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The Battery Energy Storage System (BESS) Design Option for On-Campus Photovoltaic Charging Station (PV-CS)

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Abstract

As the application of Light weight Electric Vehicles (LEVs) increase in communities, Dublin Institute of Technology (DIT) uses these small vehicles for short distance journeys around its 78 acre campus of “Grangegorman” located in inner Dublin city, Ireland. This paper presents an introduction to the campus Photovoltaic Charging Station (PV-CS) that generates clean electricity from the sun and charges the LEVs batteries which can lead to reduction of CO_2 emissions, along with fulfillment of national and international green sustainability targets. Based on the evaluation of possible options for PV-CS design, the optimal design configuration was chosen as a "Battery Energy Storage System (BESS)”. The PV generated electricity that is stored in battery banks will serve as the primary source for charging the campus vehicles, with any surplus demand being met by the utility grid. Batteries have been included in the design due to intermittent nature of Irish sunshine and the charge time requirements of campus load. This paper concentrates on the detailed sizing of the BESS via two approaches: BESS with DC generation and BESS with LEV load demand. In the first approach the outputs were normalized and grouped into specified generation categories in MATLAB. To establish the accurate BESS capacity the load demand variations of the LEVs were monitored. Based on DC generation and demand profile, the optimal capacity of BESS was chosen to be in the range of 6-8 kWh, which can accommodate up to 6 LEVs.

Keywords: *Renewable Energy Resources (RES), Battery Electric Vehicle (BEV), Light weight Electric Vehicle (LEV), Battery Energy Storage System (BESS), Greenhouse Gases (GHG),*

1. Introduction

Transport is the second biggest emission intensive sector in Europe, accounting for nearly a quarter of Greenhouse Gases (GHG) pollutions (European Commission, 2013). Since the energy consumption of transport heavily depends on fossil fuels, Battery Electric Vehicle (BEV), an alternative to conventional vehicles, can help to minimize emission levels at the usage point. Moreover, with the trends encouraged by governments and political parties, strong commitments have been made on both European and International levels to increase the penetration of Renewable Energy Resources (RES) (Da Graça Carvalho, 2012). BEVs have significant benefits in an urban context, mainly due to shorter trips, lower speed and power requirements (Smith, 2010). As shown in Table 1, BEVs capacity and technology can vary and subsequently are influenced by the size of the vehicle (SEI, 2007; World Electrified Vehicle Sales, 2013). Applications of small utility vehicles are gaining interest in both public and local sectors such as: night time deliveries, airports, in parks and golfing facilities (Standford, 2007; Heathrow Airport, 2011). Our focus is on CarryAll 13.76 kWh vehicles, which throughout this paper is referred to as Light weight Electric Vehicle (LEV).

Table. 1: Various BEV Battery Capacities

Vehicle	EV Type	Battery Technology	Battery Capacity
Nissan Leaf	BEV	Lithium-ion	24 kWh
Tesla Model S	BEV	Lithium-ion	60/85 kWh
Renault Zoe	BEV	Lithium-ion	22 kWh
Renault Kangoo ZE	BEV	Lithium-ion	22 kWh
Small Utility	BEV	Lead-Acid	13.76 kWh

Solar energy in particular has emerged as one of the prominent sources of alternative energy, with significant potential for reducing CO_2 emissions at the generation point (SEAI, 2010). Furthermore, Photovoltaic (PV) panels can be used in charging stations to accommodate the BEV's batteries charge demand (Hamilton, et al., 2010; Abella & Chenlo, 2003). This research proposes an application, where the PV-CS is used to supply the required charge of the campus LEVs. The campus fleets are adopted for short distance commutes at day/night time around Grangegorman's expanding campus allowing the generation of reliable green electricity, thus fulfilling campus's sustainability targets.

2. Solar Climate and Potential (in Ireland) :

PV systems use the photovoltaic effect to convert solar radiation directly into electricity. Solar radiation reaching the Earth's surfaces includes both direct and diffuse insolation, where the most common measurement for quantifying solar radiation is the total radiation on a horizontal surface, often referred to as global radiation (Duffie & Beckman, 2013). PV generation is directly related to the solar radiation intensity, i.e., higher solar radiation levels provide greater electricity output. Figure 1(a) from Met Éireann data (Irish Meteorological Service, 2011), illustrates the sunshine profile of Ireland. Based on this information, the annual sunshine hours for the temperate region of Ireland is between 1100-1600, where May and June are the sunniest periods during the year with average sunshine durations of 5 and 6.5 hours per day. During the month of December, the average sunshine values can be extremely low and available for only one hour (Flood, et al., 2011).

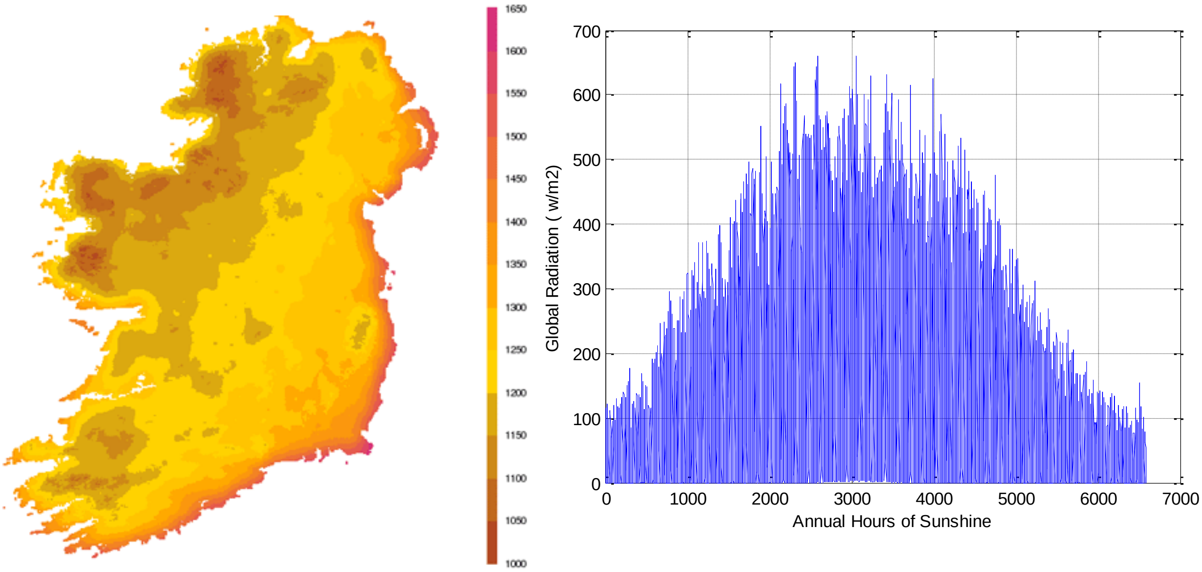

Figure. 1: Met Éireann Data: (a) Annual Hours, (b) Averaged out Global Radiation (W/m^2) of 10 years

Figure 1(b) signifies the "annual averaged global solar radiation" profile of Dublin, using 10 years of measured data by Met Éireann. The irradiance data (W/m^2) accounts for seasonal (monthly) sunshine variations and has been captured hourly every day from 04:00 – 21:00 at Dublin airport meteorological station. As can be observed from the graph, the insolation levels are greater during the summer period, reaching a maximum level of 660 W/m^2/day, while the mean value of the global radiation is ~ 140W/m^2/day. These fluctuations in solar radiation levels, and DIT campus's expansion targets, will require a sizable PV covered roof area that can harvest sufficient electricity for the campus LEVs demand.

The PV system will be installed on the Orchard-House building; it is shown along with the building plan in Figure 2 (a) & (b). This is the current charging point for the campus LEVs the CarryAll 500 which is illustrated in Figure 2 (c). The vehicle specification is summarized in Table 2. Since Orchard house is situated near the main access point of university, it is a favourable location for deploying PV-CS. The total available roof area is 3700 m^2 but the dedicated south facing area of this roof (highlighted with red-lines in figure 2(a)), is ~ 69 m^2 at an inclination of ~ 36 degrees. When considering a regular 250 W monocrystalline PV panel of 1.63 m^2, the purposed area can accommodate a 10.5 kW system composed of 42 panels.

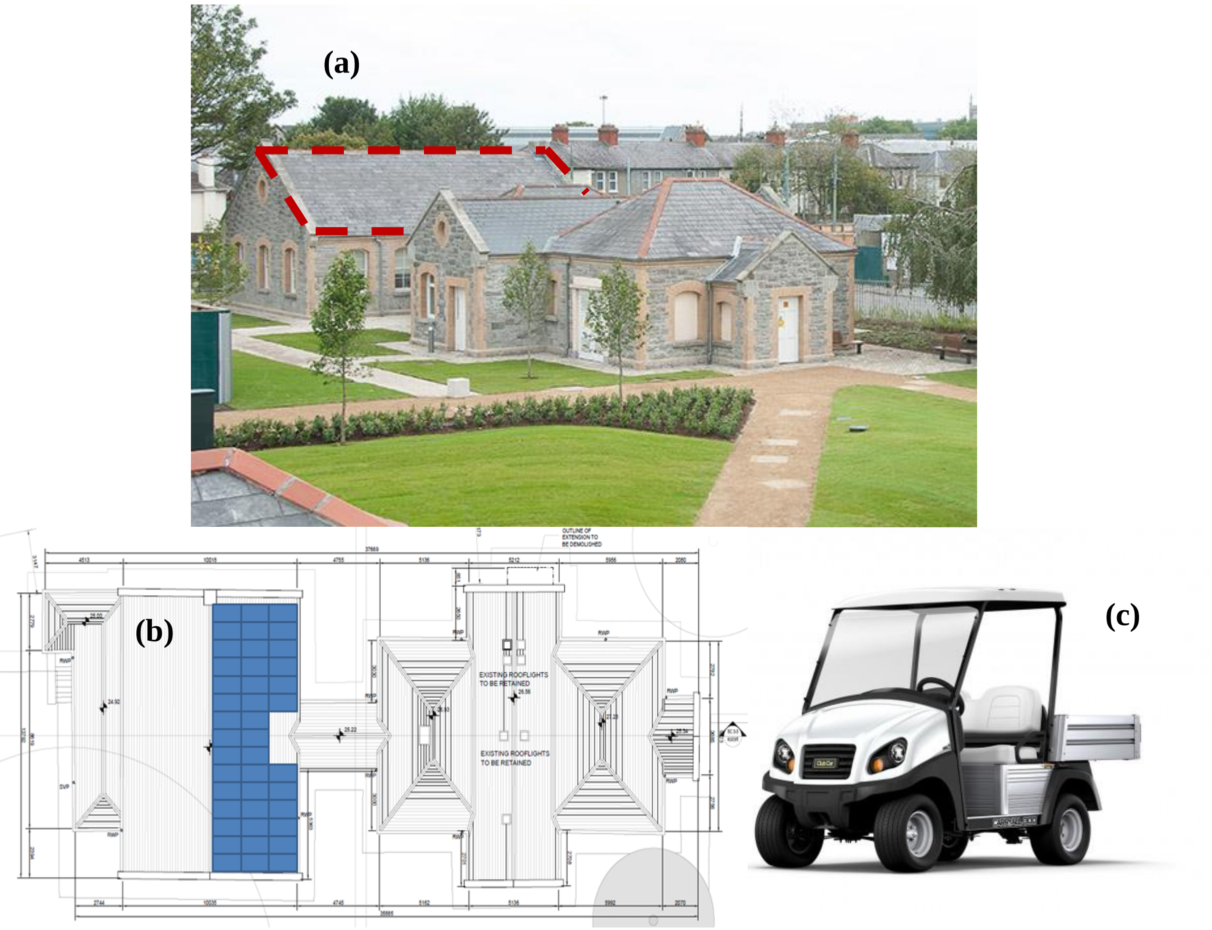

Figure.2: Orchard-House Building site (a), Roof schematic plans (b), CarryAll 500 LEV (c)

Table. 2: Specifications of the CarryAll 500 LEV

Motor Type	48 V DC
Horse Power Rated	3.7 hp (2.7 kW) rated; Peak 20 hp (14.9 kW)
Transmission	Direct/ Drive Double Reduction
Speed	15 mph (~ 25 km/h)
Battery Model	Trojan (T-145) with Flip-Flops x 8Units
Battery Voltage	48 Volts (6 Volts x 8Units)
Battery Capacity	13.76 kWh (1.72 kWh Each Unit)
Battery Capacity	260 Ah kWh (Each Unit)

3. PV-CS Design Options

In order to advance the PV-CS design, it is vital to identify the optimal design option, which has the potential to deliver electricity in a sufficient, reliable and cost effective manner. Sizing and deployment of the PV installation tends to be an iterative process, in which numerous design factors need to be examined, such as: solar potential of the site, array size, available cost, nature of the load, demand profile, operating voltage, choice of the storage unit and or grid integration (Lee, et al., 2012; Esfandyari, et al., 2015). PV-CS can be divided into a number of segments (Esfandyari, et al., 2014) such as PV and system components, cabling, protection and mounting elements, charge controller, inverter, battery storage unit and the load. Integration of each of these components can lead to a distinct system design arrangement. (Esfandyari, et al., 2015) determined the hypothetical design set-ups for the campus PV-CS and grouped the outcomes into five possible options; (i): decoupled grid (AC); (ii): decoupled direct PV (DC); (iii): decoupled PV with storage (DC); (iv): coupled PV-grid without storage and (v): coupled PV-grid with storage. These configurations are summarized in Figure 3. Furthermore, the average cost for each system component and various installation categories is presented in Table 3. These figures are quoted from PV suppliers and data reported by Sustainable Energy Authority of Ireland (SEAI, 2013).

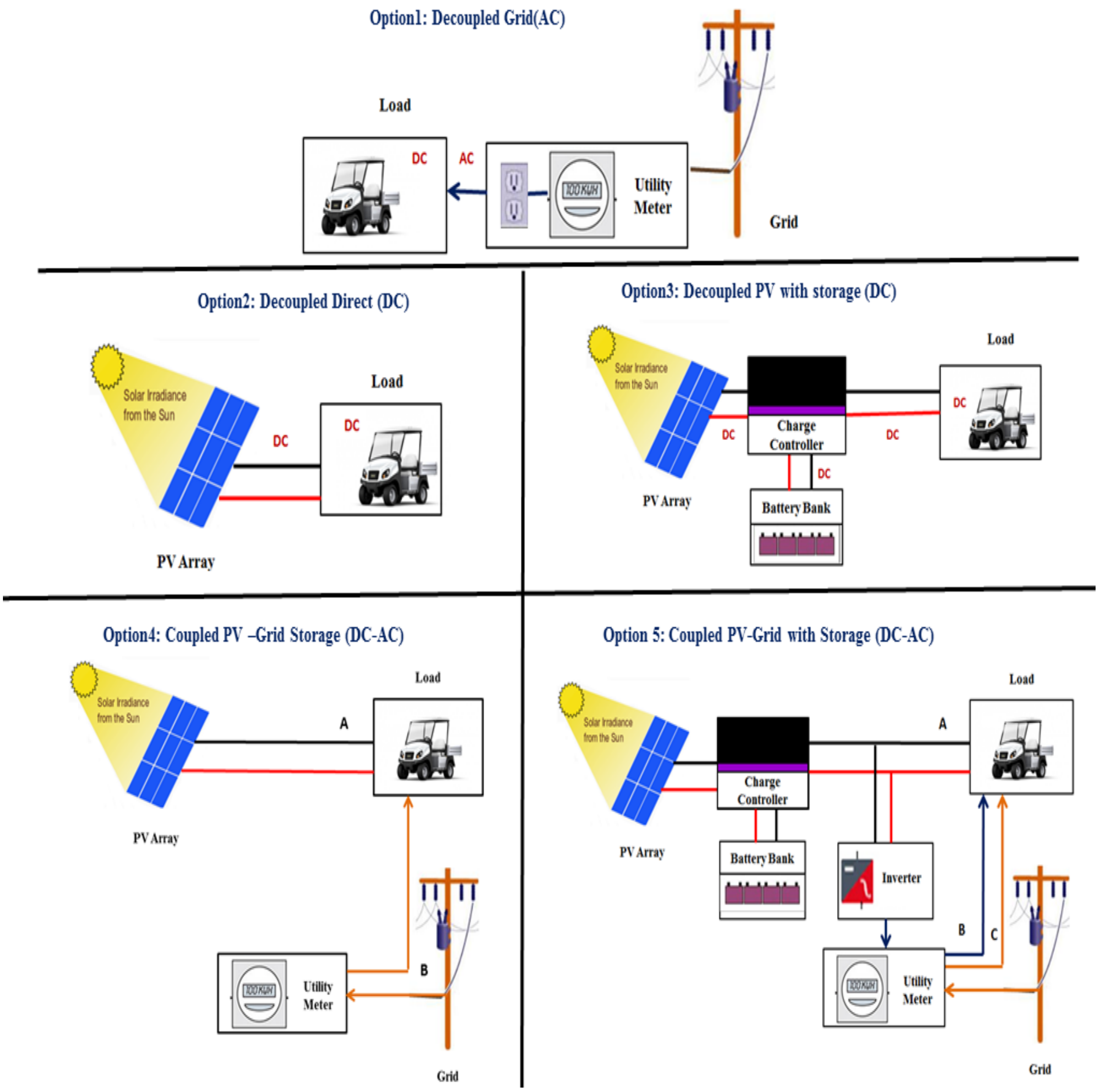

Figure. 3: Detailed Schematic for Design Options of Campus PV-CS

Table. 3: Cost breakdown for PV-CS system components and installation (SEAI, 2013)

Component	Average Cost
Solar Photovoltaic Panels	€854 per kW
Inverter	€619 per kW
Instrumentation and Control	€177
Battery (Lead Acid)	€350 (400 Ah)
Installation-Electrical	€543
Installation-Civil	€904
Installation-Mechanical	€191
Maintenance	€109
Other	€88

From Figure 3, option 1 “decoupled grid (AC);” is the existing scheme for charging the cars, where LEVs are directly fed by the grid. In this case the electricity is supplied to the load in the form of AC, via standard three pin plug sockets at 230 Volts/13 Amps. Since the LEV batteries run on the DC voltage, and each vehicle is comprised of 8 Trojan lead acid batteries at a total of 48 Volts, the AC quantities must be converted into their DC equivalent. This is achieved through the internal inverter of the vehicles. However this is not a sustainable way for energy generation, as ~76% of Ireland’s primary energy is generated from fossil fuels (SEAI, 2014). In order to address sustainability targets of: self-sufficiency in energy, improvements of security of supply and reduction of amount of GHG, solar energy was proposed as a method of green electricity generation.

Option 2, considered the possibility of synchronized design, where LEVs are directly charged using PV. In this case, solar panels are used as the primary and only source of power. The PV panels will need to be arranged on the roof of the vehicle, where DC electricity directly fed to the Trojan batteries and/or DC brushed motor. While the capital cost of system components for the case “decoupled direct PV (DC)”, will be at the lower end of spectrum (due to incorporation of minimum ancillary elements), the fluctuation in solar radiation and absence of any secondary generation will require a large LEV roof coverage. In other words, with particularly low average winter sunshine durations, (only for one hour), and the demand profile of Trojan batteries (Esfandyari, et al., 2015) that can be as high as 13.76 kWh, the installed PV capacity needs be substantial for the vehicle’s rooftop (at least 1.75 kW which will take up ~ 11.4 m^2). Thus, this option was not a viable choice.

Option 3 examined a set-up where the PV panels are installed in a standalone configuration. The “decoupled PV with Storage (DC)” will operate on DC voltage only, where the electricity generated from the fitted panels on the roof of Orchard house will be regulated through the charge controller and stored in a number of battery banks. The storage unit will serve as the primary source of energy, which will accommodate the vehicles load requirements. However, due to the absence of any back-up generator, the reliability of this set-up will be poor. Where in the event of lower sunshine hours, the depleted charge of the storage unit might not be restored leaving the LEVs batteries exhausted, unless the of the PV-array and subsequently the battery banks can be oversized to guarantee meeting the maximum load requirement but this can increase the capital cost significantly. As the result, this option was not identified as a practical choice.

Option 4 considered the possibility of running a coupled configured system. Coupled PV-grid without storage allows the load to be charged on both DC-AC voltages, depending on the available sunshine levels. The coupled possibilities are labelled as A and B in Figure 3 option 4. ‘A’ is the daytime scenario where the solar radiation is utilized as the primary source for charge generation. This means parking the LEVs during the hours of sunlight and recharging the batteries directly via the DC voltage. In the case of low solar radiation and/or higher demands, the load could be supplied by the utility grid as shown by in ‘B’. However, as the LEVs are normally used during the day and charged at night time, this option was also not appropriate.

The choice of “coupled PV-grid with storage”/Option 5 completed the design scenarios, by combining all the system configurations retrieved from the previous options. In this case the practicable methods for charge restoration of LEVs are described in sections: A, B and C. In ‘A’ PV will be used during daylight to generate electricity and this electricity will be stored in the battery storage unit. The storage unit charge could be used afterwards to charge the LEVs, thus it will not pose any limitations on user’s driving needs. In ‘B’, any surplus in PV generation where the storage batteries are full is sent to the grid. Finally ‘C’ includes the grid as the back-up generation for the load, in the event of low solar radiation and consequently resulting in no charge in the storage batteries. This design option was chosen to be the most viable choice for Grangegorman PV-CS.

4. Battery Energy Storage System (BESS) Design Option

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 storage unit. As described in the earlier section Option 5 the “Battery Energy Storage System (BESS) design option will be examined further. Since the storage component is the predominant module of this configuration, the accurate sizing of this unit is imperative. Previously, (Esfandyari, et al., 2015) applied a methodology which was adapted from (Lee, et al., 2012 ; Masters, 2004). In this manner, the battery capacity was altered with respect to: maximum daily load demand, days of autonomy, Depth of Discharge (DOD), efficiency and voltage level. The days of autonomy which accounted for the number of the days that the storage batteries need to accommodate the load, were calculated based on Peak Sunshine Hours (PSH) of 2.83 hours for a typical day in Dublin (Ayompe, et al., 2011). Thus, the selected lead acid batteries were settled to the capacity value of ~ 390-400 Ah as advised by the battery suppliers., with 40% DOD and 85% efficiency and a voltage level similar to voltage level of LEVs Trojan Lead acid batteries, i.e., 8 batteries with at 6 volts-260 Ah. Based on this methodology and with 95% system availability, the recommended storage days for the PV-CS was estimated as 4.93 days, which resulted in 72 or 32 batteries for summer and winter load profiles respectively. Yet, as stated by the authors, due to auxiliary issues associated with: efficiency, cost, sheltering and maintenance of the estimated batteries, the work required further justifications and a more pragmatic capacity value for BESS.

As mentioned earlier, BESS will be exploited as the preeminent energy source, for storing the available PV generated DC output and subsequently dispatching the charge to the load. Inappropriate sizing of the batteries, (over-sizing or under-sizing the BESS unit), will have ramifications on the cost and or reliability of the campus PV-CS. In exchange, optimization of BESS capacity will depend on a number of constraints such as: obtainable solar resource, mandatory LEV demand, available budgets and cumulative project size. The adopted approach here has examined the first two constraints; DC generation and LEV load demand, where the proposed storage size was formulated.

4.1. BESS with DC generation

Hourly recorded meteorological insolation data at Dublin airport station is presented in figure 4 where the seasonal variations in solar intensity are clear. The roof plan of the chosen building and its accessible area as illustrated in figure 4, acts as a constraint for PV deployment. The total daily horizontal insolation values (kW/m^2) were scaled to correspond to the roof area of 69 m^2. Moreover, as the designated panels are 15.4% efficient, the DC generated output was calculated (gray cross line) and is presented in Figure 4. As displayed in figure 4, the magnitude of total daily DC output varies between the minimum of 3.56 kWh/day which occurred on the 31th of December to the maximum value of ~ 63 kWh/day occurred on 15th of June. Due to the overcast climate of Ireland, the total numbers of the days with high output and close to the maximum point are quite low (especially from November-March). Previously statistical tools were adopted (Arthur, et al., 1988; Lee, et al., 2012; Ibrahim, et al., 2012), such as curve fitting, regression model and probability density distributions, for analyzing the solar radiation distribution. The approach adopted in this study was essentially based on investigating the DC generation and determining the distribution of specified generation categories in MATLAB. After inspection of several groups, case 1 and 2 were designated as the best representative scenarios.

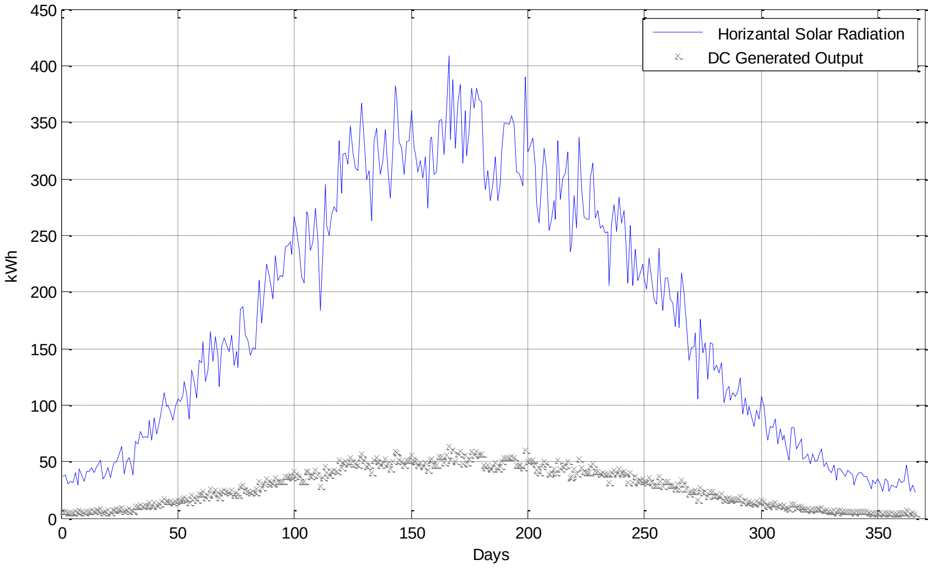

Figure. 4: Orchard House Horizontal Solar Radiation (Blue), DC Generated Output (Gray Cross Line)

The bin interval for the first case was selected as 1kW which resulted in 60 incremental generation groups. Furthermore, the bin intervals were extended to 2 kW for the second category, which reduced the incremental generation groups to 30. This was merely to examine the population density of each group profile with respect to the count of intervals. These two cases are illustrated in Figure 5, where x axis represents the generation bins and y axis depicts the population or number of occurrence for generation days.

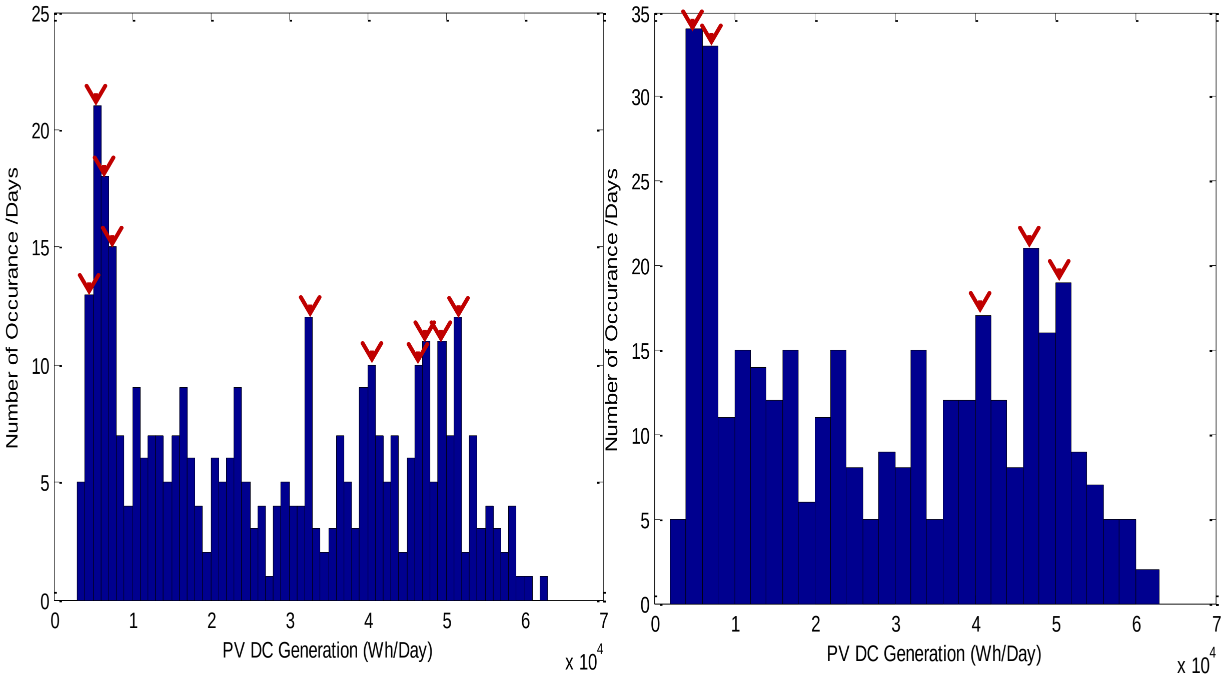

Figure. 5: PV DC Generation: (a) 1000 Watts group segmentations, (b) 1000 Watts group segmentations

In order to identify the most applicable generation band for BESS sizing, the maximum peak values in each category were extracted, tabulated and is presented in Table 4. Table 4 reports on the number of the occurrence (population intensity) of the individual peak values, the associated bin range and percentage of divergence from the potential maximum day of generation. There were 10 chosen peaks for the first case, and the peak numbers were reduced to 5 for the second case. Nevertheless the population intensity of the second category peaks contains more days of occurrence.

Table. 4: DC Generation Normalised Peak Density

Peak	Number of Occurrence /Days (Case 1 = 1k)	Bin Range (Case 1 = 1k)	Deviation from the Max (Case 1= 1k)	Percentage Of generation	Number of Occurrence /Days (Case 1 = 2k)	Bin Range (Case 1 = 2k)	Deviation from the Max (Case 1= 2k)
1	13	4-5 kWh	92%	8%	-	-	-
2	21	5-6 kWh	90.5%	9.5%	34	4-6 kWh	90.5%
3	18	6-7 kWh	88.89%	11.11%	33	6-8 kWh	88.89%
4	15	7-8 kWh	87.3%	12.7%	-	-	-
5	12	32-33 kWh	48%	52%	-	-	-
6	10	40-41 kWh	35%	65%	17	40-42 kWh	35%
7	10	46-47 kWh	26%	74%	-	-	-
8	11	47-48 kWh	24%	76%	21	46-48 kWh	24%
9	11	49-50 kWh	22.3%	77.7%	-	-	-
10	12	51-52 kWh	17.5%	82.5%	19	50-52 kWh	17.5%

As it can be seen from the table, over the course of the year the generation bands which had the higher distribution densities were between 4-6 kWh, 6-8 kWh 40-42 kWh, 46-48 kWh and 50-52 kWh. Thus, the battery size/days of autonomy would need to be matched to the most appropriate generation band.

4.2. BESS with LEV Load Demand

In order to determine the prospective PV-CS BESS unit, the second technique inspected the daily load profile of the campus vehicles. This was to quantify the accurate demand band of the LEVs as well as average and maximum demand bands. The demand profile was measured using a designated power meter “Hawk5000”. The Hawk meter with its capability to monitor the electricity supply and consumption by means of Current Transformers (CTs), was wired up to the current charging point. The energy meter captured: current, voltage, real power, power factor, and energy at a specified sampling interval.

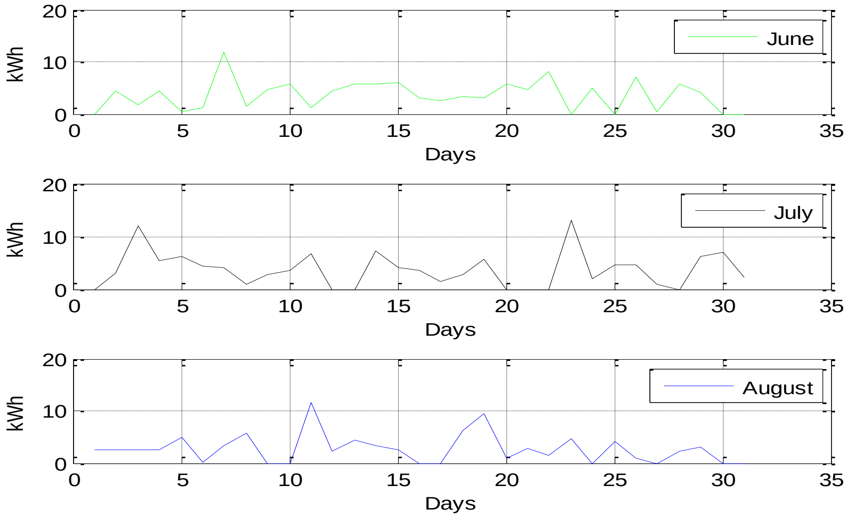

Figure. 6: Load Demand Profile of two LEVS (June-July-August 2015)

The desired sampling rate in this case was selected and varied between 1 to 5 minutes. Every time a load was plugged in to the charging point, the variations of measurement signals were sensed by CTs and stored in the data logger. Figure 6 presents the daily energy requirements of the two LEVs. The data was collected for over 3 months (June - July - August 2015). It is summarized in Table 5, the maximum load demand of the LEVs was on 23th of July (13.03 kWh/day - close to the total capacity of one vehicle). The average demand of the total load was 2.11 kWh/day. This value emphasises the variation of the rate of charge.

Table. 5: Load Demand profile of Two LEVs (Maximum and Average)

Generation	Maximum DC Generation Output	Maximum Load Demand	Average DC Generation Output	Average Load Demand
10.5 kW (STC)	62 kWh/day	13.03 kWh	28 kWh/day	2.11 kWh/day

In order to identify the most appropriate size of BESS, generation potential and demand profiles were measured. As the average load demand of each vehicle is limited (2.11 kWh/day for the total campus load), when the cost factor of the batteries were considered the generation ranges of 4-6kW, 6-8kW were viable. Moreover, with the new battery technologies in the market, for example the Tesla Powerwall (Tesla, 2015), which are lightweight rechargeable batteries offering reliable operation and security at 7 kWh per unit, the 6-8 kW range was perceived as a better option. In other words, if the BESS unit was matched to 6-8kW, it could accommodate almost 6 campus vehicles.

5. Conclusion

Introduction of a PV-CS in DIT Grangegorman campus, Dublin, Ireland that generates clean electricity from the sun and charges the campus LEVs batteries, can substitute a portion of the charge supplied from the conventional utility grid, and further help to achieve suitability targets. In this paper design options for PV-CS were discussed. Due to intermittent nature of Irish sunshine and user's charging habit, the choice of coupled PV-Grid with storage unit/ BESS was identified as the most viable solution. Yearly averaged values of solar insolation for Dublin were examined and appropriately scaled to represent the DC generated output of 10.5 kW PV array with 15.4% efficiency. In order to size the BESS unit accordingly BESS was investigated in conjunction with generation and demand requirements. Since the load demand of the two LEVs was, within the DC generation ranges of 4-6kW, 6-8k, these ranges were selected for BESS sizing. With reference to the new technologies in the battery industry for example Tesla Powerwall at 7kWh, the 6kw-8kW range was recognised as possibly a better option. This capacity band with reference to the average load demand of 2.11 for two LEVs could accommodate up to 6 cars. .

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