, converter rating, type of module, and battery technology). A monitoring system that includes the acquisition of more variables will better reveal the real operation of the system and how it is used by the public. The first prototypes under test have not included a limit on recharging time. Limiting the recharging time will enable more users to benefit. It could feature a variable time recharge, adjusted to seasonal variations, limiting the time that a single user could recharge their e-scooter in the winter months, when battery recharging is more difficult. A new system control will enable optimising the rating of the power converters (that could include lithium-ion batteries). In recent years, lithium-ion batteries have emerged as a competitive solution in the storage market. The main advantages of lithium-ion batteries are: mature technology; low price; high capacities; high cycle durability; recyclability; easy replacement; high

efficiency; reliability; and low-maintenance. For the same size needed for a lead-acid battery, three times more capacity could be installed, and so increasing the availability of energy in the warm and hot months in which more sunshine coincides with a greater use of e-mobility solutions. Due to reduced shadowing losses, PV modules built with 120 half-cut cells also are under considerations for the next units of the e-scooter recharging dock. These PV modules are connected in parallel to sub-modules with 60 half-cut cells in series. Partial shadows in one sub-module have no effect in the other sub-module, so increasing the energy produced by the PV module.

VI. CONCLUSION

The first experimental results of a novel sustainable e-scooter recharging dock are presented in this article. The recharging dock is conceived as a stand-alone PV system, and contains a PV module, a lead-acid battery, and a commercial power converter that includes a PWM charge regulator and an inverter. The most important constraints considered during the sizing process are outlined and linked to the selection of the components used in the recharging dock. The proposed system facilitates the deployment of electric mobility solutions in urban environments, with all the advantages of this type of mobility. Taking in consideration the components selected for the experimental prototype and the seasonal characteristics of the region where the first unit is installed, the extra autonomy provided by the e-scooter recharging dock varies from 31.2 km in December to 109.9 km in June. The calculation is made considering the technical specifications of the most sold e-scooters in the region and considering an average consumption of 12 Wh/km.

The basic monitoring system included in the charging dock used for the experimental part of this article records the variations of the battery voltage at intervals of 15 minutes. Comparison of the battery voltage and irradiance profiles demonstrates the correct operation of the proposed e-scooter recharging dock. This comparison also enables identifying when O&M operations are needed in the recharging dock because in these cases the battery voltage curves do not follow the irradiance variations.

The list of benefits provided by the proposed e-scooter recharging dock have been detailed in this article. Potential stakeholders in the use of charging stations and their reasons for adopting this sustainable solution have also been identified. The adoption of a mobile solution for e-scooter recharging is interesting for both public and private sectors. Likewise, the advantages that the proposed system brings to e-scooter users have been identified, facilitating the use of e-scooters on longer journeys than the e-scooter's own autonomy allows in hilly cities, or as a means to compensate for the loss of battery capacity due to ageing.

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