DESIGN OF AN AUTONOMOUS SOLAR CHARGING STATION FOR E-BIKES

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ABSTRACT: An autonomous solar charging station for e-Bikes has been developed. For an optimal design of all system components, both a prototype has been built, and a model has been created. Validation of the model has been done by taking measured irradiance and measured total electrical load profiles as input for a period of one month. The output in terms of PV yield, grid feed-in, SOC of battery bank, etc. has been compared with the real measured values of these parameters. This validation gives much confidence in the model, although care needs to be taken for low SOC values, at which a high accuracy of the model is mandatory to distinguish between 'able to power' and 'unmet load'. Full year round modeling results are performed by using TMY-data for irradiance, and an electrical load very nearby real measured load patterns including some seasonal effects. These simulation runs show a reliability of 94.9% for the current configuration with 7 e-Bikes and a well-equipped charging station. The system was found to have a relatively high degree of reliability (>90%) even when the system was used with twice the number of bikes it was designed for. Turning the heavy consuming advertisement screen completely off, a perfect reliability of 100% is found. This demonstrates that the designed system is quite flexible with the number of e-Bikes it can cater to and is far more sensitive to full-time auxiliary loads in the charging station.

Keywords: Battery Storage and Control, Optimum Sizing, Reliability, Stand-alone PV Systems, Storage

1 INTRODUCTION

A bicycle parking and charging station with a 5.52 kWp solar roof, was recently constructed in Eindhoven, the Netherlands (see Figure 1). The aim is to investigate the feasibility of stand-alone solar powered charging for electric bikes, so-called e-Bikes.

The primary goal of this research is to find the optimal system design for the autonomous operation of such a charging station. High autonomy of the system provides the flexibility of an off-grid installation. Even in a country with a high-quality grid, like the Netherlands, this could have the advantage of a better business case; the longer the distance between the preferred location of the station and the existing grid, the more economical benefit this off-grid installation gives. Also in areas with a lot of cabling and piping (gas, water, sewage, chemicals,…) in the ground, it is an advantage to build off-grid. Last, but not least, a significant amount of customers prefers to produce their own solar energy, instead of buying solar energy from somewhere else.

Figure 1: Prototype of the Solar Mobility Station installed in Eindhoven, the Netherlands.

For quantifying the autonomy of an off-grid system, many parameters exist [1]. We prefer to focus on the following Key Performance Indicators (KPI's) [2]:

- Unmet load, E_{unmet}: the sum of all electrical energy that the system was unable to deliver [kWh/year].
- Loss of Load Probability, *LoLP*, which is defined as the ratio of the unmet load and the full year load including that unmet load [Arno] $LoLP := E_{unmet} / E_{load,fullyear}$ [%]
- Reliability, $R := 1\text{-}LoLP$ [%]

2 EXPERIMENTAL SETUP AND RESULTS

2.1 Experimental Setup

The charging station is designed from an aesthetic point of view, with a ground floor layout of 6 m x 5.5 m and a roof under a 15º tilt. To keep the costs as low as possible, the project developers preferred the readily available 60-cells crystalline PV-panels with a standard dimension of 1.6 m x 1.0 m. However, it was impossible to get the solar roof densely packed with these PV-panels only. Therefore additional 48-cells crystalline PV-panels were also used in a way that is difficult to notice for passing viewers on street level. Each PV-field is connected to the 48V DC bus of the system (via an MPPT-controller); see Figure 2. The DC bus is connected to a battery bank of 4 series connected 12V lead acid batteries with a capacity of 220Ah and a combined voltage of 48V. Hence the nameplate capacity of the battery bank is 10.6 kWh. This type of batteries (AGM deep-cycle) has a maximum DOD of 80%, which implies that the usable capacity is 8.5 kWh.

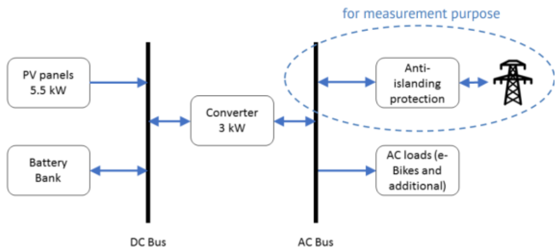

Figure 2: Electrical layout of the system

Because all the electrical applications in the charging station need different DC voltages (5V, 12V, 24V, 36V, …), a design has been chosen in which all loads have their own normal charger on the AC bus. The electrical applications - and motivations to include them - are:

- e-bike chargers: the main function of the station is charging e-Bikes
- Screen: for advertising purposes
- LED lighting: only in night and when persons detected by a motion sensor
- Automatic sliding doors: for a secure shelter with a convenient entry
- Smart Card Reader: to allow only persons who are subscribed to the system
- Security camera: anti-theft mitigation
- WIFI-router: to make sure that the smart phones of the user always have internet
- Smart lock-by-app gateway: needed for communicating which user is allowed to open/close the lock of which e-Bike

The AC bus is connected to the grid with anti-islanding protection. The purpose of this connection is to be able to measure the unmet load. Please note: in a completely autonomous system, one can never measure how much kWh is missing or unmet, only how much time the load could not be served.

Between the DC and AC bus, an inverter charger (Victron Energy Multiplus 3000) is installed. This device can act as a charger when AC voltage is converted to DC voltage, e.g. for battery charging. It acts as an inverter when converting DC from PV or batteries into AC for the loads or the grid. The size of 3 kVA(=2.6 kW) seems rather low for a 5.5 kWp PV solar roof. However, one has to realize that we are not maximizing full year PV-yield. The sizing has been done making sure that in the very low irradiance days of winter, the PV-field is large enough to survive several of these days. The total AC-load that is needed to run the station is well covered by 2.6 kW.

2.2 Experimental Results
The measurement equipment of Victron Energy gives one-minute time series of all the electrical currents in Figure 2.

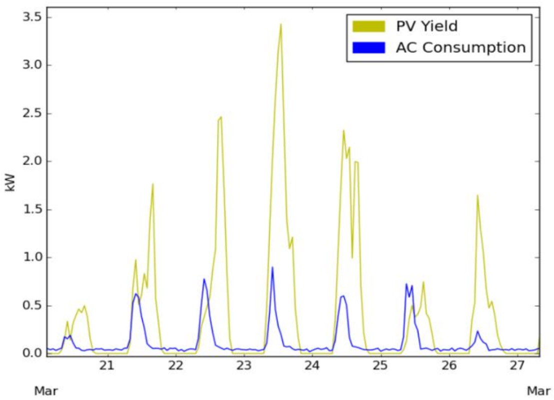

Figure 3: Power of the input (PV Yield) and one of the outputs (AC consumption) as a function of time for one week in March 2017.

Figure 3 shows the input electricity from the PV, and the output electricity of the e-Bike charging for an arbitrary week in the total test period. One can see that charging takes place mostly early morning. This is caused by the scenario of these e-Bike users: they were allowed to use the e-Bike for their commuting traffic, and they have no extra charger at home. When they arrive in the morning in the station, the e-Bike battery will be charged immediately. This coincides nicely with the pattern of the upcoming solar irradiance. This is beneficial for the life time of the battery bank in the station. However, one should note that other e-Bike scenarios, like the popular bike sharing principle, could give other charging patterns.

Although the experimental results are quite powerful, they also have limitations. First, it takes quite long to measure only one set of design parameters (battery capacity, number of e-Bikes, etc.). Because the autonomy is tested to its critical values only in winter, one needs a full year for each 'design'. Moreover, this prototype cannot easily be transported to another location or shifted towards another direction. All these aspects can be better investigated with a model.

3 MODEL METHODOLOGY AND RESULTS

3.1 Model Methodology
The electrical layout of Figure 2 also serves as the basic principle for the model, first described in [3]. All the energy generated by the PV system is used to power the e-Bikes and additional loads, charge the batteries or fed into the grid – each of which is individually measured. The major losses in the system are heating, battery storage losses, inverter and MPPT losses. Since the objective is to observe/use the system in stand-alone mode, the surplus energy sent to the grid may also be considered as a 'loss'.

Calculating each current effectively, is done in the software package HOMER [4]. Input in the model is irradiance of TMY-data of the location of installation, Eindhoven in the Netherlands [5]. The total AC load is the sum of a base load (based on real measurements) and a constructed e-Bike charging pattern load depending on the assumption (or measurements whenever available) of the e-Bike scenario.

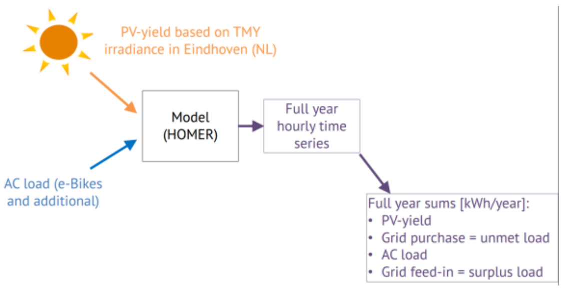

Figure 4: Sketch of modeling methodology.

The output of the model is a time series of 8760 hourly values of PV-yield, grid feed-in, grid purchase, SOC, and many more. The last step is summing up to full year values. See Figure 4 for a complete overview of the modeling methodology.

3.2 Modeling Results

The full year sums of the four most important parameters are plotted in Figure 5. One can see that the PV-yield is around 4500 kWh/year; off course not depending on the amount of e-Bikes in the station. A very small, but still visible, amount of unmet load can be seen. This gives a few days per year with just not enough electricity to fully charge the e-Bikes. Gauging if this is acceptable by the users will be monitored in the upcoming winter period (2017-2018). With increasing number of e-Bikes to charge, the unmet load becomes larger and most probably unacceptable in the case of 20 e-Bikes.

On the negative side of the y-axis, one can see the AC-loads and the grid feed-in. The latter is just surplus load that is of no interest because the prototype is not designed for maximum power production; moreover the kWh-sale value at the location of the prototype (premises of large institute) is just € 0.045 / kWh. Of course, this can be very different at other locations in the Netherlands!

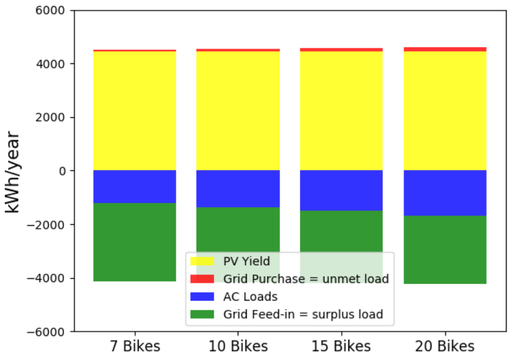

Figure 5: Full year sum results for the current design including the screen.

From Figure 5 the KPI's are calculated:

- unmet load, E_{unmet} = 62 kWh/year
- $LoLP$ = 5.1 %
- reliability R = 94.9 %

Zooming into the time series (not plotted in any Figure) looking for the unmet load, it is observed that 5 days in winter have a period of a couple of hours with unmet load. This is too much for the commercial proposition of a high-end product. But please note that the chosen type of screen (LCD) is a quite heavy user of kWh's. Several mitigation strategies can easily be implemented in a commercial follow-up, e.g.: alternative screen, or no screen at all, or turning screen off at low SOC of the battery bank.

The model has been of great value for understanding the interdependencies between the solar PV capacity, the battery capacity, the number of e-Bikes served by the station and the probability that the user will find sufficient loading capacity at the station when he arrives. Trusting and relying on the model becomes easier if the model is validated.

4 MODEL VALIDATION

4.1 Model Validation Setup

For the validation of the model, we make use again of the software package HOMER, but now in a different way. At the input side of the model, we have to consider:

- solar irradiance: G_{POA} [W/m^2] is measured minutely (and averaged into hourly values) with a sec. standard pyranometer at test facility SolarBEAT [6], less than 50 meters from the station.
- electrical load: the real total load (sum of all applications) is measured with a class 1 kWh-meter

These are fed into the program for the month of May 2017. At the output side of the model, we can monitor:

- PV-yield
- Grid purchase
- Grid feed-in
- AC loads
- SOC

all available at one hour time series.

The comparison of the measured and modeled version of a parameter shows the validation and the quality of the model.

4.2 Validation Results

In Figure 6, the comparison on daily PV yield is shown. The difference seems to be both on the over-estimation and under-estimation up till 2 kWh/m^2/day. Given the complexity of the full setup, this seems quite OK.

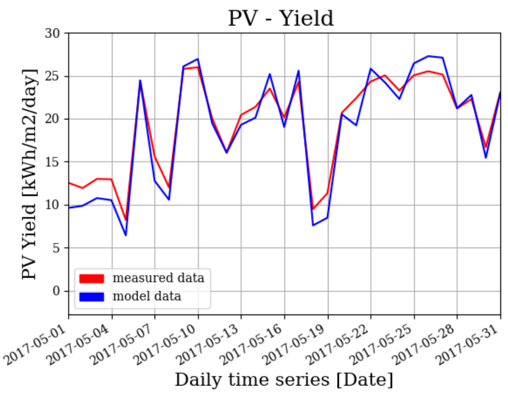

Figure 6: Daily PV Yield for May 2017. Measured yield in red and modeled yield in blue.

The most critical parameter is the SOC of the battery bank. Figure 7 shows the SOC for the same period and using the same colors for model and measurement.

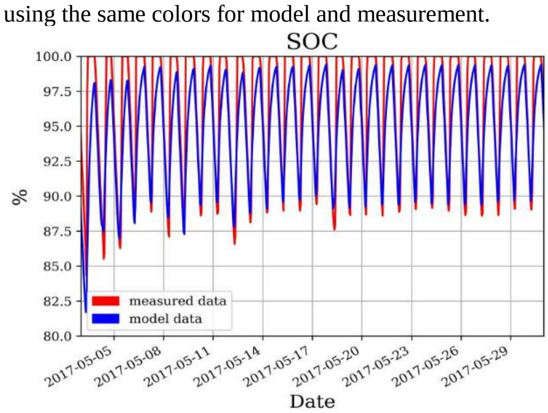

Figure 7: Timeseries of SOC for May 2017. Measured SOC in red and modeled VOC in blue.

The overall impression of Figure 7 looks quite good with deviations on the order of 2.5%. However, in the critical period of low irradiance persistent for a couple of short winter days, this 2.5% can make the difference between a fully charged e-Bike and a half full e-Bike, or even an empty e-Bike. Therefore, we will closely monitor the upcoming winter period 2017-2018.

5 OVERALL RESULTS

5.1 Current Design

With the current design parameters the KPI are presented for a situation of 7, 15, or 20 e-Bikes in Table 1.

Table 1: KPI's for current design.

Nr. of e-Bikes	Unmet load	LoLP [%]	R [%]
7	62 kWh/yr	5.1%	94.9%
15	116 kWh/yr	7.0%	92%
20	162 kWh/yr	9.6%	90%

Please note that the LoLP is by definition a critical parameter, because only the sum of electricity to the loads (≈ 1200 kWh/yr) is in the denomination, whereas the system could provide much more (≈ 4000 kWh/yr) in case of grid-connection. The 7 e-Bike case would give a questionable reliability, because it was observed that these 62 kWh are a sum of 5 days with unmet load for a couple of hours. So the 15 and 20 e-Bike cases with a reliability of 92% and 90% is too poor for a high-end product.

5.2 Increasing battery bank

Of course the reliability can be improved by increasing the battery bank. This has two major drawbacks. First and most important: the extra investment costs, because the batteries are the most expensive parts of the station. Secondly, the space occupied by the batteries in the current station comes from a neat design. Increasing that size gives a more bulky electricity cabinet, which could become too large to be accepted by the customer.

5.2 Scenario Screen Off

As mentioned before, the advertising screen consumes quite some electricity. Switching this screen completely off, shows very interesting results; see Table 2.

Table 2: KPI's for current design without screen.

Nr. of e-Bikes	Unmet load	LoLP [%]	R [%]
7	0 kWh/yr	0.0%	100.0%
15	7 kWh/yr	0.8%	99.1%
20	22 kWh/yr	2.2%	98%

Now, we see a completely 100.0% reliable solar charging station for the case of 7 e-Bikes. For the case of 15 e-Bikes a small unmet load of 7kWh/yr is seen, corresponding to a reliability of 99% which could be acceptable for the users.

5.3 Scalability

One has to realize that the latter needs already a dense packing, hence it is not meaning full to run the model for even more than 20 e-Bikes. On the other hand, less e-Bikes will not be viable from an economical point of view. For customers that would like solutions for more than 20 e-Bikes, a larger version of the station needs to be developed. In principle this would definitely be possible as all components are scalable, but goes beyond the scope of this paper.

6 CONCLUSIONS

The paper demonstrates the results obtained after investigation of real-time reliability and performance of a solar powered charging station. Based on the experience of the researchers, most, if not all of the issues faced over the course of the project were related to the e-bike systems, such as theft, bike security and bike range and bike range anxiety, rather than the energy availability of the solar charging station.

A model was designed using the HOMER software in order to apply the results of the real system to other scenarios, both in terms of system design as well as in terms of loading. This model was then validated against the measurements taken from the built system and found to have high degree of accuracy, giving acceptable results when matched with the live system.

Based on the model, the system was found to have a relatively high degree of reliability (>90%) even when the system was used with twice the number of bikes it was designed for. This increased to an extremely high value of >99% when the advertising screen was switched off. This demonstrates that the designed system is quite flexible with the number of e-Bikes it can cater to and is far more sensitive to full-time auxiliary loads in the charging station. Further options for increasing the energy reliability of the system are considered, in particularly the scalability of the designed system, which is important from a commercial perspective.

This study demonstrably shows the technical feasibility of an autonomous solar charging station for electric bikes, functioning with a high degree of reliability throughout the year, as well as the validity of the parallelly created model for estimating e-Bike loads for a given system.

7 REFERENCES

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