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# Modelling and Energy Management Optimisation of Battery Energy Storage System Based Photovoltaic Charging Station (PV-CS) for University Campus

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# MODELLING AND ENERGY MANAGEMENT OPTIMISATION OF BATTERY ENERGY STORAGE SYSTEM (BESS) BASED PHOTOVOLTAIC CHARGING STATION (PV-CS) FOR UNIVERSITY CAMPUS

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## ABSTRACT:

As utilization of Photovoltaic Charging Stations (PV-CS) that generate clean electricity from the sun increase, Dublin Institute of Technology (DIT) adopts this application for accommodating the required charge of small campus Battery Electric Vehicles (BEVs). This paper presents the virtual simulation of the 10.5 kW Battery Energy Storage System (BESS) based PV-CS model. Transient System Simulation (TRNSYS) built-in climatic data and modular structure properties were adopted to replicate the experimentally proposed PV-CS, where special attention was paid to the electrical measurments and energy flow signals. The objective was set to model the PV-CS system, formulate an energy managment optimisation and justify the ideal value and or potential range of the equivalent battery size. The primary assessment for energy management of the charging infrastructure was performed through the formulation of analytical energy balancing optimization. The energy balancing approach adopted the Simple Payback Period (SPP) method in order to investigate the acquired positive gains (Gain-1 and Gain-2) by BESS unit. The key variables for tuning the BESS capacity were load profile and size of BESS. The resultant measurement signals from TRNSYS were monitored and compared to their analytical equivalents, where verification and conclusion on accuracy improvements for BESS capacity and reliable system performance were drawn.

Keywords: PV System, PV Charging Station (PV-CS), Battery Electric Vehicle (BEV), Battery Energy Storage System (BESS)

## 1 INTRODUCTION

Almost 95% of the world's transportation energy comes from petroleum-based fuels; largely $CO_2$ emitting gasoline and diesel that are likely to be depleted by 2049 [1]. As the result, Green-House Gas (GHG) emissions from the transport sector are substantial and hence, Europe is accounting for nearly a quarter GHG emissions [2].

Battery Electric Vehicles (BEV) powered from renewable generated electricity are an alternative to the conventional vehicles and ideal solution for reversing these trends [3]. BEVs can offer significant benefits, i.e, such as lowering $CO_2$ emissions and achieving an environmentally sustainable future, when charged with PV generated electricity. This can result in zero emissions at both generation and usage points [4].

Solar energy is an abundant source of renewable energy with enormous potential for delivering clean and reliable electricity. Photovoltaic (PV) technologies are advancing at a rapid rate on the global scale, and as predicted by International Energy Agency (IEA) PV will account for 11% of global electricity generation by 2050 [5]. PV can be harnessed in the paradigm of PV charging station (PV-CS) on both urban and remote scales, to charge batteries and accommdate load demand.

PV Charging Station (PV-CS) that charge batteries with zero emissions at the generation point, is the focus of this research [6]. The proposed PV-CS is designed to supply the required charge of the campus BEVs load. The campus fleets are two CarryAll 13.76 kWh vehicles, which are referred to as Light weight Electric Vehicles (LEVs). These vehicles are utilised for short distance commutes at day/night time around Dublin Institute of Technology's (DIT) expanding campus at Grangegorman, Dublin 7, thus fulfilling the campus's sustainability targets systems.

## 2 OBJECTIVE

The objective of this paper is: to develop the TRNSYS based PV-CS modelling and verify BESS unit capacity. The specific objectives are: development of the numerical model for performance of PV-CS (Option that incroprates BESS unit) via relevant TRNSYS components and input-ouput mapping, evaluation of BESS sizing curves for optimal size and energy managements. The optimization problem was formulated with an objective to select the BESS capacity while meeting the required daily load demand.

This paper is organized as following: Section 3 provides the design and system development of PV-CS. Section 4 details the modelling procdure of BESS based PV-CS in TRNSYS platform. The energy managment optimisation formaulation is described in section 5. Comparison of the TRNSYS and theoretical energy management signals and numerical simulation results for BESS capacity sizing are discussed in section 6. Finally, the conclusion on TRNSYS performance and verified BESS size is presented in section 7.

## 3 PV-CS

### 3.1 Design option

PV based charging stations have been considered in numerous applications on both urban and remote scales system. The system on the high level can include various components such as: PV and system components; controller, energy storage system and load [7].

Likewise, several prominent design options exist such as: coupled PV-grid without storage where PV is used as the primary source of generation and any insufficiencies is accommodated via the grid [8-9]. The addition of storage as part of the design is denoted as coupled PV-grid with storage [10-11].An alternative option can exclude the grid that is referred to as standalone PV charger or decoupled PV. This is an applicable choice in remote areas where grid extension is unavailable or costly [12]. Standalone configuration can also include auxiliary storage or decoupled PV with storage, [13-14].

To consistently utilize the solar generated electricity in Grangegorman where solar radiation and charging habits of the users fluctuate, the designated PV-CS design will incorporate a Battery Energy Storage System (BESS). In this case, PV generated electricity during daylight will be exploited and stored in the BESS unit. Thereafter, BESS would act as the primary supply to accommodate the LEVs demand. The appropriate BESS capacity is the prevailing factor to accomplish the charging scheme [15]. Hence, based on the chosen BESS capacity once the unit is fully charged, the surplus generation from the PV can be spilled in the utility grid. Besides, the grid can work as the back-up for charging the load, particularly when the stored charge in the batteries is low and close to the Depth of Discharge (DoD) capacity limit.

### 3.2 BESS unit

Sizing of a BESS based system, when excluding the grid option, can be undertaken by taking into account load estimation, battery sizing and PV sizing as well as solar resource estimation, charge controller specification and system wiring [16]. Lee et al [17] monitored the load profile of various appliances and the BESS storage size capacity estimated with respect to 95% and 99% system availability via Peak Sunshine Hour (PSH). PSH is defined as “the equivalent number of hours per day, with solar irradiance equalling 1000 [Watt /m$^2$]“. Consequently the size of the PV array was estimated based on inverter losses, system voltage, PSH and temperature coefficient. Based on the estimated values, costs of the various systems were estimated, (99% tilted, 95% tilted, 99% axis tracking, 95% axis tracking). These included the cost of: PV panels, inverter, charge controller, BESS, O&M costs and labour cost. The most viable option was identified as 99% tilted axis with the estimated cost value of $ 89,000.

Likewise, the campus BESS capacity was evaluated based on: Peak Sunshine Hour (PSH) and correlation between generation and load demand [6-15]. In the first case, the days of autonomy that determine the self governing properties of the batteries were calculated according to PSH of 2.83 hours for a typical day in Dublin. This resulted in 72 or 32 Trojan compatible batteries for summer and winter load profiles respectively. In the second approach, the DC outputs of the array were normalized, grouped into specified generation categories and correlated with the load demand profile of the LEVs, where the optimal capacity was obtained to fall in the range of 6-8 kWh.

## 4 MODELLING PROCEDURE

### 4.1 TRNSYS

TRNSYS is a modular, open-source, Fortran-based energy modelling program, that is currently adopted for a variety of thermal and photovoltaic system modelling [18]. For effective simulation of PV-CS, TRNSYS modular structure requires identification of the applicable system components. The components in TRNSYS system are referred to as TYPEs. Each TYPE has a set of time-independent parameters as well as time-varying inputs that allow estimation of the matching outputs.

TRNSYS simulation tool has been used in several studies for system sizing [19-20-21]. A standalone PV system model for residential house lighting was implemented [20] using TRNSYS 16. The model incorporated a battery unit and was tested using the Ipoh city (Malaysia) weather data. The sizes of the PV and battery components were determined via the PSH method. The simulated results were further correlated with the experimentally measured data [19], and TRNSYS simulation model gave comparable results to the actual measurements [21] conducted an analysis on the system performance of battery based standalone solar home systems in Malawi for rural electrification. The equivalent model in TRNSYS considered low and high isolation profiles and was further compared to the experimentally designed system. The results showed the system was more reliable in high insolation areas.

### 4.2 Model components

The PV-CS model was developed to replicate the experimentally proposed model in [9].The model created through the connection of selected components in TRNSYS. The flow diagram for this model and the components utilised are shown in Table 1.

| Component | TYPE | Measured |
|---|---|---|
| Solar radiation processor | 15 | Irradiance |
| PV panels | 94a | Power, V I |
| BESS | 47 | Power/SOC |
| Charge controller | 48 | Energy balancing |
| Unit converter | 57 | - |
| Printer | 65 | - |
| Online plotter | 25 | - |

**Table 1 PV-CS components TRNSYS TYPES**

In order to replicate the experimentally proposed PV-CS the climatic scenarios of the installation site were considered. The weather conditions in TRNSYS was obtained using TRNSYS' built in meteorological library (TYPE 15). A four parameter model of PV system i.e., TYPE 94a, was used to present an empirical equivalent circuit model and predict the current-voltage characteristics of the 10.5 kW crystalline PV array. The battery/BESS (TYPE 47) that is currently limited to lead-acid type utilised power as an input. Subsequently the capacity was adjusted and the variations of BESS State of Charge (SOC) and power over time were considered given the rate of charge or discharge. For the purpose of this work it was assumed that the SOC of battery is initially at its minimum limit. The charge controller (TYPE 48) operated as a power conditioning device on maximum power tracking system [18].The limit on fractional SOC in controller was arranged to 0.4 and higher than lower limit of 0.1 on SOC. This was to make sure that charging the BESS by PV had priority over serving the load. Hence, the PV generated electricity would primary be stored in BESS and used at night time (when the solar energy is unavailable) to charge the load. Finally, TYPE 14 served the purpose of defining a time-dependent load profile for the campus LEVs. The pattern of forcing functions was established by a set of discrete points indicating the value of the function at various times throughout one day cycle.

### 4.3 Input-output mapping

The manner in which the input and output components were connected influenced the system control and its convergence. As illustrated in Figure 1, for input-output mapping, weather component/solar insolation, i,e, the total solar radiation at the slope angle of 10 degrees, was used to represent the solar radiation of the site. The radiation values were fed as inputs into crystalline PV panels, and the irradiance and DC output power of the panels were derived. PV's Maximum Power Point (MPP) was converted from Watts to KJ/hr and linked as inputs to the charge controller. The charge controller, with an energy balancing capability, along with the BESS system represented the key components for overall energy management relating to the charging infrastructure. Thus, it was important to ensure the chosen controller TYPE was matched with BESS unit. Hence, Mode 1 of TYPE 48 was coupled with Mode 1 of BESS TYPE 47. The fractional SOC and power of BESS were linked to the charge controller as inputs and outputs. The charge controller also measured the daily load power profile of the site which was converted to KJ/hr. This was mainly to establish the overall system control and correlate the charge/discharge between generation, BESS and load demand. All the output finals such as irridaince, energy balancing parameters and BESS unit values were converted back to their kWh for energy managment analyses.

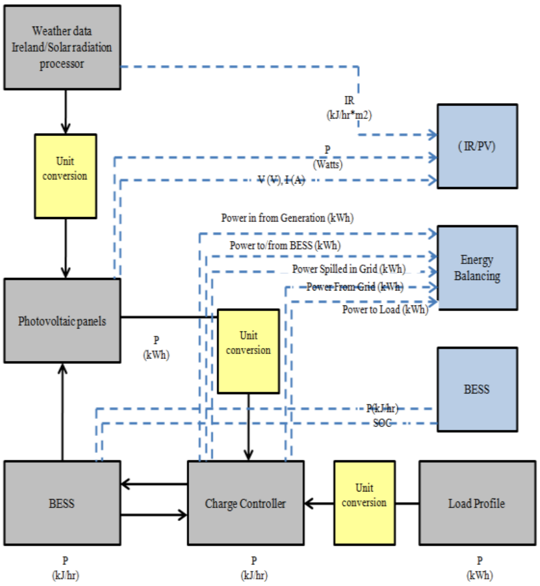

**Figure 1 PV-CS TYPES input-output connections**

Figure 4 presents the complete implemented PV-CS model in TRNSYS with all the system components expalined above.

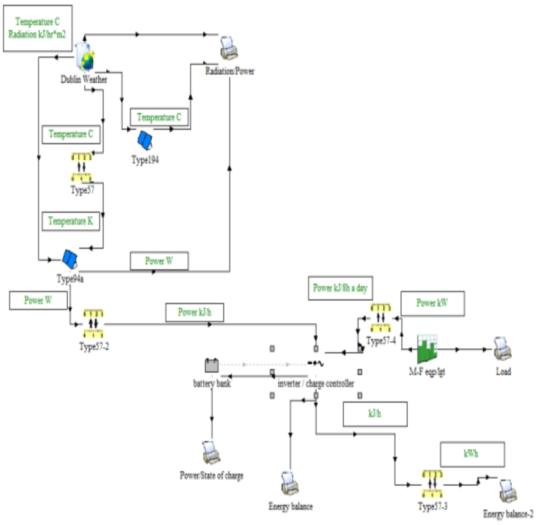

**Figure 2 PV-CS TRNSYS model with all in-built components**

As a consequence, the primary assessment for energy management of the charging infrastructure was performed through formulation of theoretical energy balancing optimization. The size of the lead-acid based BESS unit in TRNSYS was subsequently matched to the identified values obtained from this energy balancing approach. Moreover the resultant measurement signals from TRNSYS were monitored and compared to their theoretical equivalents.

# 4 ENERGY MANAGEMENT

## 4.1 Empirical

Accordingly, the energy balancing optimization adopted the Simple Payback Period (SPP) method in order to investigate the acquired positive gain by BESS unit, while the key variables for tuning the theoretical BESS capacity were load profile and size of BESS. The parameters used for energy appraisal are listed in Table 2. At this point, battery losses were not considered into system modelling.

| Energy balancing parameter |
|---|
| Energy at the beginning of the day in BESS (Start cycle) |
| Energy stored at the end of the day (Theoretical) |
| Energy stored at the end of the day (Actual) |
| Load covered from the battery |
| Energy bought from the grid |
| Energy remained for the next day |
| Energy spilled into the grid |

**Table 2 Energy balancing control parameters**

Weather and solar radiation data from TRNSYS model was utilised on hourly basis for annual period. PV DC output data was merged and the total daily output generation of the system was acquired. To illustrate a realistic load demand scenario, the maximum capacity specification of 13.73 kWh for one LEV, provided from the manufacturer was considered. Moreover, it was vital to examine the incremented BESS volume for a range of load values. As a result, the maximum load (100%) was iterated by an established factor of 20% inspired by 80%-20% Pareto principal [22], and the relationship between load covered from the battery and the overall demand was perceived. The basic method of load iteration and BESS tuning is listed in the Table 2.

| Variables | |
|---|---|
| Load | 100%-80%-60%-40%-20% |
| BESS | 7kWh-14 kWh-21 kWh |

**Table 3 Load iteration factor and BESS capacity tuning**

As shown in Figure 3, in order to implement the empirical method the following steps were considered. Initially the energy stored at the beginning of the procedure, at day 1 in BESS (Start cycle) was assumed to be zero. Nonetheless, this value was determined for each individual day of year with respect to the energy that remained for the next day. Energy available at the end of the day to BESS (Theoretical) was sum of the following parameters: start cycle + energy remained from the previous day/for the next day + daily solar generated energy at the end of the day. Energy stored at the end of the day (Actual) was assumed to be equal to the total energy available at the end of the day, unless: total energy available at the end of the day > Maximum possible capacity of BESS. In this case, Actual value = Maximum possible capacity of BESS. Load covered from the battery was arbitrated according to minimum value between Actual value and Maximum possible value of Load. Hence, Load covered from the battery would be equal to Energy stored at the end of the day (Actual), unless Energy stored at the end of the day (Actual) > Maximum value of Load. Only under this scenario, Load covered from the battery was capped to be equal to Maximum daily load demand. Energy bought from the grid was estimated based on; the supplementary energy needed for accommodating the remaining load that was not covered via BESS. When the Energy stored at the end of the day (Actual) > Load covered from the battery, this energy was carried over the next day as part of Energy remained for the next day. Finally, Energy spilled into the grid was obtained by the difference between Energy available at the end of the day and Energy stored at the end of the day (Actual). In other words, the slurps PV generated energy was spilled into the utility grid.

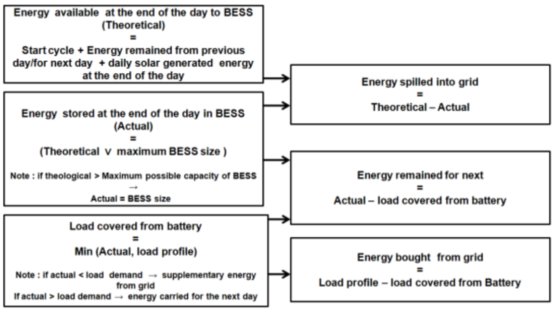

**Figure 3 Logical description of energy control management**

Moreover, as tabulated in Table 4, the aforementioned energy balance values were adjusted to their cost equivalents. Annual savings were the energy costs avoided annually consisted of annual energy savings multiplied by the cost per unit. These were obtained from operation of PV-CS and referred as Gain-1 and Gain-2. In other words, these gains were defined as Load covered from the battery + Energy spilled into the grid. Energy spilled into the grid for Gain-1 was assumed to be dumped energy that made zero profit, as there is currently no feed-in-tariff for selling the electricity back to the grid in Ireland. On the other hand, for Gain-2 the boundary was defined in such a way that surplus energy spilled into the grid would be used to serve the other campus’s energy demand as the PV-CS is collected within a civic area. Thus, Energy spilled into the grid was set to be equal to half of electricity tariff/ Energy bought of 0.18 cents per kWh. However, this price was versatile which can be altered to different scenarios as part of the future work. Finally, SPPs were altered with respect to the inventory gains influences. SPP was defined as the minimum amount of time in years that would be required for the positive cash flow to surpass the initial assessment of PV-CS, excluding the time value of money. In other words, the payback period was defined as the ratio of capital cost investment for building and deployment of PV-CS over the annual cost savings resulted from BESS incorporation.

# 6 Results

## 6.1 Empirical results

The energy for Case 1&2 sample load ratios and BESS unit sizes, i.e. case 1 : 7 kWh, case 2 : 14 kWh and case 3: 21 kWh, for total yearly period. as it was specified in Table 3, is shown in Figure 4 and 5.

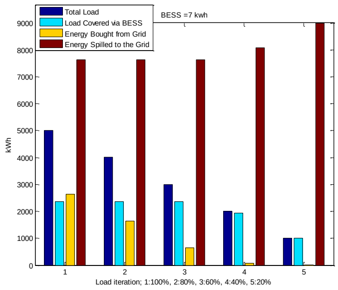

**Figure 4 Load iteration for 1 unit of 7 kWh BESS**

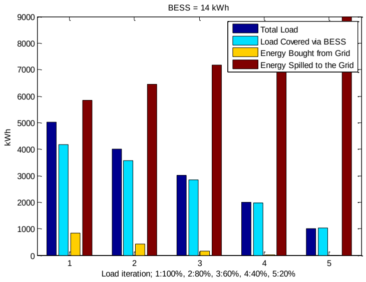

**Figure 5 Load iteration for 2 unit of 7 kWh BESS**

The aforementioned energy balance tables were adjusted to their cost equivalents, where the average cost of the system components were extracted from [15]. These results are summarised in Figure 7 and 8.

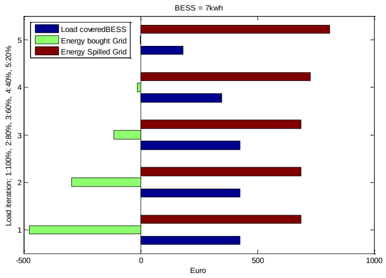

**Figure 7 Positive/ negative cash flows 7 kWh BESS**

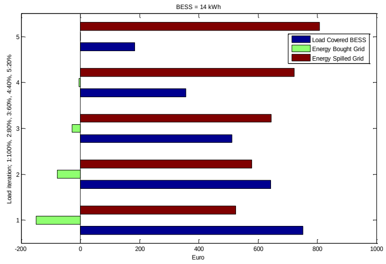

**Figure 8 Positive/ negative cash flows 14 kWh BESS**

When deciding between the optimal BESS capacity for PV-CS project, the decision was made to accept the case with the shorter payback. Figures 9-10 present (a) Gain-1, Gain-2, and (b) SPP1 and SPP2

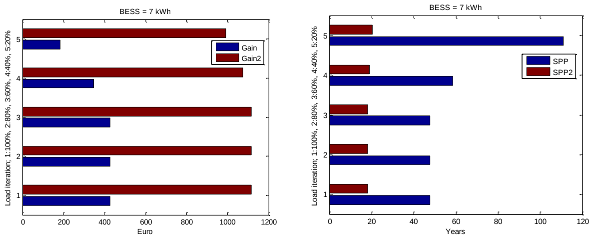

**Figure 9 Economic analyses for Case 1: 7 kWh BESS unit**

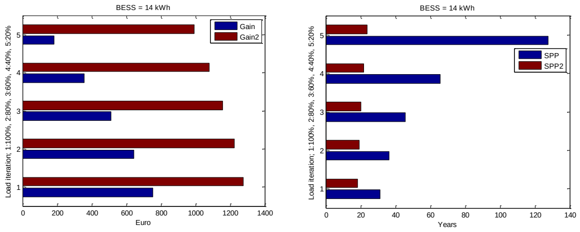

**Figure 10 Economic analyses for Case 2: 14 kWh BESS unit**

Since there were no constraints applied at this point in the system study, the price of energy spilled influenced the optimal choice. As the optimization was performed for 3 different BESS sizes (Case 1, 2, 3), it gave each case 33% chance of captivation. The difference between Case 2-3 was negligible, thus the optimization was focused on the assessment between Case 1 and 2. The values of SPPs (SPP1 – SPP2) are summarized in Table 5 and 6. By looking at the green fields in the energy tables for SPP of Case 1 and 2, it was evident that for 60% - 100% of the load demand, SPP value of Case 2 was shorter which subsequently led to a more desirable choice. On the other hand, when the load demand is smaller and in the range of 20%-40%, Case 1 was identified to be more viable. With SPP2, the results were quite similar and the differences between values were insignificant. This was mainly due to the cost of selling electricity back into the grid.

The concept of 80%-20% which is referred as Pareto principal was developed by Pareto an Italian economist could be applied to for finalising the scenarios. The principal states; “80% of the output is a direct result of about 20% of the input”.While Pareto optimization is a widely accepted rule of thumb, the validity of this approach in business field and software is particularly indispensable. In this case it could be referred to 33% - 60% and 33% -40% for the explained scenarios above.

| Variables | SPP_C1 | SPP_C2 | SPP_C3 |
|---|---|---|---|
| 100% | 47.58 | 31.17 | 34.11 |
| 80% | 47.58 | 36.43 | 40.48 |
| 60% | 47.58 | 45.75 | 51.25 |
| 40% | 58.36 | 65.70 | 74.20 |
| 20% | 110.99 | 127.71 | 147.33 |

**Table 5 Scenario comparison for BESS sizing for Case1,2 and 3 for Gain-1**

| System | SPP_C1 | SPP_C2 | SPP_C3 |
|---|---|---|---|
| 100% | 18.22 | 18.36 | 20.59 |
| 80% | 18.22 | 19.17 | 21.62 |
| 60% | 18.22 | 20.76 | 22.91 |
| 40% | 18.89 | 21.72 | 24.62 |
| 20% | 20.47 | 23.63 | 26.86 |

**Table 6 Scenario comparison for BESS sizing for Case1,2 and 3 for Gain-2**

However, if BESS was tuned for more numbers, the 33% value could be varied to a difference percentage. In summary, if the fleet are to be enlarged in the future, there would be the probability of serving more cars from the installation, thus designing PV-CS for Case 2 could be a more reliable option.

## 4.2 TRNSYS

In order to verify the obtained energy performance values from the emprical optimisation approach, the results were compared with their equivalent values obtained from the output performance of TRNSYS model. As explained in Figure 4, in the TRNSYS based approach, the components were adjusted once more with respect to the Table 3 methodolgy. Hence, in this case the *n* number of BESS capacity and load values were iterated. This energy and cost data generated via this approach were very comparable to their empirical equivalents. In other words, TRNSYS provided similar range of data and thus same conclusion could be drawn for choosing the BESS capacity.

## 7 CONCLUSION

The main motivation behind campus PV-CS scheme is to harvest electricity, thus accommodating the load requirements of campus LEV fleet. This paper presented a deterministic method for sizing of the BESS based via energy managment optimization and TRNSYS electrical signals. The obtained sizing curve from the two approches were compared the result were similar. The recommeded size of the BESS unit would mainly depend on the load demand of the buggies and the energy tariffs for spilling the electricty into the grid.

## 8 ACKNOWLEDGMENTS

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