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Techno-economic Evaluation and Environmental Benefit of PV-based Electric Vehicle Charging Station on University Campus

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Abstract— Smart utilities comprise an important aspect of modern smart cities. The aim of this work is to present a case study for implementing a solar- energy based electric vehicle charging station (for the first time on a campus in Egypt) at the British University in Egypt. The total amount of energy needed for charging each electric vehicle (EV) was estimated to be 13.3—16.2 kWh. The EV is operated by 12 batteries. The station was designed to provide energy sufficient for charging up to two vehicles daily during summer. Thus, the station sizing was based on provision of 16.2 KW and the system components were designed and selected accordingly. Measurements were made to evaluate the system output, efficiencies and solar radiation in both summer and winter. The results indicate that these parameters vary with day time. The economic study showed that the payback period is 10 years and 6 months. The environmental study showed that such system will save around 7,968.96 kg/kWh/year of CO_2 emissions yearly.

Keywords—solar energy-based charging station, electric vehicle charging station, techno-economic.

I. INTRODUCTION

The transportation sector is still largely powered by fossil fuels and heavily contributes to large amounts of greenhouse gases (GHG). It has been stated that the transportation sector represents 28% of the total energy consumption and it is responsible for 23% of the harmful carbon emissions worldwide [1]. Therefore, electric vehicles (EVs) that do not consume fossil fuels are one of the most effective ways to solve these problems. However, the spread of these types of cars is challenged by consumer' awareness, acceptance, and trust. Limited range, high purchase price, safety of power batteries, and insufficient or lack of charging facilities are all reasons for mistrust [1-4].

The integration of smart-streetscape elements (SSSE) based- on renewable energy sources (RE) into modern smart cities (thriving for sustainability) is a hot topic for researchers and business developers. energy streetscape elements (ESSE) are created from integrating renewable energy (RE) devices with streetscape elements [5]. Creating sustainable neighborhoods using ESSE will help in reducing energy taken from government and will affect neighborhood economic state, as well as helping in reducing the growth of global problems such as carbon emissions, ozone depletion, and climate change. The spread of EVs and availability of charging stations are useful and good practices for smart cities and compounds.

A recent study [6] has analysed the technoeconomic aspects of building electric vehicles charging stations, elaborating on work showing economic feasibility of integrating EVs and renewable energy charging on a college campus of Rio de Janeiro, Brazil to significantly reduce the emissions of typical pollutants in the transportation sector. The same trends were also reported byGrande et al. [7] for an independent PV-battery hybrid system for charging EVs in Madrid, Spain and by Vermaak and Kusakana [8] for EV charging station based on renewable energy in the rural areas of the Democratic Republic of Congo. All the results showed that the off-grid PV-battery system is feasible and reliable both technically and economically. In addition, such EV charging systems could significantly reduce air pollution compared to grid-connected charging. Two different operation strategies for charging stations were simulated and the results were analyzed to select the optimal system configuration. The simulation results showed that the best operation scheme was to use the charging station continuously to charge multiple vehicles all day or 24 h [4]. It was interesting to read the authors [4] concluding that using HOMER Pro software shows that the hybrid PV/WT/battery EV charging station is the best technoeconomic solution for renewable energy EV charging stations in some areas but not for others. Moreover, previous work [6] has confirmed the feasibility of renewable charging stations at a university campus.

In this context, the faculty of engineering at the British University in Egypt has taken action toward this issue by establishing a photovoltaic solar station for charging electric cars. This project targets the reduction of greenhouse gas (GHG) emissions by the transportation sector. The project supports BUE electric vehicles through securing a clean energy supply source, which does not depend on the electricity provided by the grid which depends on fossil fuel but uses green solar energy instead. The photovoltaic solar station to charge electric vehicles and cars has been installed on the roof of Building B (part of the premises of the Faculty of

Engineering). This photovoltaic solar station consists of 14 solar panels (12 for the charging station and an additional two for educational and research purposes), an inverter and four batteries.

II. BUILDING AND OPERATING THE CHARGING STATION

A. *Sizing, Design & Building Stage*

A self-generated/ PV based off-grid charging station (CS) supported by (batteries) energy storage system (ESS), to support variable irradiance conditions, was proposed for building the BUE CS. The station sizing was based on charging one EV daily in winter and up to three in summer. The EV is operated by 12 batteries. The sizing results showed the designation of the CS to be as follows (12 540-Wp solar panels supported with four 12V, 150Ah Lead-acid Gel Batteries and Opti Hybrid off-grid inverter 6kVA internal charger = 48V, 50A, PWM). However, due to unavailability in the market a 3kVA inverter was recommended to be used. The battery specifications are as follows 6 V - 225 Ah & 6 V - 185 Ah. The total amount of energy needed for charging each vehicle was estimated to be 13.3—16.2 kWh.

The total energy needed for charging a vehicle is 16200 W, accordingly the sizing of the charging system was based on the capability of the station to charge two electric vehicles per day on average (three vehicles during summer and one during winter) which is translated to a total energy of (16200W X 2 = 32.4kWh). The number of solar panels needed to fulfill such a need are based on average sunshine time per day 6.5 hours ($\frac{32.4\ kW}{6.5} = 4984.62$ Watt). The available PV panels in the market (545 Watt rated power) were used and the number of solar panels needed was calculated with a factor of 1.3 to account for the system losses ($\frac{4984.62\ \text{X}\ 1.3}{545} =$ 12 panels. The inverter sizing should be 1.2 larger than the hourly load to avoid load losses in the inverter (4984.62 X 1.20 = 5981.544 W) and as explained above, an 3kVA inverter was used. The batteries were sized by considering a total Energy demand (32.4 kW), Battery losses (15%) , Depth of Discharge (40%) , Nominal battery voltage (12 V) and days of autonomy zero according to the weather nature in Egypt. The battery size $= \frac{32.4}{0.85\ X\ 0.6\ X\ 12} = 5.295\ Ah$. The available batteries specification in the market were 12V, 150Ah Lead-acid Gel Batteries so according to the calculation 3 batteries are needed however four were purchased to compensate for the inverter.

A study on a similar system has shown [9] that PV generation is sufficient to charge the EV battery till 1.5 C-rate. The increase in EV battery C-rate indicates that PV generated is not sufficient to charge the EV battery, which leads to decrease in DClink voltage. Therefore, the DC-link voltage is maintained constant during power fluctuations. The researchers [9] have designed a smart control system in MATLAB/Simulink. The performance of the proposed system was analysed by considering three modes which were categorized as EV battery charging (i) with off- grid charging system (OGCS) in absence of ESS, (ii) with OGCS in the presence of ESS and (iii) with ESS in the absence PV generation. Every mode was analysed for 12 s. on the basis of charging rate (C-rate) replicating the power demand at different time intervals of the EV battery. Initially, the EV battery is charged at 0.5 C-rate for 3 s. and a step of 0.5 C-rate is added at every 3 s. up to 12 s. Whenever the power demand increases or decreases in terms of C-rate, the connected ESS and PV generation participate accordingly in the aforementioned modes. It has been shown [9] that PV sources coordinated with ESS are efficiently used during variable irradiance conditions, including surplus power condition or unavailability of EVs. Using ESS utilizes the maximum renewable energy (RES) and thus the system results in an efficient and eco-friendly off-grid CS.

Accordingly, the station was built on top of the roof. The installed accessories included DC cables, MC4 connector, steel structure, clamps, and bolts. Fig. 1 shows the station and the charging process. Fig. 2 shows the layout of PV system connection for charging the EV.

B. *Monitoring Stage*

The station was installed on 09/08/2022 on the roof of Building-B (part of the premises of the Faculty of Engineering) as shown in Fig. 2. Building-B was chosen to install the solar station on its roof top according to its orientation. Building-B is located on the south direction and there is no building surrounding building B from the south direction, meaning that there is no shading on the building roof top all year. The batteries and invertor were installed in service room on the roof top of building B, for protection from the heat and solar radiations which decrease the lifetime of the batteries. The construction process of the station took place in 4 days, two days for site delivery, were the contractor deliver the panels and metal structure. while the other two days for installations and testing process. The station consists of 14 solar panels as shown in Fig. 2. The CS measurements were recorded following the installation. The readings were taken from the invertor meter. Table 1 shows a sample of the readings taken during charging and not charging. Readings are available for 11 months up-to date.

TABLE 1

Readings	Charging	Off- charging
Input, PV, V	131	112
Output, PV, V	54.8	56.3
Invertor, V	229	229
Invertor, A	10.5	0
Grid, V	0	0
Grid, A	0	0
Load, KW	1.69	0
Load, KVA	2.41	0
Batt, V	0	55.9
Batt, A	0	71

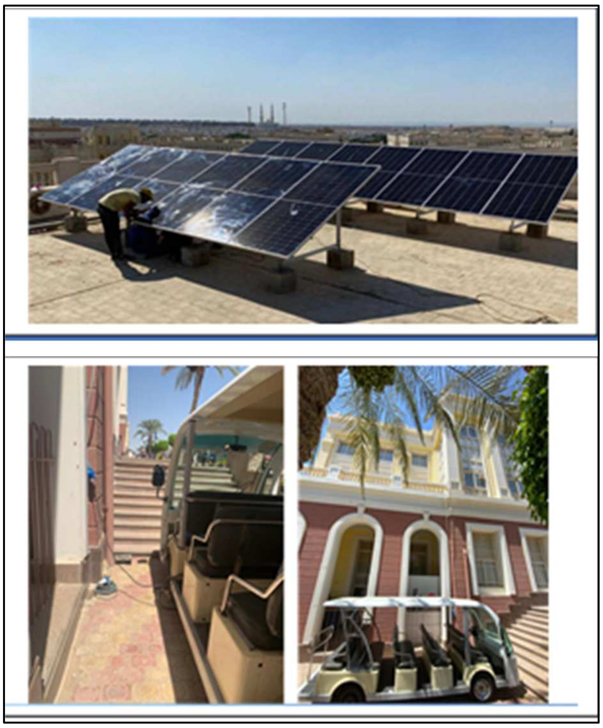

Fig. 1 The system installed on roof and vehicle charging.

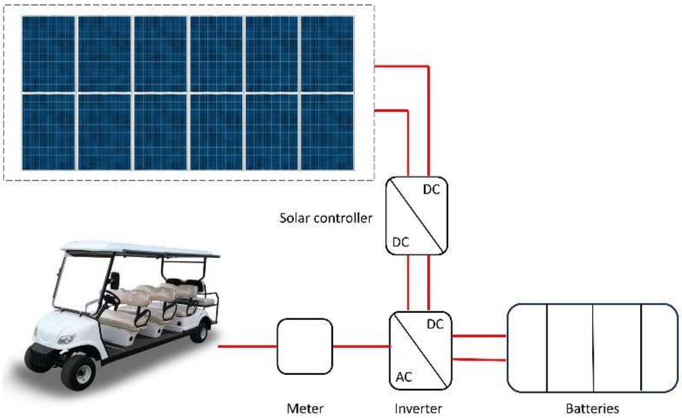

Fig. 2 Layout of PV system connection for charging EV

III. Economic & Environomental Feasability

A. Economic Feasability

The electric car station was funded by *Science, Technology & Innovation Funding Authority (STDF), project number 33460,* so the total price paid is considered an Equity and was about 210,000 EGP that breakdown to (43.5%) for the PV Solar panels, (7.4%) for the batteries and (9.5%) for the inverter. The remaining costs (39.8%) covered the cables & accessories, PV stands, Design of the system and instillations costs. These components were acquired from a local distributor available in the local market in Egypt. Such a system has the capability to produce (1440) KWh yearly which is used to charge (3) EV per day that are used for in Campus transportation. The annual degradation factor for such system is (0.5%) annually [10] .The interest rate was taken in 2022 when this project started to be around 12%, however in 2023 it became 18.75% [11] and it is expected to return to its normal rates by 2025 so to avoid complicated calculation 15% rate was chosen as an average, The life expectance for the PV panels module is 25 years which is the same time frame for the project life time. The Business electricity price rate offered by the government is 1.15 EGP/KWh such rate is subjected to inflation rate of 15% based on previous data and future prediction due to the instability in the exchange rate of the currency. The operation and maintenance cost of such system is expected to be 2% of the intaial equaty of the system . Net present value (NPV) was calculated according to the mentioned data that resulted in 9,170 EGP which represents the amount of cash saved from implementing such a system. Also this is small amount however the environmental outcome from the renawble energy is benificial on the long term. It is also worth mentioning that the payback period occurs at 10 years and 6 months as shown in Fig.3 , the discounted payback period ocuurs at 20 years and 6 months and the internal Rate of Return (IRR) is 14.64% .

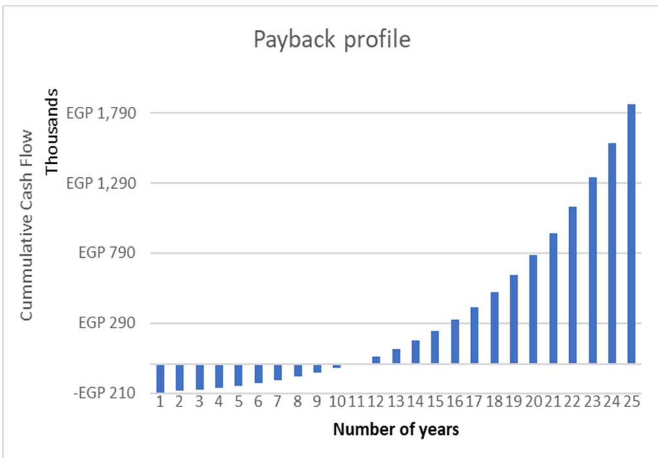

Fig. 3 Payback Profile

B. Environomental Feasability

Electric vehicles Contribute to reduceing greenhouse gas emissions from the transportation sector but the actual reduction in emissions depends mainly on the source from which the electricity is produced. The level of emmision depends on the type of carbon intensity in the fuel used to operate the power station. Considering the natural gas which is the most common type of fuel for the power station in Egypt. According to Energy Information Administration (EIA) generating electricity from power stations that operate using natural gas produces 1.22 pounds of CO_2 for every 1 kWh [12] as shown in Table. 2.

Fuel	Pounds of CO2 per million Btu	Heat rate (Btu per kWh)	Pounds of CO2 per kWh
Coal			
Bituminous	205.691	10,080	2.07
Subbituminous	214.289	10,080	2.16
Lignite	215.392	10,080	2.17
Natural gas	116.999	10,408	1.22
Distillate oil (No. 2)	161.290	10,156	1.64
Residual oil (No. 6)	173.702	10,156	1.76

Table. 2 The amount of carbon emission produced from Natural Gas Source [12]

∵1 b (pound) = 0.4536 Kg

∵The carbon emission produced from Natural gas= 1.22 b/kWh

∴ CO_2 =1.22×0.4536 = 0.5534 kg/kWh

∵ The energy produced from the solar station and used to charge the electric vehicles is 48 kWh/day

∴ The carbon emissions produced in case the same amount of electricity were to be produced from normal natural gas power plant are 48 x0.5534 = 26.5632 kg/kWh/day and the CO_2 emissions/year = 26.5632 x 12 x 25 = 7,968.96 kg/kWh/year.

IV. DISCUSSION

Electric vehicles are becoming increasingly popular and the global demand of shifting from conventional vehicles to electric vehicles is getting more and more vigorous. EVs provide a solution to the environmental crisis as they offer a transportation method with zero tailpipe emissions and a reduction in the use of fossil fuels. Despite that, EVs still need electricity to charge their batteries and the electricity normally come from fossil fuels which still has a negative impact on the environment. According to the US Department of Energy, the carbon emitted to charge 1 EV is around 200 grams of CO_2 per mile driven. This research evaluated the technical and economic implementation of EV charging stations that has zero carbon footprint which offers a hand to mitigate climate change.

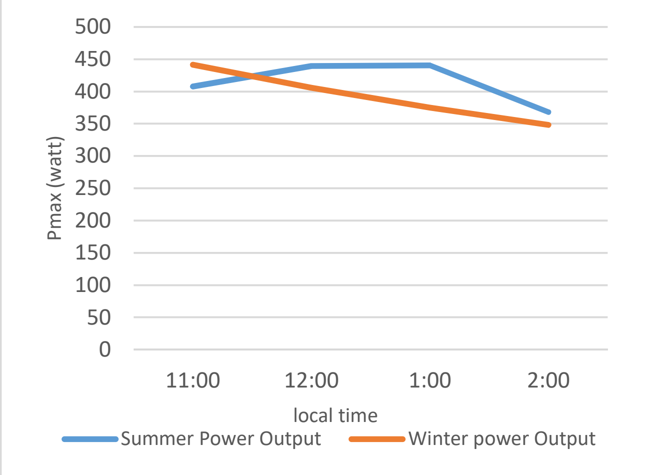

Fig.4 A comparison between the PV panel power output in a typical day in summer and winter

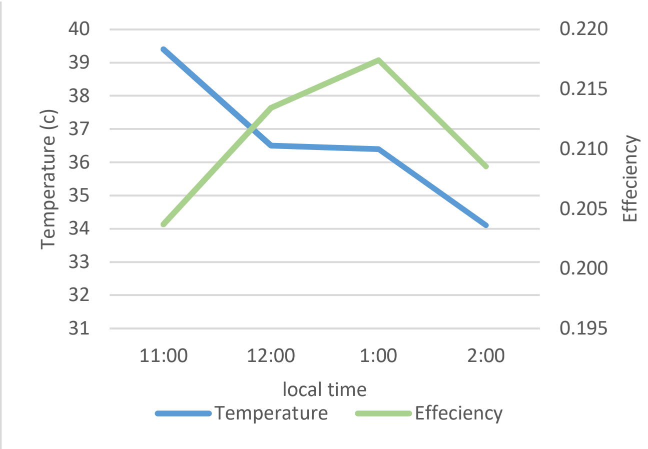

Fig. 5 Efficiency of PV panels VS their temperature (in Summer)

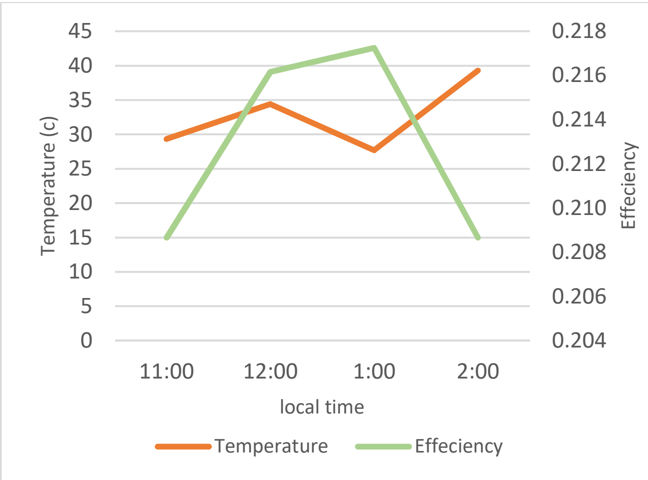

Fig. 6 Efficiency of PV panels VS their temperature (in Winter)

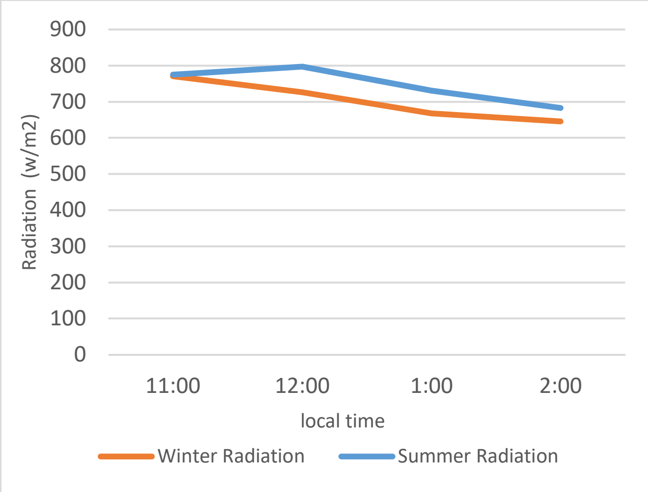

Fig. 7 Solar Radiation During Summer and Winter

The PV powered EV charging station investigated in this research proved to be technically and economically viable. As it can provide the required power to charge BUE campus EV during summer and winter time with payback time of around 10 years and 6 months.

The Solar panel Performance was analyzed using Photovoltaic panel analyzer model I-V400W made by HT company. The Data gathering was done during different Summer and winter months at consecutive 4 hours from 11 am to 2 Pm. The data averages were then used to plot Figs. 4, 5, 6 and 7.

Fig 5 shows the capability of the station to provide power above 350 W in Winter and around 450 W during summer season. It can be seen from Figs 4,5,7 that when the Solar Radiation Increases and the PV Panel Surface Temperature decreases the power output, and the efficiency tend to increase. Similar Trends were noticed from Figs. 4, 6, 7 For the winter Season, these observed trends are Similar to that mentioned in the literature [12].

Further enhancements can be made to the station to increase the power delivered to the EVs and thus reduce the charging time. These enhancements can include the cooling of the PV panels during summer season, installing larger capacity inverters and increasing the capacity of the station.

V. Conclusion

The dependency on electric vehicles is becoming one of the important solutions proposed towards saving the environment and reduce air pollution. Using a renewable energy as the solely energy source to drive the whole charging station was the main challenge that faced the BUE team who worked on developing such a system which is considered one of its kind in the region to exist in a university campus. The project concluded the following:

- The station is designed to charge one to three EVs daily.
- The EV is operated by 12 batteries. of 6 V - 225 Ah & 6 V - 185 Ah
- The total amount of energy needed to charge each EV was estimated to be 13.3—16.2 kWh.
- The number of photovoltaic panels needed to deliver the required amount of charging energy was estimated to be 12 PVs of 540-Wp supported with four 12V, 150Ah Lead-acid Gel Batteries and Opti Hybrid off-grid inverter 3kVA.
- During the installation process, 12 panels were connected in series. This formation can provide the maximum charging capacity of 3 EVs daily.
- It was shown that the station can provide power above 350 W in Winter and around 450 W in Summer.
- An economic study showed that the payback period is 10 years and 6 months. And an environmental study showed that such system can save around 7,968.96 kg/kWh/year of CO_2 emissions annually.

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