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### ► To cite this version:

Korbinian Götz, Jakob Steger, Clemens Pizzinini, Ioannis Tsanakas, Johan Giliomee, et al.. Development and piloting of a novel decentralized solar PV charging system for sustainable e-mobility in rural Africa. EU PVSEC 2023 - The 40th European Photovoltaic Solar Energy Conference and Exhibition, Sep 2023, Lisbonne, Portugal. pp.020504-001 - 020504-007, 10.4229/EUPVSEC2023/5DO.10.4 . cea-04554445

**HAL Id: cea-04554445**

**<https://cea.hal.science/cea-04554445>**

Submitted on 22 Apr 2024

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This presentation was selected by the Sc. Committee of the EU PVSEC 2023 for submission of a full paper to one of the EU PVSEC's collaborating peer-reviewed journals.

## DEVELOPMENT AND PILOTING OF A NOVEL DECENTRALIZED SOLAR PV CHARGING SYSTEM FOR SUSTAINABLE E-MOBILITY IN RURAL AFRICA

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**ABSTRACT:** This paper presents the rationale, objectives and preliminary research results of the EU-funded project SolCharge. The project addresses the two major barriers for rural communities in sub-Saharan Africa (SSA): (1) no access to electricity and (2) no access to mobility. Therefore, the project proposes a decentralized transportation hub (DTH) based on a stand-alone solar charging station to harness solar energy and replace transportation which depends on pollutant internal combustion engines. The project targets 33 million smallholder farmers in SSA who rely on transportation to improve the economic success of the agricultural sector in SSA. SSA has abundant access to sunlight, making it a perfect location for solutions based on photovoltaic (PV) technologies. First, the project will develop a stand-alone solar charging station to be able to use solar energy for electric mobility in a decentralized manner in rural areas. Smallholder farmers will benefit from the use of electric vehicles as part of a transportation hub to address their mobility challenges and access to economic success. The vehicles will be utilized to transport agricultural goods, using the electricity generated in the process. To make the service available to the users and run it profitable, the DTH is combined with a service model that provides on-demand transportation. The impact of the system will be tested in Ethiopia and South Africa and the whole DTH will be evaluated with a life cycle analysis (LCA). The LCA addresses the potential to reduce the environmental impact of electric vehicles and the solar charging station with the means of circular economy.

**Keywords:** *e-mobility; solar charging station; off-grid PV system; decentralized transportation hub; life cycle analysis.*

### 1 INTRODUCTION – CONTEXT

#### 1.1 Sustainable transportation and Stand-alone Solar Charging Stations

Sustainable, affordable and reliable transportation is indispensable in the rural African context. Current transportation solutions in rural Africa are scarce and highly unsustainable where found. Where a transport solution is present, the majority of vehicles are imported near the end of their lifetime. As a result, these vehicles are fuel inefficient, highly pollutant and present high costs of spare parts and maintenance. Besides such means of rural transport are based on imported fuel, which leads to issues as increased greenhouse gas emissions, fuel cost currency dependency and sporadic unavailability during shortages.

Off-grid solar PV charging stations comprise a very topical and emerging solution for remote electrification, particularly in regions such as sub-Saharan Africa (SSA). Recent developments focus mostly on improving the energy management, sustainability, and bankability of such systems. Additionally, decreasing the installation and operations and maintenance (O&M) cost is also large focus point, as the cost of PV modules themselves has significantly decreased in recent years [1-5]. Stand-alone solar charging stations (SASCS) raise a number of technical issues, mostly related to the lifetime durability (and sustainability) of the batteries. It was shown that, since the end-user practically pays for the number of charges rather than for the energy use, batteries are often discharged below the appropriate discharge level. This, in turn, significantly shortens their lifetime [1]. Even when SASCSs are community-owned, the lack of users' technical training leads to deep discharges and thus lower service lifetimes in the long-term. Thus, another relevant

challenge whose importance has been highlighted by several earlier studies is that of the need for local technical training of SASCS users and asset managers. In particular, in order to develop a solid business model, a solar charging station has to be monitored and serviced. This requires technical skills, which is not usually available locally, but that would otherwise be too costly if left unsupervised. From a market and end-user perspective, SASCS typically address the electricity demand of low income-low demand end users in the proximity, which cannot afford or access their own reliable electricity generation system. Thus, one can classify the market segment of solar charging stations as the first step towards electrification. The following step would be to own and operate such system(s), which would provide better flexibility and availability of the energy service (more power and at a lower cost per unit), yet require a higher income (either for the initial investment or, in the long-term if it is to be acquired e.g. by a microfinancing approach). Subsequently, solar PV-powered mini-grids would be the third step, providing another level of energy services, both in quantitative and qualitative terms (e.g. self-consumption, flexibility, etc), at an even lower cost [1].

On a broader view, there are also many socioeconomic challenges towards a greater market uptake of SASCS, as there is not yet one definite, sustainable and successful business model that can be replicated ubiquitously [6,7]. In fact, limited but existing research on SASCS shows that scalability is possible with such technology [8]. As true as this conclusion seems, questions remain regarding the distribution, exploitation, business modelling, and financing of SASCS – questions that have so far gone unanswered in the research. This means that the scalability of SASCS stands at a low TRL, i.e. around 2 to 3.

### 1.2 LCA Analysis of renewable energy systems in Africa

The current developments in transport emissions show the relevance of leapfrogging fossil fuels and easing the barriers of electric mobility in Africa: According to Ayetor et al. (2021), Africa's transport emissions are growing every year at a rate of about 7 %, compared to a growth of 0.8 % in the United States of America [9]. The authors state that with the current rate, the emissions in Africa will double by 2030 compared to the ones of 2015 if no measures are established. In addition, Africa is the second most populated continent with the lowest level of motorization in the world [10]. To overcome the connected burdens of a lack of mobility and rising emissions due to motorization, SolChargE proposes a local emission-free solution for rural transport with solar energy. To show the potential in mitigation of emissions the project proposes a Life Cycle Analysis (LCA) of the system regarding the decentralized transportation hub (DTH). Besides the investigation of the status quo of road vehicle emissions, [9] gives advice for future actions to lower transportation emissions. This implies the assessment of future transport systems and their impact on how they decrease emissions in a standard methodology as proposed by LCA. Farquharson [11] analysed the impact of the electrification of the motorcycle fleet in Kigali, Rwanda. Therefore, the author analysed trip data from a commercial ride sharing platform with 118 drivers in a 30-day period. The fleet is modelled with a comparable commercially available electric motorbike with a swappable battery concept. Different scenarios are analysed for battery charging, such as from the current electrical-grid generation mix, a peat-based and an increased solar-based electricity generation. The author assesses the resulting emissions and costs and concludes that electrification may not only offer emission and health benefits but also an economically feasible solution. Yet, the electricity mix for charging has the major influence on the emissions and shows the potential for solar charging solutions [11].

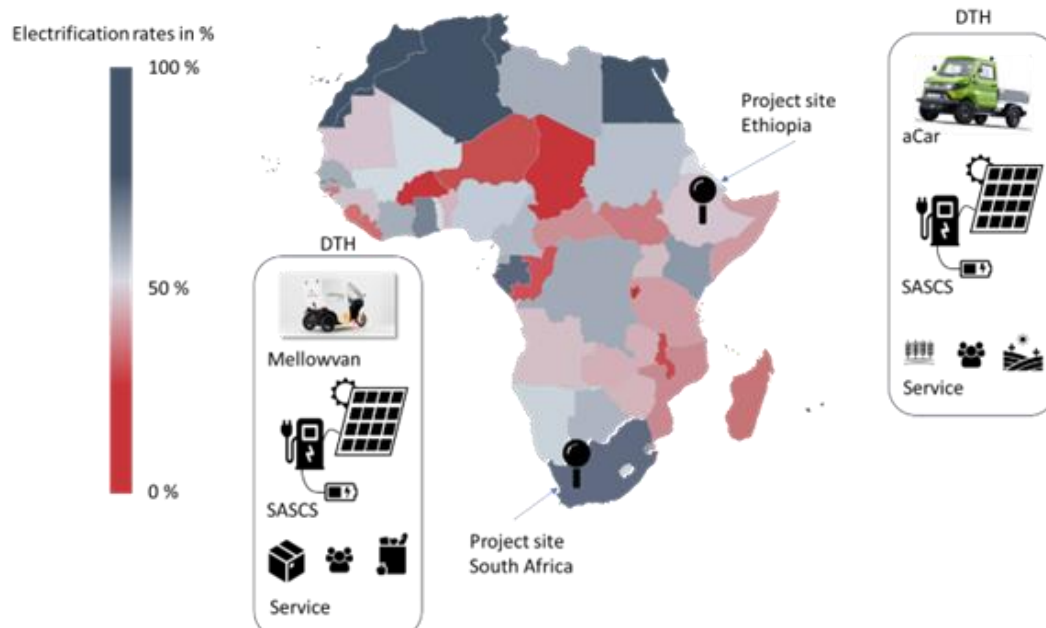
Schünemann et al. [12] proposed electrified cargo bikes as an eco-friendly freight transportation in cities which can be powered by commonly used mini grids in

African countries. The authors raise the question if the cargo bikes are environmentally friendly, if they are assessed for their impact on the environment during the whole life cycle, and how they perform compared to other urban transport modes. The question is answered by conducting an LCA on the use case of an electric cargo bike used in Ghana. The LCA show savings of 4-8 % in greenhouse gas emissions with the inclusion of solar-powered e-cargo bikes in the Accra region. Their results show the relevance of LCA as well as solar powered charging [12]. The same results are shown by [13], who assessed the impact of replacing an ICE bus fleet with electric busses in Africa over their whole lifetime. The authors do not just see a reduction of lifetime costs up to a maximum of 47 % in South Africa due to solar charging, but also significantly lower CO<sub>2</sub>-emissions. Charging the electric bus from the grid exemplary in South Africa causes 489 % more emission than with solar energy.

## 2 OBJECTIVES – SCOPE/METHODOLOGY

### 2.1 The project's motivation and objective

Communities in SSA face a multitude of interconnected challenges rooted in their lack of access to electricity (Fig.1). Rural areas are increasingly left behind; for instance in Ethiopia, only 1 % of the rural population has access to electricity, even though they make up for 85 % of the total population [14]. The most solutions for providing fast access to electrification are based on decentralized solutions, which are able to function without direct connection to major energy sources. In the context of SSA, many (if not most) of said decentralized solutions have come to rely on solar energy—and with reason. With its overabundance of sunlight (some regions average 6.5kWh/m<sup>2</sup> of solar radiation per day), sub-Saharan is seemingly the perfect location for solutions reliant on photovoltaic (PV) technologies. However, it remains unclear whether decentralized solar-powered solutions will be able to tackle the challenges facing SSA today (and in the future).



**Figure 1:** Electrification rates of the African continent; presentation of the project sites with the respective decentralized transport hubs (DTH) and their components.

We reckon that, while decentralized energy solutions may be one piece of the puzzle, it alone cannot adequately confront ‘wicked’ problems currently impacting SSA’s rural communities, to achieve sustainable development. This is especially true of the difficulties facing the continent’s 33 million smallholder farmers who, even when given access to solar energy, continue to encounter barriers to economic success. The project proposes electric mobility in combination with decentralized solar energy, to improve the live and economic success of the rural population. The research question arises, how can the region's inhabitants be addressed by transport modes, which offer them the access to points of interest, in a manner which permits rural SSA to leapfrog over noxious modes of transportation reliant on polluting internal combustion engines?

The SolChargE project's answer is the investigation of the impact of a decentralized transportation hub (DTH) which includes a standalone solar charging station (SASCS), a battery electric vehicle (BEV) and an operational model. On this aspect, the project will seek to define and assess parameters specific to SSA (Ethiopia and South Africa in particular) and design a DTH (Fig. 1). The methodology for the system design of the three components (SASCS, BEV, operational model) must ensure scalability and parametrization to different locations and circumstances.

To assess the impact of the system, a Life Cycle Assessment (LCA) and the Life Cycle Costing (LCC) will be performed to ensure every step is able to include positives outweighing possible economic, social, and environmental negatives. The specific details associated with such analyses will be defined as the project moves forward and is further described in the next section. It will be our team’s endeavour to bring the scalability of SASCS, especially in Africa, to a TRL of at least 5 thanks to our analyses’ application within relevant environments.

## 2.2 Methodology of the project

The methodology for this research project is broken up into five axes/milestones: (1) understand, (2) develop, (3) production, (4) operation and (5) recycle.

- For the first milestone of the project, we start with the understanding phase. Requirement analysis is done across diverse work packages such as the SASCS development, business model design, capacity building and DTH definition. Literature review is conducted to understand contextual parameters which will influence these work packages. This includes technical parameters for the SASCS, a database on the best practices for the business model and the identification of local stakeholders. Concluding with interviews with experts in the field, parameters for these work packages are finalized and incorporated in a database.
- Succeeding requirement analysis, the development phase commences for the second milestone. Layout and prototyping for the SASCS is done by developing a technically feasible concept and building a minimum viable model to be tested in a lab environment. Optimal configurations are identified and adopted for the next phase. The business modelling is based on the full product life cycle and based on stakeholder needs, value chains and information flows. The business model contains a parametrizable cost model, which is adjustable to different locations and circumstances in order to

investigate the necessary pricing strategy for the DTH operation and its payback period. Capacity building for each stakeholder comprises workshops and lectures offered on concept development. The development phase concludes with component and parametric system modelling for the DTH.

- Production starts with local sourcing and procurement assessment for the SASCS. Required materials and components are determined with a focus on regional or national sourcing of second-life components. An in-lab production facility to test innovative solutions is set up in South Africa and Ethiopia where a general quality measure for all components and materials is developed. Along with a production strategy developed for the business model, capacity training focusses on production. Finally, a fully functioning prototype is built by students and technicians involved in capacity building. Meanwhile, operational training for the following phase also commences. Simultaneously, a simulation model based on analysis of scalability, environmental impact and socio-economic impact is built to determine the optimal DTH configuration across a defined area.
- Operation commences with the implementation and evaluation of the DTH. It will prove successful by working seamlessly in the field and generating valuable data that can be analyzed with a focus on optimizing second-life potential. Feedback from all DTH stakeholders regarding the developed business model is utilized to develop a proof of concept thereof. Focus is put on the user-facing pricing strategy and transport services offered by the DTH. To prepare for the final recycling phase, capacity building regarding efficient recycling commences during the operation phase. As part of the DTH simulation assessment, a life cycle impact assessment with a special focus on business model transferability is conducted.
- The recycling of the DTH aims to ask an important question: How does the operation influence the quality of DTH components and their usability for a circular usage? Each component is categorized according to the different circular principles; whilst CEA performs further diagnostics on PV module reuse and battery degeneration. An optimal recycling strategy is developed accordingly and documented in an online handbook. Finally, all project-related findings are to be made publicly available and technical manuals made open source as part of knowledge dissimulation. The project concludes with results validation of the DTH simulation and impact assessment.

## 3 PRELIMINARY RESULTS

As shown in the methodology, the first steps in the project include the collection of requirements for the DTH in order to design a standalone solar charging station, which is the enabler for the BEV to run the operation. Since the requirement of the project is to offer a cost-efficient and scalable solution, it is evident that the cost of the standalone solar charging station plays an important role in the design process. Additionally, the design shall not be limited to one specific location.

3.1 Background

Standalone charging stations are necessary for the success of BEV adoption worldwide, especially in rural areas with no grid connection [15, 16]. Studies show that standalone PV systems emit less CO<sub>2</sub> over their lifetime compared to conventional systems run by fossil fuels [16, 17, 18]. However, the challenges of these stations are the economic viability and system reliability due to high capital cost, limited PV and battery capacity and the intermittency of the PV technology [19]. Therefore, the authors of [16, 20, 21] conclude that more accurate techniques for better energy management are necessary to make standalone PV stations competitive, with the potential being in more accurate energy scheduling for optimal energy utilization.

In the context of this research, the objective is to identify and analyse the electricity cost that standalone PV charging stations can provide for user-selected locations and different mobility scenarios in rural areas of SSA. Moreover, the research must show how reliability affects costs, with PV systems not being considered reliable compared to conventional fossil fuel methods [19].

3.2 Sizing of the standalone charging station

The stationary battery of the standalone charging station is one of the most significant cost contributors for PV systems with the purpose of enabling reliability during solar intermittency [18]. Therefore, the applied common sizing approach of [22], which uses autonomy factors based on the nocturnal energy demand, and the maximum days in a row without enough solar irradiation, tends to oversize the battery and is therefore not suitable for cost-sensitive applications. The main potential lies in oversizing the provided PV power to enable the stationary battery to be charged optimally in challenging solar periods [23].

The aim of the presented methodology is to fundamentally analyse how much PV power is constantly available to charge the BEV battery for the demanded mobility and the stationary battery for storage. This goal requires the correlation of the PV power with the capacity of the stationary battery. Hereby, a reasonable design of the whole charging station is achieved instead of only focusing on single components as the stationary battery.

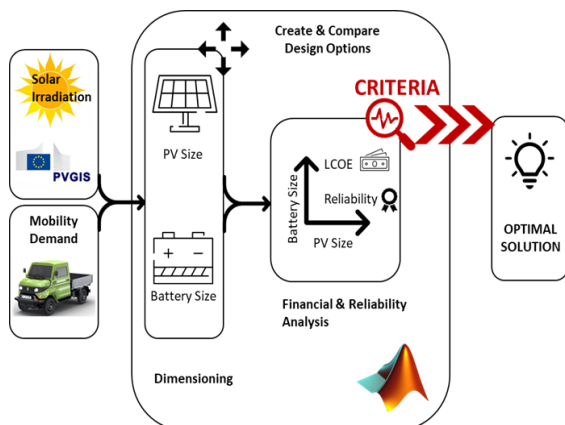


Figure 2: Sizing methodology overview.

Figure 2 gives an overview of the methodology leading to the optimal solution. The input consists of the mobility scenario to determine the energy demand and the solar irradiation data of the location where the station is operating. Those are used to size the PV power and the stationary battery capacity by generating multiple design

options. The optimal design is then chosen by the reliability criteria and the Levelized Cost of Electricity (LCOE [€/kWh]).

The daily energy demand is determined from the chosen mobility scenario and is used as a basis to determine the standard size of a PV panel area according to [22]. For this project, the mobility scenario allows the vehicle to be charged over night from 23 p.m. to 8 a.m. and during noon from 12 a.m. to 2 p.m. (Fig. 3). During the rest of the day, the vehicle must be available for driving.

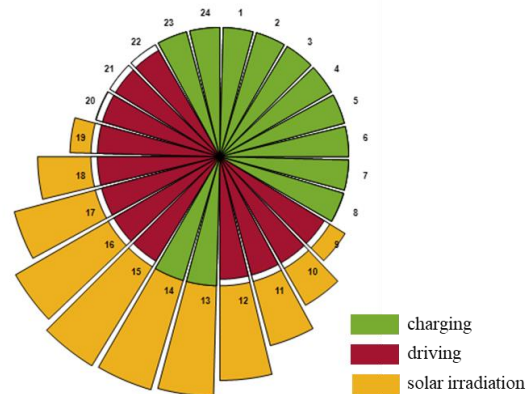


Figure 3: Mobility scenario over a day with 2 h of charging during the day.

In order to find the optimal design, multiple design options are generated: Those include the necessary PV power, being oversized by a factor ranging up to twice the initial value which is derived from the method of [22], and a range of fitting stationary battery capacities. The range of PV power and battery capacity is displayed on the horizontal and vertical axis in Fig. 4. All design options are then analysed for energy availability over the period of the year 2020 with hourly PVGIS solar irradiation data and hourly mobility demand data. The simulation analyses hourly if the vehicle must be charged and if either the PV panels provide the energy directly or the stationary battery. If no car is available for charging, the produced PV energy charges the stationary battery. Otherwise, if solar energy is available, but neither the vehicle nor the stationary battery can be charged, the excess energy is discarded.

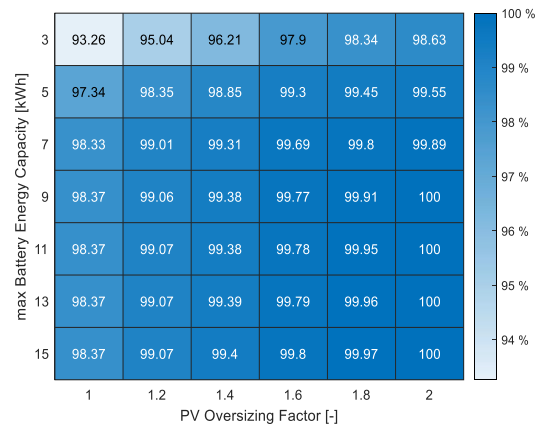


Figure 4: Reliability of the design options in providing the daily requested energy demand in percent over a year.

The simulation enables us to determine the times when not enough energy is available to charge the BEVs. Furthermore, the LCOE of each station design is

calculated to enable a cost comparison of the different designs. The two criteria of (1) the reliability to provide energy over the course of a year and (2) the LCOE associated with the station designs determine which design option is optimal. For the purpose of this project, a reliability of a minimum 99% is chosen. Of all station designs with a minimum 99% availability, the one with the least cost is the optimal design. Figure 4 displays an example of the reliability enabled by different station design options for the mobility concept of Fig. 3.

3.3 Sizing / Simulation Results

To demonstrate the results of the methodology, the authors simulated one battery electric vehicle of the type aCar with a 33 kWh battery, which operates with the mobility concept shown in Fig. 3. The aCar is assumed to drive 85 km every day with a consumption of 0.318 kWh/km and charged with 2.5 kW in its depot in Bishoftu, Ethiopia.

Figure 4 shows the simulated design options according to the methodology presented in Section 3.2. The optimal design with minimum 99% reliability and least LCOE is given for the calculated scenario with an oversizing factor of 1.2 (4.4 kW<sub>peak</sub>) and a 7 kWh stationary battery.

In Fig. 5 the significance of the reliabilities of the charging station is shown on an annual basis: The figure displays the number of days in one year for each station design, where less than 80% of the demanded energy is provided. The impact of oversizing the PV panel area significantly improves the reliability of the station design, for instance, oversizing with a factor of 2 decreases the number of days to one-third for the same battery capacity of 3 kWh. The increase of the stationary battery capacity has a great impact on smaller batteries; however, the improvement rate fades after the 7 kWh battery, which is in our case the optimal solution.

max Battery Energy Capacity [kWh]	3	130	103	79	49	40	34
	5	56	40	26	13	11	9
	7	36	24	15	6	5	4
	9	35	23	14	5	2	0
	11	35	23	14	5	1	0
	13	35	23	14	5	1	0
	15	35	23	13	5	1	0
			1	1.2	1.4	1.6	1.8
		PV Oversizing Factor [-]					

Fig. 5: Number of days per year where less than 80% of the required energy can be provided.

The pie chart in Fig. 6 displays the percentage of the component's contribution to the Total Cost of Ownership (TCO) of the station. The PV Modules are the most significant cost contributor with 44% of the station's costs, followed by the stationary battery costs with 27%.

Figure 7a illustrates the solar energy of the PV system for the optimal standalone charging station over one year in more detail: The figure visualizes the excess energy,

which is produced but not needed for the demand of the car in blue bars, whereas the missing energy, which is not available for the demand of the mobility scenario in black bars. Figure 7b shows the compensation of the daily energy lack by the stationary battery. The black in a) and b) are equivalent, showing the amount of energy lacking on the critical days of the year. The chosen capacity of 7 kWh of the stationary battery can compensate for some of the daily energy deficiency. However, there is still a deficit which is displayed with the red bars, due to the chosen reliability of 99%. The bottom chart of Fig. 7c allows an evaluation of the number of days per year when not enough energy can be provided with a reliability of 99%. It displays how much of the demanded daily energy is provided on the deficient days of the year. It is visible that even on the worst days of the year, still 75% of the demanded energy can be provided.

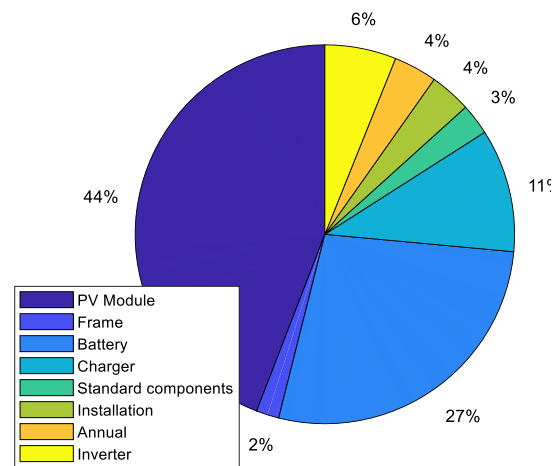
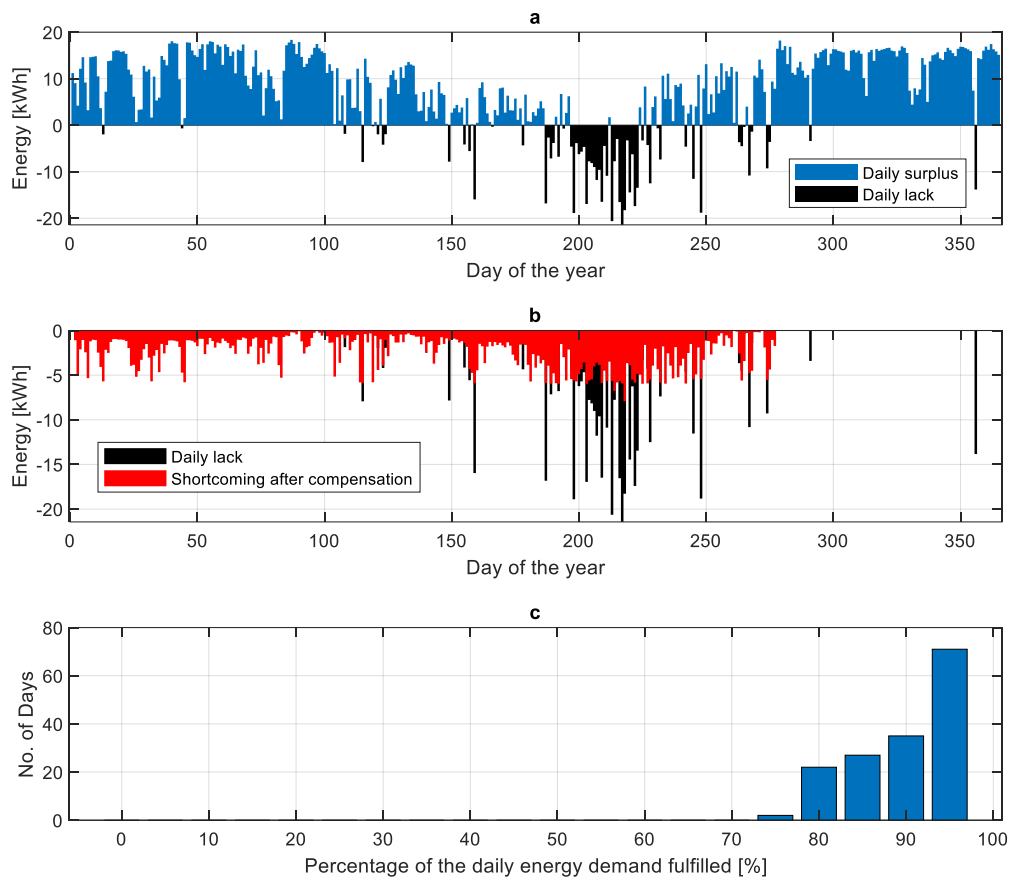


Fig. 6: Percentage of the cost contributing elements for the proposed charging station.

The methodology presented in this paper proposes a charging station design based on the variation of the most influential costs, which are the PV panels and the battery. The optimal charging station is selected based on reliability and energy costs. The reliability of a station design is assessed by following the energy utilization over the course of one year of operation, while costs are calculated based on the specific elements of the station. The methodology selects the optimal station design by the lowest LCOE, with a 99% reliability. As a result, the methodology enables the determination of the charging station size, as well as the LCOE that can be offered by simply specifying the location and mobility demand.

The methodology was implemented in MATLAB with the input of PVGIS solar irradiation data and the mobility demand based on the scenario described by two mobility project partners operating in rural SSA. The optimal design on the chosen inputs is a PV power of 4.4 kW<sub>peak</sub> and a stationary battery capacity of 7 kWh. The methodology can be adapted to different mobility scenarios and locations, in order to assure future research with more complex mobility scenarios. The presented methodology has the potential to contribute to future research efforts by determining the LCOE for BEVs in rural SSA and elsewhere. The insights can assist researchers in their investigations and support local decision-makers in making informed choices regarding investments in electric mobility.



**Figure 7:** a) Visualization of the daily surplus energy and lack of energy; b) Compensation of the lack of energy with the stationary battery; c) Number of days where the energy demand is not met and % demanded energy provided on those days.

#### 4 CONCLUDING REMARKS – FUTURE WORK

In the SolChargeE project, we aim at developing a decentralized transportation hub (DTH), based on a stand-alone solar charging station (SASCS), to harness solar energy for sustainable e-mobility in rural sub-Saharan Africa. Towards this goal, the project will be implemented through five main research activities/steps: i) Development (sizing and design) of the SASCS, ii) Production (local sourcing based) of the SASCS system, iii) Installation and monitoring/assessment of the DTH in the field, iv) Recycling study for the DTH including life cycle analysis and v) business model development.

The sizing methodology represents the groundwork and current (ongoing) research of the SolChargeE project, particularly on the SASCS development. The method enables a parametric design of various mobility scenarios and locations all over sub-Saharan Africa, to enable a scale-up of standalone charging of battery electric vehicles in areas with no or low electricity supply. However, it becomes evident that a more detailed mobility scenario, which is based on actual demand profiling and usage data is necessary to make a reliable design of the standalone charging station. Additionally, the component costs in the cost model for the LCOE differ enormously in different locations over sub-Saharan Africa or are not available. Therefore, the next steps of the SolChargeE project, with regard to this activity, include the gathering of actual real-world mobility data of a BEV in an operational model and the component prices in the project locations of South

Africa and Ethiopia, to enhance the sizing model. As soon as the standalone charging station is built, it can be evaluated in real-world scenarios.

Following this activity, in the next 12 months our research will focus on:

- In short-term: finalizing the drafting the technical layout (and specifications) as well as the open-source development guidelines for the SASCS production.
- In mid-term: Local SASCS production workshop and functional (installation-ready) SASCS demonstrator.
- In long-term: Installation and evaluation of preliminary monitoring/testing results of the DTH in operation.

As the SolChargeE project progresses on these activities, in next year's EUPVSEC we aspire to present a comprehensive overview of key results, lessons learnt and return-of-experience from the design optimization, implementation and field operation of the SASCS and DTH in the two demo sites.

#### ACKNOWLEDGEMENTS

The authors acknowledge the valuable contribution of all partners of the SolChargeE project. SolChargeE is a project funded in the context of Pillar 1 call of the LEAP-RE project/program. The LEAP-RE project has received funding from the European Union's Horizon 2020

Research and Innovation Program, under Grant Agreement 963530.

For CEA team, part of this work was also supported by the French National Program “Programme d’Investissements d’Avenir - INES.2S” under Grant Agreement ANR ANR-10-IEED-0014-01.

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