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Essentials for On-Campus Photovoltaic Charging Station(PV-CS): Grangegorman

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ESSENTIALS FOR ON-CAMPUS PHOTOVOLTAIC CHARGING STATION (PV-CS): GRANGEGORMAN

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Abstract

As Light weight Electric Vehicles (LEVs) are gaining interest, Dublin Institute of Technology (DIT) realises the value and application of these vehicles for short distance commutes around its newly built campus of "Grangegorman" located in inner Dublin city. Introduction of the campus Photovoltaic Charging Station (PV-CS) that generates clean electricity from the sun and charges the LEV's batteries can help achieving Ireland's 2020 targets on both national and international levels. This paper highlights the design essentials of on-campus PV-CS, via assessments of: LEV load consumption, vehicle tracking and sizing of the storage unit. The pattern for LEVs charging and load consumption was studied on a daily basis utilising a designated energy meter while the typical journeys were tracked using a GPS device. The specified conceptual calculations resulted in appraisal of 5 possible design options. The components for each configuration are listed and the significance of each case discussed, where "coupled PV-grid with storage" option is chosen as the most viable choice of design. The potential size of storage batteries was projected with respect to *average* and *peak* demand variations. Battery density, weight and efficiency were identified as the main barriers, which will require future economic and technical investigations in this field.

Background

Transport accounts for around 25% of EU greenhouse gas emissions, making this sector the second biggest consumer of energy in Europe [1]. Moreover, the electric automobile industry is rapidly expanding with the advancements in Battery Electric Vehicles, Hybrid Electric Vehicle, and Plug-in Hybrid Electric Vehicles (BEV/HEV/PHEV) [2]. Battery EV (BEVs) is an alternative to conventional vehicles, as this energy storage technology has zero emissions at the usage point, i.e., due to shorter trips, lower speed and power requirements [3]. BEVs battery capacity can influence the size of the vehicles [4][5][6], and one of which are the small utility based BEVs. The application of these small vehicles is gaining interest in both public and local sectors such as: night time deliveries, airports and leisure facilities [7][8]. In this study the BEVs used are 13.76 kWh utility battery based Light Weight EVs (LEVs), which according to the manufacturer their typical energy usage is 25 kWh per 100 km [9]. Although BEVs have the advantage of mechanical simplicity, the limited battery charge and the lack of charging points, make their travel range limited [10]. Several methods for charging BEVs have been proposed in [11][12][13][14][15]. One such method is through the use of a photovoltaic (PV) charging station, which can lead to zero emissions at the generating point [4]. This research explores an application; where the PV-CS will be used to accommodate a portion of the campus LEVs required charge. The LEVs are adopted by general operation staff and night time security staff for short distance commutes at day/night time around the 78 acre university's expanding site. The twofold design, i.e., utilisation of LEVs in conjunction with PV renewable resource, can help maximizing the net sustainability gain, and further help achieving Ireland's 2020 targets on both national and international levels.

Design Essentials (Prerequisites for installation of PV-CS in Grangegorman)

The main motive behind DIT's PV-CS scheme will be to harvest green electricity, thus accommodating the load requirements of campus LEV fleet. In order to correctly size the system, it is essential to look at the available roof area, load profiles and the typical journeys that these vehicles undertake over the course of night and day, especially during active periods. This is to ensure PV generation can meet the utility LEVs battery's energy demand. Figure1 shows the map of Dublin city centre, (Dublin 1 and Dublin 7), and DIT's Grangegorman campus with Orchard House highlighted as this is the location for the PV-CS installation.

Figure 1: Dublin and Grangegorman Campus Map

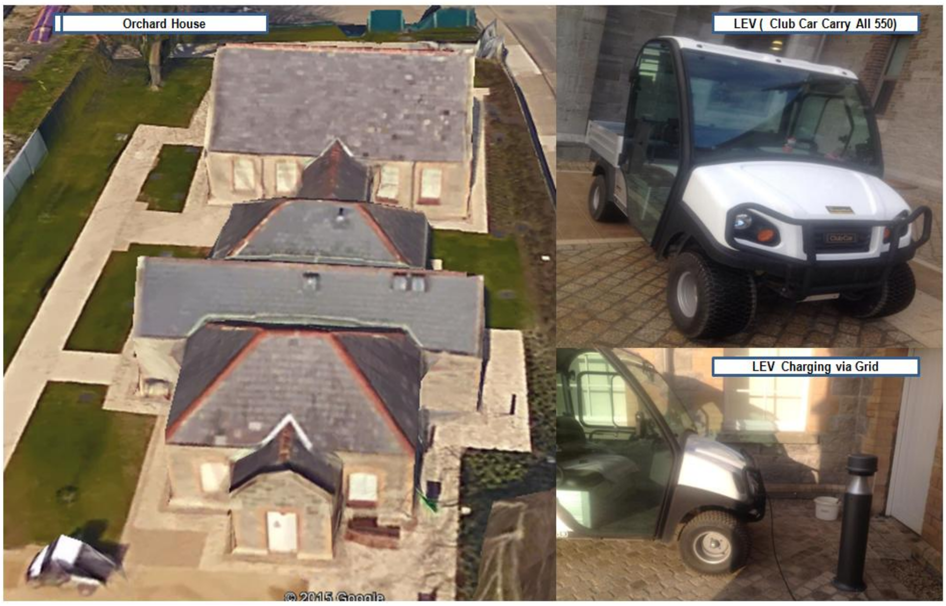

Figure 2: Orchard House- Utility Campus LEVs

Moreover, Figure 2 displays a close up image of Orchard house and the LEVs. Orchard house is the current location where the LEVs, (2 x CarryAll 500), are parked and have the batteries recharged, i.e., one vehicle at a time, exploiting the standard three pin electricity wall sockets at 230 Volts/13 Amps. As the result, Orchard house is the chosen location where the charging point will be deployed. This particular building has a total roof area of ~ 3700 m^2, and the dedicated south facing area of this roof takes ~ 69 m^2 of the total space. When considering a regular 250 Monocrystalline PV panel of 1.63 m^2, the purposed area can accommodate a 10.5 kW system, (42 panels).

In order to determine the prospective PV_CS's array size yield performance, it is important to observe the charging patterns of the cars, and further estimate the LEV's load demand consumption. This is to verify whether the generation can consistently satisfy the load demand and/or produce supplementary reserve. As the result, the user's vehicle usage/ charging habits were initially observed via a number of questionnaires. The surveys covered questions such as: average speed, start-stop waypoints, number of the passengers and excess load. The results clearly indicated that the LEVs were routinely plugged into the grid in the late evening and only one vehicle at each time. Depending on the state of the charge of the load batteries, the typical charge up times was reported between 4-8 hours. In order to perform an accurate demand profile survey of the campus LEVs, a dedicated "Hawk5000" energy analyser was utilised. The Hawk meter with its capability to monitor the electricity supply and consumption by means of Current Transformers (CTs), was wired up to the charging spot plug top. The energy meter captured measurement variables such as: current, voltage, real power, power factor, and energy at a specified sampling interval. The desired sampling rate in this case was selected as 1 minute. Every time a load was plugged in to the charging spot, the variations of measurement signals were sensed by CTs and stored in the data logger. Figure 3 presents the preliminary daily energy requirements of the LEVs. The data is populated for over a period of 2 months, (May-June, June-July). Table 1 displays the details of energy consumption for the distinct day of the week. The energy was measured in kilowatt -hour per day (kWh/day).

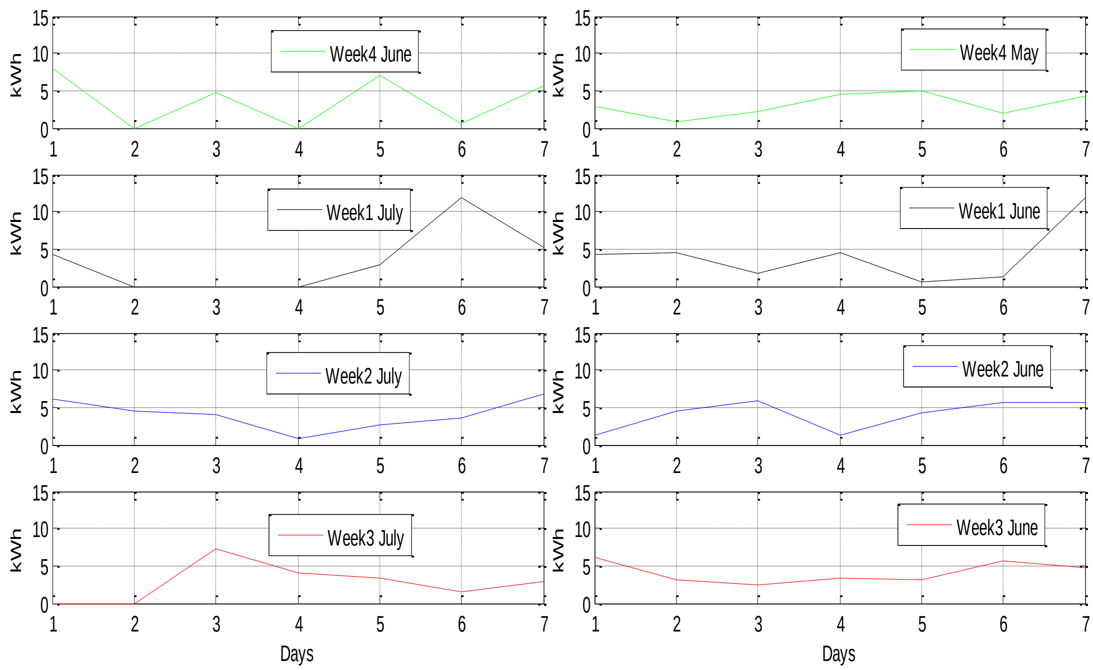

Figure 3: Sample Load profile (May-June, June-July)

As it is evident from Figure 3 and Table 1, a vehicle depleted a significant amount of charge on 6th of June; 11.85 kWh/day, and 12th of July; 11.95 kWh/day. Thus, the *average* and *peak* load consumptions were chosen as; 6 kWh/day and 12 kWh/day.

Table 1: Sample Daily Load profile (May-June, June-July)

Days	1	2	3	4	5	6	7
Week4May	2.9 kWh	0.85 kWh	2.25 kWh	4.44 kWh	4.9 kWh	1.93 kWh	4.28 kWh
Week1 June	4.34 kWh	4.43 kWh	1.62 kWh	4.45 kWh	0.53 kWh	1.15 kWh	11.85 kWh
Week2 June	1.38 kWh	4.59 kWh	5.86 kWh	1.17 kWh	4.33 kWh	5.66 kWh	5.65 kWh
Week3 June	6.08 kWh	3.01 kWh	2.41 kWh	3.24 kWh	3.16 kWh	5.74 kWh	4.72 kWh
Week4 June	8.04 kWh	0 kWh	4.84 kWh	0 kWh	6.99 kWh	0.47 kWh	4.72 kWh
Week1 July	4.2 kWh	0 kWh	0 kWh	0 kWh	2.98 kWh	11.95 kWh	5.283 kWh
Week2 July	6.16 kWh	4.42 kWh	4.06 kWh	0.88 kWh	2.66 kWh	3.67 kWh	6.71 kWh
Week3 July	0 kWh	0 kWh	7.18 kWh	4.06 kWh	3.46 kWh	1.39 kWh	2.80 kWh

Furthermore, for projection of energy consumption of the typical campus routes, a Global Positioning System (GPS) device, (Garmin GPS60), was stationed in one of the vehicles, on 5th of June. The GPS sensor recorded variables such as: time, date, elevation, and displacement, speed, at sampling time of 30 seconds. This was to capture the movement of the LEV, and identify the most common travelled routes.

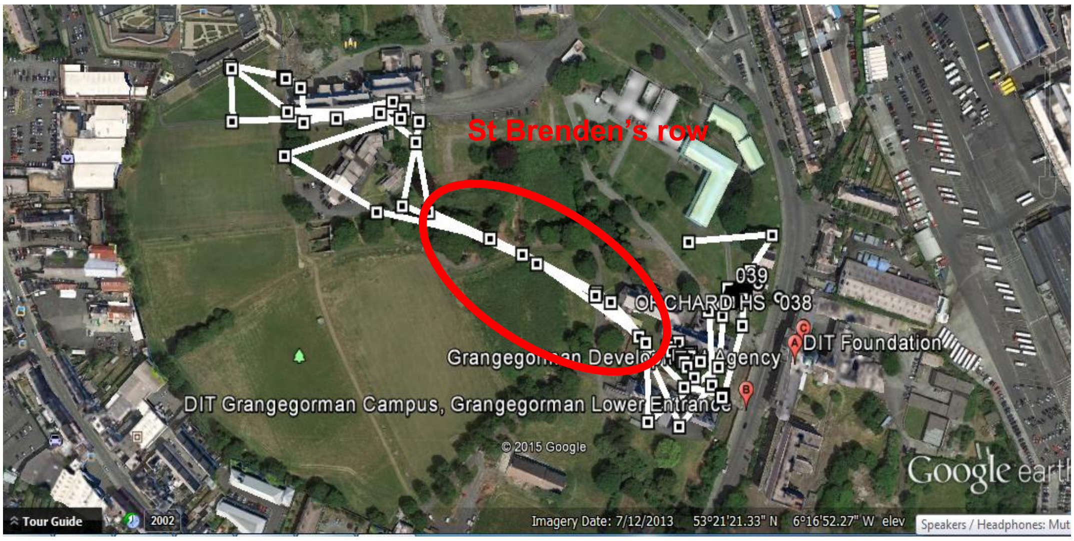

Figure 4: Daily Load profile (Sample Data)

Figure 4, outlines the trips that took place, i.e., from 8PM until midnight, by the sample vehicle, while the secondary vehicle was plugged to the grid for charge restoration.

As shown in Figure 4, St Brenden's row is the most travelled route throughout the campus, as it is used for interconnection between one side of DIT to the other side. This passage has the longest travelling length, since all the vehicles must drive back to Orchard house waypoint. According to [11], the required LEVs power requirement for travelling around any of the routes, i.e., from one waypoint to another, depends on speed variations, tire frictions, aerodynamics dissipations and mass elevations. Thus, to justify the energy requirement of the tracked routes and optimization of the routing network energy consumption, an ongoing load profile data acquisitions and GPS tracking are currently taking place.

Design Options

PV-CS where the PV array is used to convert solar power into electricity can include various components such as: PV and system components, i.e., cabling, protection and mounting elements, charge controller, battery storage unit and the load [16]. Integration of each of these components leads to a distinct system design arrangement. Figure 5 encapsulates 5 possible configurations; option1: decoupled grid (AC); option2: decoupled direct PV (DC); option3: decoupled PV with storage (DC); option4: coupled PV-grid without storage and option5: coupled PV-grid with storage.

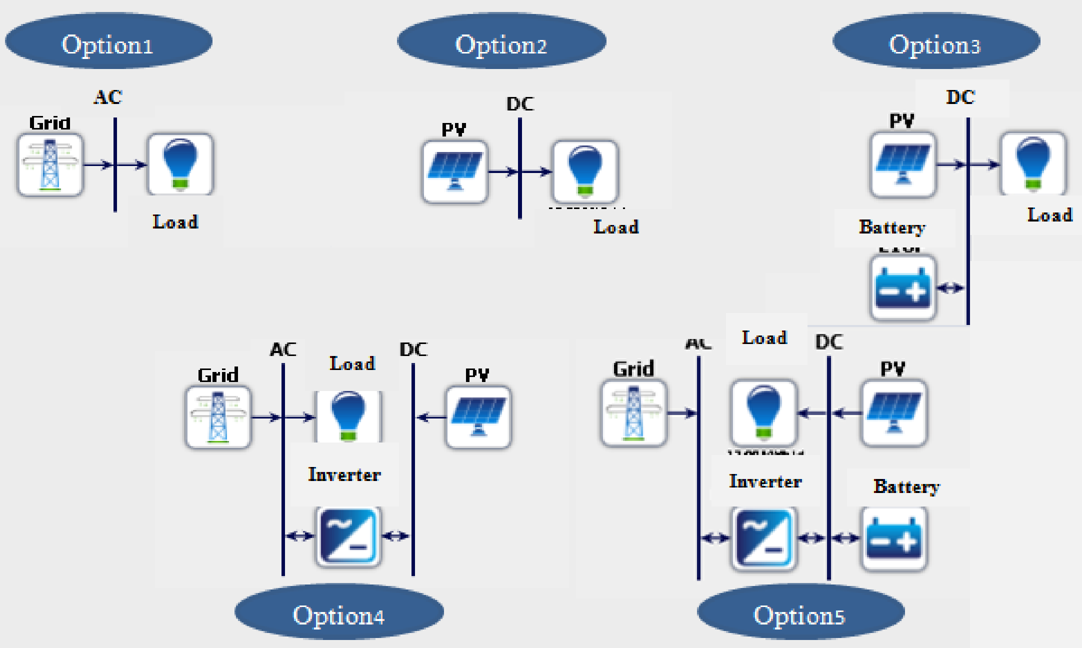

Figure 5: Design Options and System Components

Additionally, these options are tabulated in Table 2. Hence, the presence of the relevant system components in each system configuration is indicated by a curser.

Table 2: Design Options System Components

Design Options	Grid	PV	Inverter	Battery	Load
Option1: Decoupled Grid(AC)	✓	x	x	x	✓
Option2: Decoupled Direct PV(DC)	x	✓	x	x	✓
Option3: Decoupled PV with storage(DC)	x	✓	x	✓	✓
Option4: Coupled PV-Grid without storage(DC-AC)	✓	✓	✓	x	✓
Option5: Coupled PV-Grid with storage (DC-AC)	✓	✓	✓	✓	✓

Option 1 is the existing scheme for charging the cars, where LEVs are directly fed via the grid. The components present in this configuration are, the conventional AC gird and the load. Although the current low-cost of electricity tariffs and the modest size of the load make this option affordable, the price of conventional based fuels will increase over time. Further to this, there will be no potential for lowering of campus GHG emissions from this option.

Option 2 refers to a design configuration where the LEV will be directly charged via synchronous power generation from a PV installation. In this case the solar panels will be used as the primary and the only source of power. The PV panels will need to be arranged on top of the vehicle, where DC electricity directly fed to the Trojan batteries and/or DC brushed motor. However, with reference to winter demand of 12 kwh/day and the absence of back up generation, the required size of the PV array would need to be quite substantial (6 kW which will take up ~ 40 m^2). As the result, this is not a viable option.

Option 3 which is also a standalone PV design will incorporate the estimated battery storage units. In this case, the PV panels are fitted on the roof of Orchard house. The electricity generated from the panels will subsequently be stored in the battery banks, and depending on the chosen size of the storage, used to serve the vehicles demand. However, due to intermitted level of Irish sunshine and the lack of any secondary generation, this option is not recognized to be applicable.

Option 4 will follow the coupled integration system design of PV, i.e., primary source of generation, and grid, as back-up source of electricity. In this case, the Orchard house PV arrays will be utilised to charge the cars directly. Hence, the dual control configuration will also allow by-passing the inverter and directly operating on DC voltage. In order to use the PV electricity the cars must be parked and plugged to the charging station during the daytime. In the case of low solar radiation and/or higher demands, the load could be supplied by the grid. However, as the LEVs are normally used during the day and charged at night time, this option is also not identified to be optimal.

Option 5 will build on option 4, by adding the storage unit. In this case, the PV will be used during the 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 this suggested design will not pose any limitations on user's driving needs. Once again, the grid option will be included as the backup generation. Due to all these reasons, this design configuration is chosen to be the most viable option for Grangegorman.

Preliminary Battery Sizing

As it is stated above, Grangegorman's designated PV-CS design, i.e., "coupled PV-grid with storage", will integrate battery storage unit. In this case, the solar energy can be stored in number of battery banks, and utilised at the desired time. In other words, the energy dispatch can be performed with some appropriate time delay. As it was mentioned previously, the total array size and the required area were estimated at 10.5 kW and 69 $m^{2.}$

In exchange, for estimation of conceptual storage unit capacity numerous factors were considered. Although the characteristics of batteries differ depending on their manufacturer and specifications, in general Equation (1) was harnessed for calculating the battery's capacity [17]. As suggested by the equation, the fundamental factors for estimation of the battery capacity (Ah) are: autonomy storage days, daily load demand (kWh), battery efficiency (%), Depth of Discharge (DoD) and system voltage (V).

[17].*Eqn.1*

$$Battery\ Capacity = \frac{Daily\ Load\ Demand\ (kWh)}{Efficiency\ (\%) \ x\ Depth\ of\ Discharge\ (DoD)\ x\ \ voltage\ (V)}\ x\ Days\ of\ Autonomy$$

The days of autonomy accounts for the number of the days that the storage batteries need to accommodate the load, due to absence or intermittence level of sunshine. Thus, the storage days would highly depend on the solar resource potential and Peak Sun Hour (PSH) [18]. PSH is defined as " the equivalent number of hours per day, with solar irradiance equalling 1000 [Watt /m^2] " [19]. In other words, as illustrated in Figure 6(a) [19], the level of irradiance will be at its maximum point during the noon period, hence, at the midpoint of the graph between sunrise and sunset. According to Ayompe, et al, this value was taken as 2.83 hours for a typical day in Dublin [20].

Moreover, solar irradiance and load demand variations both have an influence on the storage unit capacity [16]. Hence, the amount of solar irradiance on a given area is often indicated as an average daily value during a particular month [19], however, the level of irradiance and PV array output performance can vary immensely with respect to summer/winter solar potentials.

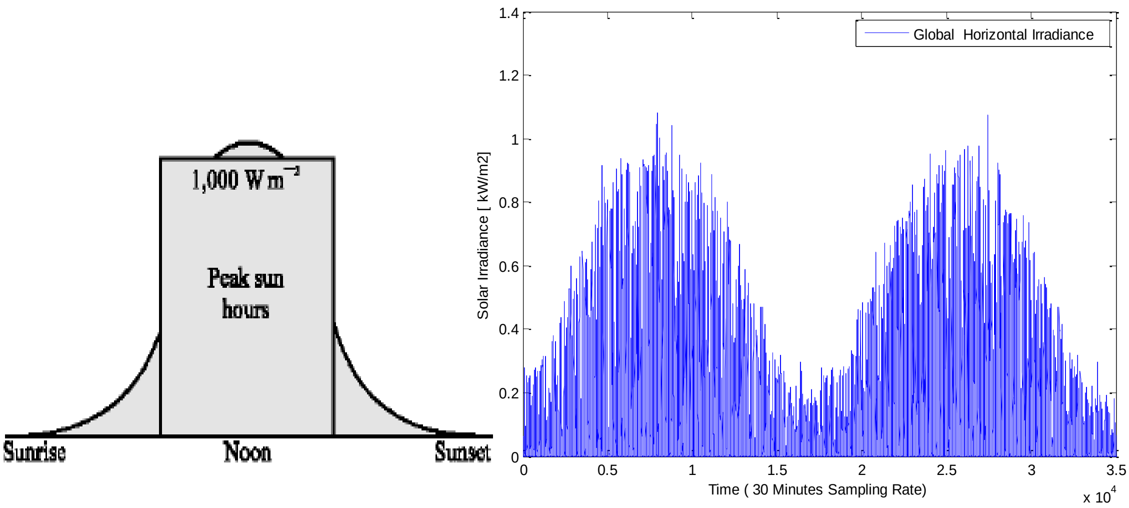

Figure 6: Solar Data, 6(a); Peak Sun Hours, 6(b); Dublin 2 years Sample Global Solar Profile

Figure 6(b), implies a sample solar radiation profile of Dublin city centre, which was gathered by Dublin Energy Lab (DIT) researchers over a course of 2 years, at the sampling frequency of 30 minutes [21]. Thus, to account for seasonal modifications of PV generation, i.e., 100% and 30% summer and winter PV array output performance and campus load demands, the *average* and *peak* loads were subsequently assigned to summer and winter consumptions.
In addition, the specific batteries type and characteristics, i.e., voltage level, efficiency and (DoD), were considered [22]. Although Lithium-ion rechargeable batteries' higher level of energy, power density, efficiency and life span make them particularly an attractive option for energy storage in applications, i.e., in this case LEVs as well as PV-CS storage unit, yet the price of the lithium-ion are much higher than their correspondent lead acid batteries [23]. Hence, according to the local tenders, the price can diverge approximately to 5 times more than the lead acid batteries, i.e., the cost of the chosen lead acid batteries is currently 350 euros for each battery unit. As the result, the conceptual storage batteries were chosen to be the common commercialised lead acid batteries. Due to the capacity and voltage level of LEVs Trojan lead acid batteries, i.e., 8 batteries each at 6 volts -260 Ah, the storage batteries were settled to higher capacity values at 390-400 Ah with 40% DoD and 85% efficiency, (as recommended by the battery suppliers [9][24]). The voltage level of the storage batteries was also chosen to be equivalent to the system voltage level at 48 volts DC.

Based on the methodology in [18], while accounting for 95% system availability and 2.83 hr of PSH, the recommended storage days for DIT's PV-CS was estimated as 4.93 days. Using the stated equation above, this approach resulted in 86 kWh and 174 kWh storage capacities subsequently. These meant 32, i.e., 4 strings of 8 batteries, and 72; 9 strings of 8 batteries, units of lead acid batteries for summer and winter load demands. However, when other aspects such as weight, housing and maintenance of the batteries are considered, these estimated values become quite ambiguous which will require further validations.

Moreover, the current average cost per kW for each system component, were projected in Table 3. These values are based on Sustainable Energy Authority of Ireland (SEAI) available data [25], and quotes from relevant bodies/industry.

Table 3: Cost for PV-CS individual components (including installation and maintenance)

Component	Average Cost per kW
Solar Photovoltaic Panels	€852
Inverter	€619
Instrumentation and Control	€177
Installation- Electrical	€543
Installation - Civil	€904
Installation - Mechanical	€191
Maintenance	€109
Other	€88

Finally, all these information require further additional validations on both technical, i.e., optimal dual PV grid controller, battery sizing, as well as economic aspects of the design. It will also be vital to perform additional justifications on required storage days, and put advance investigations in alternative battery categories.

Discussion

As it was emphasised earlier, the primary purpose of this research will be to maximize the solar electricity production for Grangeogorman, which will result in reducing GHG emissions and fulfilling Ireland's sustainability targets on national and European levels. The size of the campus is growing, and this will have an impact on the number of the cars and LEVs load demand. As the result, it will be necessary to have a more reliable and energy efficient storage mechanism. Although the cost parameter of the lead acid batteries makes them more affordable, these batteries are very bulky in weight and have lower efficiencies. On the other hand, lithium-ion batteries have many advantages such as higher energy density, low maintenance and longer life cycle when compared to lead acid batteries [26]. Yet the higher cost factor makes them less practicable. TeslaMotors has recently introduced the new storage lithium-ion battery product to the market at a more cost effective scale. Hence, "Powerwall" [27], the light weight rechargeable batteries which offer reliable operation and security of performance". Therefore, it is very beneficial to put supplementary investigations in the field of alternative batteries.

Conclusion

Introduction of a PV-CS in Grangegorman that generates clean electricity from the sun and charges the campus LEVs, can substitute a portion of the charge supplied from the conventional utility grid. In this paper design options for PV-CS were discussed and design configurations reviewed. The option design of "coupled PV-Grid with storage unit" was identified as the most viable solution. However, additional investigations for accurate battery sizing are required.

Acknowledgment

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