IARJSET

ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⋇ Impact Factor 7.105 ⋇ Vol. 9, Issue 5, May 2022

DOI: 10.17148/IARJSET.2022.9554

DESIGN AND ANALYSIS OF GRID CONNECTED PV SYSTEM FOR UNDERGROUND RAILWAY METRO STATION CONSIDERING COMMERCIAL ASPECTS

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Abstract: This paper investigates the possibility of an Electric Vehicle (EV) charging station at the parking space of a railway metro station in New Delhi, India. As the solar potential in this part of the world is very high, thereby solar system is integrated with the grid to fulfill the energy demand of the EVs parked at the railway metro station parking area as well as the other auxiliary load. Three different case are examined in this paper grid only mode, grid-PV mode, and grid-PV-battery mode. All the three cases are compared with each other in terms of cost of energy (COE), net present cost (NPS), electrical output of different components of system, and pollutants emitted. Hybrid Optimization Model for Electric Renewables (HOMER) software is used for simulation purpose and verification of the results. From the simulation results, Grid-PV system found to be most feasible solution among all and grid only mode is least suitable.

Keywords: Renewable energy resources, net present cost, cost of energy, hybrid energy system, battery energy storage.

1. INTRODUCTION

Future smart grids are anticipated to see two main trends in energy usage:

1. Photovoltaic (PV) systems for large-scale decentralized renewable energy generation.
2. The emergence of battery electric cars (EV) as the method of transportation of the future.

To begin with, the usage of renewable energy sources such as solar energy has been more accessible to a broader audience as the cost of PV panels has decreased [1]. With their enormous surface area on flat rooftops, parking lots at railway metro stations, industrial sites, and office buildings in India have a significant potential for photovoltaic (PV) panels. This potential is now mostly untapped. Second, as compared to fuel cars, EVs offer a clean, energy-efficient, and noise-free mode of transportation. Due to the waste of oil and the environmental effect of its usage, the number of EVs is anticipated to grow rapidly in the next years. As a result, efforts to decrease urban pollution and greenhouse gas emissions tend to be coordinated. One of the most pressing issues in the development of EVs is the scarcity of charging infrastructure.

At present, the transportation sector is going through three revolutions, i.e., autonomous driving, shared mobility, and electrification . So, when planning for the charging infrastructure for the electric vehicles, it is crucial to take into account the synergies and potential interactions among these three emerging revolutions. With the increase in the adoption of electric vehicles, a new emerging significant electrical load is introduced to the power grid, which will require changes in the infrastructure [3]. The transfer of electrical energy is done only via the distribution grid, which limits the energy that is flowing in the transmission lines . The large-scale reconstruction of the distributions grid to meet the EV's charging requirement is difficult.

According to the study, 29% of the greenhouse gasses was released from transportation sector while 28% was released from electric sector in the US. If we take a detail look into the transportation sector, it is seen that big portion of this amount (59%) comes from light-duty vehicles and 70.19% of this is due to the passenger vehicles. From 1990 to 2017, the CO_2 emission caused by passenger vehicles was increased by 20.5% and keep increasing with the growing population. In another study, it is revealed that 30% of the EU' s total CO_2 emission comes from the transportation and 60.7% of this is due to the passenger vehicles. Although the CO_2 emission is likely to reduce due to the increasing utilization of renewable energy sources, CO_2 emission in transportation sector keeps increasing. This shows that conventional vehicles should be replaced with more environment friendly types such as hydrogen and electric cars.

India is blessed with enormous solar energy potential. India's land area receives about 5,000 trillion kWh of energy per year, with most parts receiving 4-7 kWh per sq. m per day . Solar photovoltaic power can be effectively harnessed in India, allowing for massive scalability. Solar also allows for distributed power generation and allows for rapid capacity expansion with short lead times.

The effect of EV station operation on the electrical network has been studied by many writers. They discuss several techniques for levelling the load curve. Xu et al. proposed a coordinated charging approach to enhance the impacts of EV charging on the electricity demand curve as well as EV station profitability. Zhang and Qian proposed a technique for charging electric vehicles at night. Cao et al. suggested an intelligent charging technique for electric vehicles in response to time-of-use pricing that reduces network load during peak times. Fazelpour et al. devised a two-phase method to combine smart parking with a plug-in hybrid electric vehicle. The programme, for starters, optimises the size and placement of renewable energy installations as they go through the system. Then it optimises the EV charging characteristics. This lowers power losses and improves the network's voltage profile.

Some studies address the issue of where these EV stations should be built and even how big they should be, but they make assumptions regarding demand and operation. To place fast-charging stations in a city, Sadeghi-Barzani et al. utilised a mixed integer non-linear optimization method, taking into account construction and electrification costs, EV energy loss, and electric grid loss as goals. They simply specified the number of EVs arriving at the station in the model, but they ignored the arrival time or the station's occupancy. To minimise power losses and voltage variations in the distribution system, Wang et al.] developed a multi-objective planning model for EV charging stations. They looked at a set demand and didn't think about how the billing process worked. To locate the EV station, Sungwoo and Kwasinski utilised a geographical and temporal model of EV charging demand. They utilised a queueing theory and a fluid dynamic traffic model. Xiang et al. created a model to help decide where charging stations should be placed and how big they should be. They took into account interactions with the electrical grid, but not other kinds of energy sources.

Most of the literature available focuses on the mathematical modelling of the EV charging station and its impact on grid. But very less emphasis is given on the economic aspect of this and there is scope for comparative analysis of different configurations power system. Following are the main aims of this paper:

1. Identifying the best charging topology for electric vehicles and underground metro station lighting in terms of power density, efficiency, and control.
2. Developing an electrical charging system for EVs that is reliable and stead
3. Ensuring proper power management between hybrid sources and electric vehicles.
4. Comparing different configurations viz. grid only, grid-PV, and grid-PV-Battery in terms of COE, NPC, and harmful pollutants emitted.

2. EV CHARGING IN PARKING AREA USING PV

The Type 2 Mennekes plug is the most common charging plug type in India for AC charging. At the Level 2 charging power level, it allows both single and three phase AC charging. However, in the future, DC charging using Chademo and the Combined Charging Standard (CCS) will be the most popular charging method for charging EVs from solar panels at work for the following reasons:

1. By their very nature, both EV and PV are DC.
2. EV charging may be done in a dynamic mode, in which the charging power varies over time.
3. Vehicle-to-grid (V2G) protocol is facilitated by DC charging.

3. MODELLING OF DIFFERENT COMPONENTS OF THE PROPOSED SYSTEM

3.1 PV System

A solar cell is a basic technology for converting photon energy into pollution-free power. When multiple solar cells are connected in series and parallel, a PV module is formed. In order to build PV arrays, these modules are connected in series and parallel, resulting in the generation of clean and green electricity. A single solar cell can be thought of as an electrical circuit component. It contained a diode, a photocurrent generator, which represented current generation from light, and two resistors, one in series and the other in parallel, which represented the Joule effect and recombination losses. A single diode solar cell model is then created from this combination.

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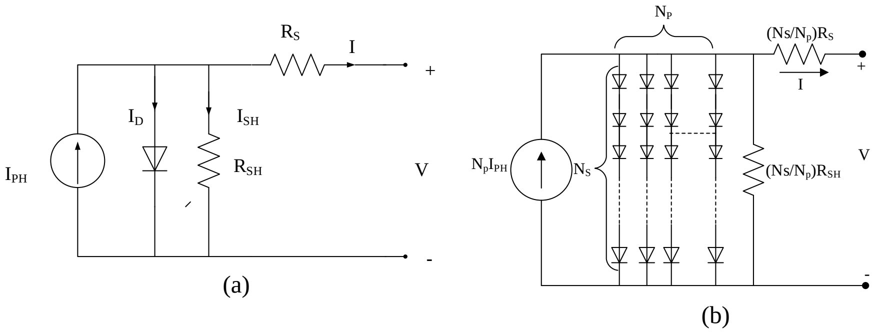

Fig. 1 Schematic representation of (a) PV cell and (b) PV module

The well-known one diode equivalent circuit of a PV cell is shown in Figure 1 (a), where R_{sh} and R_s represent the inherent shunt and series resistances of the cell, which are widely thought to have extremely large and very tiny values, respectively. In the corresponding circuit, the currents I_{PH}, I, I_{SH}, and I_D represent the cell photocurrent, cell output current, current through shunt resistance, and diode current, respectively. A schematic representation of a PV module is shown in Figure 1 (b). Table 1 [resents the different specifications of the PV system.

Table. 1 The PV module's specifications.

Parameters	Value
V_{OC}	47.5 V
I_{SC}	9.64 A
Operating temperature	47ºC
Temperature co-efficient	-0.5%/ºC
Ground reflection	20%
Derating factor	80%
Efficiency	17%
Life time	25 years
Capital cost	50000 ₹/kW
Replacement cost	50000 ₹/kW
O&M cost	100 ₹/kW/year

3.2 Battery Energy Storage System (BESS)

Currently, electro-chemical batteries remain the most common and widely used ESS in HRES due to their wide availability and relative high maturity. Different types of electrical battery systems (e.g. lead-acid, Li-ion, NaS, Ni-Cd, Ni-MH) are available from which plumbing batteries are the obvious choice for the work today due to their low cost, high recyclability and a relatively high level of safety. A series and parallel combinations of batteries of the same rating are used to obtain a larger current and voltage rating. In general, the capacity of BESS in ampere hour (CAh) and watt hour (CWh) is vital to determining the system's reliability. The specification details of the battery energy storage system is shown in Table 2.

Table 2. Specification details of BESS [28–30]

Parameters	Value
Nominal voltage	12 V
Nominal capacity	3.12 kWh
Maximum capacity	260 Ah
DoD	60 %

DOI: 10.17148/IARJSET.2022.9554

Roundtrip efficiency	85 %
Capital cost	₹25000
Replacement cost	₹20000
O&M cost	₹250/year
Life time	10 years
Parameters	Value

4. INPUT DATA AND CONTROL STRATEGY

4.1 Solar Resources at the Selected Location

NASA's Surface Meteorology and Solar Energy database is referred to obtain the solar radiation data at the given location. There is abundance of solar radiation availability at the specified area with monthly average solar radiation amounts to 5.02 kWh/m2/day and average clearness index of 0.58.

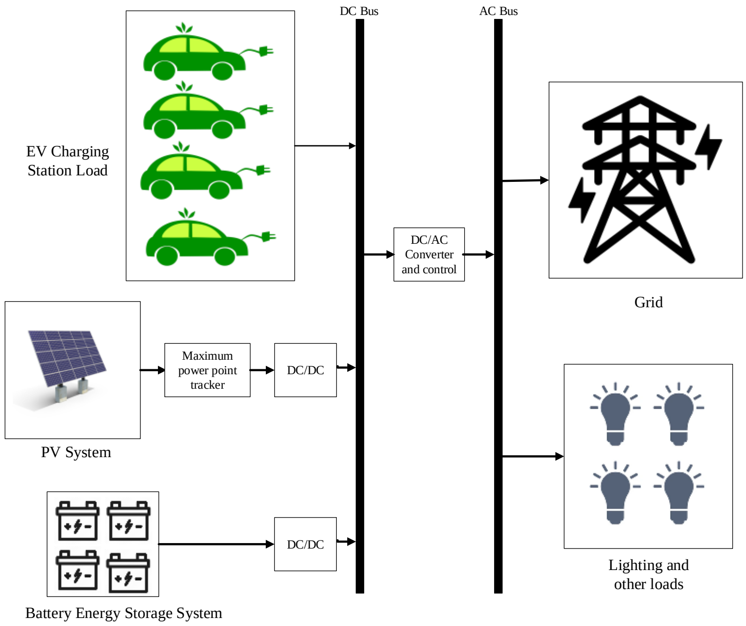

Fig. 2. Proposed system configuration

4.2 Load Profile

Mainly two types of loads are considered in this work:

1. EVs charging station load
2. Lighting and other load of the Metro Station

In the parking are of the Metro station there is space of 20 EVs and these can be charged simultaneously. The average size of the battery of the EV is assumed to be 40 kWh. The charging station is equipped with level-2 chargers of 10 kW capacity that can fully charge the EV battery in four hours. The peak load of the charging station is 200 kW and with 0.6 load factor average energy consumption is 2640 kWh. The lighting load and other load consist of LED flood lights installed in the compound of the metro station and consumption related to UPS, and equipment for maintenance and cleaning work inside the Metro Station premises. This total load accounts to be around 122 kW peak with load factor of 0.3. This accounts 878.5 kWh of average daily energy consumption. The total daily average energy consumption is around 3518 kWh for both EV charging station and other types of electric load of the Metro station and commutative load factor of 0.55. Figure 3 shows the daily load profile and Figure 4 shows the monthly load profile of the system.

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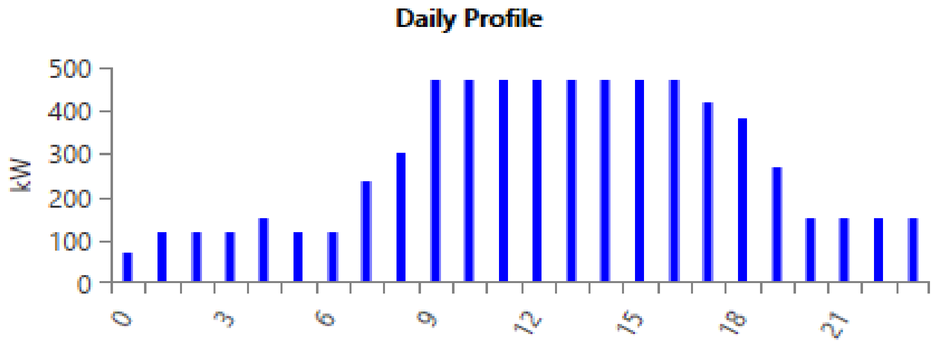

Fig. 3. Daily load profile

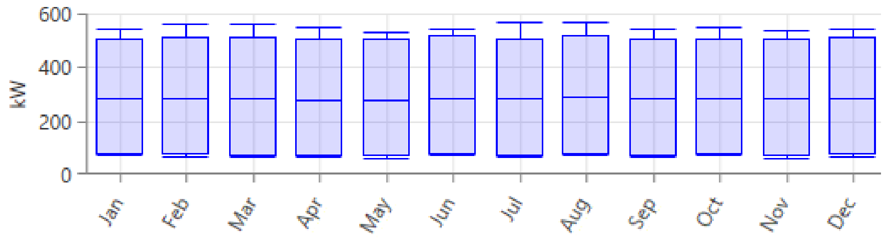

Fig. 4. Monthly load profile

4.3 Grid

The Metro station is well connected to the grid. The electricity is purchased from the DISCOM at the average price of ₹7/kWh and sell back to grid at average price of ₹3.5/kWh. Although, the continuity of supply from the grid is assured, but the grid electricity is mainly from conventional energy resources and for integration of RERs to the system not only the green energy will be available but also the cost of energy will be less as compared to the conventional energy resources based electricity generation system.

4.4 Control strategy

The cycle charging (CC) approach is a dispatch technique in which a generator operates at full output power whenever it needs to supply the primary load. The fixed cost of a generator is equal to the cost of its hourly operation and maintenance, as well as the cost of its hourly replacement and no-load fuel consumption.
The following assumptions are established for the first two elements in order to analyse the charging pattern of electric vehicles.

- It is expected that EVs arrive at PBES in the same pattern as light-duty vehicles purchasing petrol at a gas station.
- As the sample size grows, the charging period of electric vehicles can be viewed as a condition influenced by a number of random variables, thus we assume that that the charging time is distributed according to a Gaussian distribution.
- Even if all of the charging stations were full, the waiting EVs would not pick another.
- The charging technique of the chargers should determine the charging power of each charger.

EV charging techniques currently include AC charging, DC charging, and wireless charging, among others. These charging methods are appropriate for a variety of charging situations. AC charging is typically utilised for automobiles that need to be charged for an extended period of time. DC charging is primarily employed in public charging stations and charging stations in intercity highway service areas in cities. When compared to the previous two charging methods, the cost savings and convenience provided by wireless charging technology are incredible, and its future potential cannot be overlooked.
However, due to the expensive cost of wireless charging for electric vehicles, as well as limits in technology maturity and infrastructure equipment, wireless charging technology is currently not widely deployed. The simulation procedure is then depicted in Figure 5 and explained as follows.

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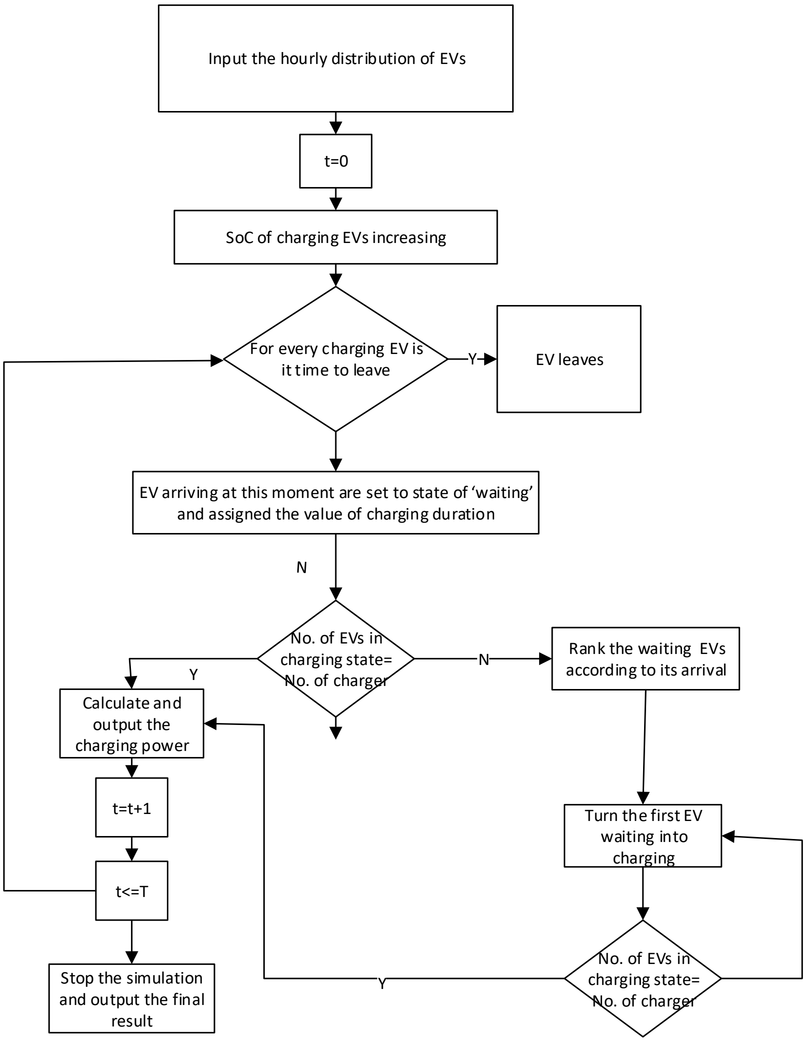

Fig. 5. Cycle Charging Control Strategy

5. SIMULATION RESULTS AND DISCUSSION

In this work a comparison is carried out between different combinations viz. Grid-PV-BESS, Grid-PV, and only Grid.

5.1 Only Grid

As the name suggests, only grid is the source of electricity for the total load which is to be served. Only Grid based power system for fulfilling the electricity demand of EVs charging Station in the parking of Metro Station along with its Lighting and auxiliary load. In New Delhi, the commercial unit price of electricity is around ₹7/kWh. The Net Present Cost of this configuration is ₹ 133 million.
The major portion of the system cost accounts for the O&M cost i.e. payment to the DISCOM for consumption of electricity. The remaining portion of the cost goes to the converter system cost, i.e. capital cost, replacement cost, and salvage value. The COE for this case is ₹7.9/kWh for the period of 25 years. Figure 6 Shows the cost summary of this case, where it can be clearly seen that major portion of the cost is related to grid and some system converter accounts the remaining cost.

As the grid is the only source of power, there is 0% RERs share. Figure 5.2. shows electricity consumption across the year. Electricity purchased per year is 1,426,734 kWh. Table 3 depicted the quantity and type of harmful pollutants emitted in case when the grid is the only source of electricity. In this case there is small capacity shortage (9kWhr/year)

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also occurs due to maintenance work on the grid network. However, the capital cost in this case is zero because no initial investment is required for the infrastructure by the consumer but O&M cost is on higher side in the electricity bills to be paid to DISCOM.

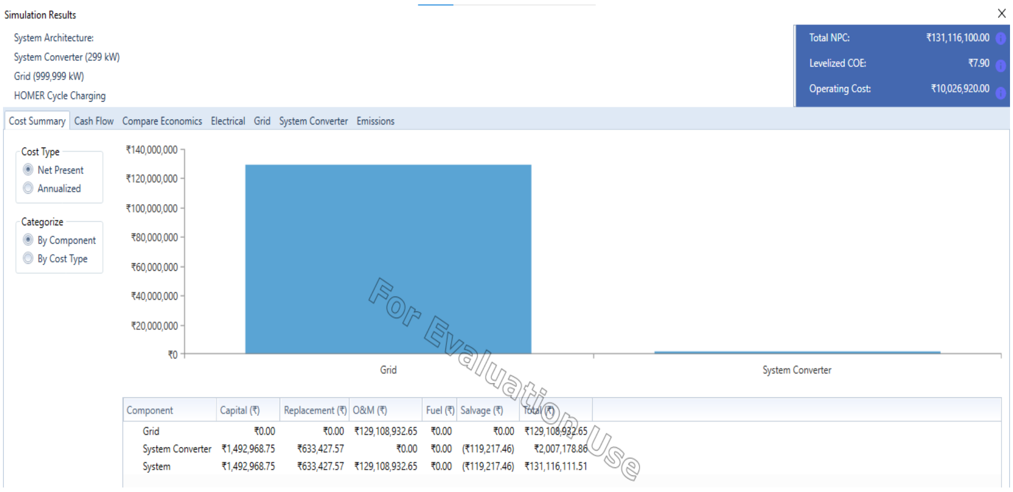

Fig. 6. Cost summary for grid only case

Table 3. Pollutants emitted in grid only case

Quantity	Value	Units
Carbon Dioxide	901,696	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	3,909	kg/yr
Nitrogen Oxides	1,912	kg/yr

5.2 Grid-PV

In this case, PV system is also integrated to the grid. As only 7000 m^2 rooftop area is available and usable area for PV installation is 500 m^2, thus the total installation of PV is only 500 kW as per the area availability. The NPC of the system decrease at a good amount i.e. ₹ 85 million and COE also reduces up to ₹4.59/kWh. The net energy purchased from the grid reduces as the electricity now also available from the PV system. Figure 7 shows the cost summary of Grid-PV case. From the figure it can be observed that O&M charges from the grid reduces to ₹ 85.6 million from ₹ 129 million.

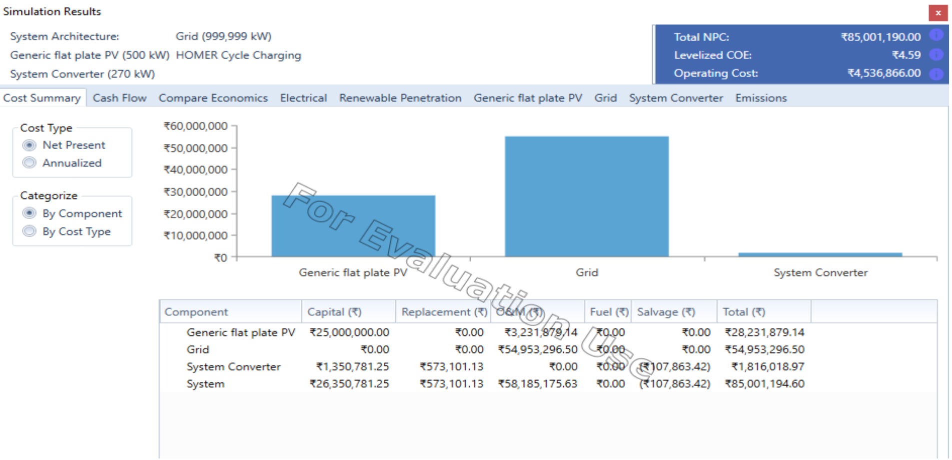

Fig. 7. Cost summary for Grid-PV case

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Table 4. Electricity purchased/sold from/to the grid across the year

Month	Energy purchased (kWh)	Energy sold (kWh)	Net Energy purchased (kWh)	Peak demand (kW)	Energy charges
Jan	62936.692022	14359.824417	48576.867605	278.909574	₹390,297.46
Feb	51977.786890	13417.870262	38559.916629	265.019401	₹316,881.96
Mar	55160.281627	15915.893140	39244.388487	262.261352	₹330,416.35
Apr	49766.915978	14097.734231	35669.181747	249.245082	₹299,026.34
May	51692.433290	12028.802909	39663.630381	260.225193	₹319,746.22
Jun	52130.509006	9058.052882	43072.456124	273.925686	₹333,210.38
Jul	61414.537634	7047.012646	54367.524988	284.545299	₹405,237.22
Aug	63859.380739	7875.840399	55983.540339	270.758101	₹419,450.22
Sep	56475.003706	14455.741592	42019.262114	253.754691	₹344,729.93
Oct	52133.717591	15276.145016	36857.572575	244.888857	₹311,469.52
Nov	58653.316902	14839.827911	43813.488991	281.875786	₹358,633.82
Dec	65971.665337	11435.146784	54536.518553	281.296860	₹421,778.64
Annual	682172.240721	149807.892188	532364.348533	284.545299	₹4,250,878.06

Of the total consumption, 45.2% of the electricity is purchased from the grid and PV panels generates accounts 54.2%. The outage due to maintenance of grid network now covered by PV-Battery combination and in this case net power outage occurs is very low in comparison to previous case. The amount of pollutants emitted in this case is significantly lower as compared to previous case as shown in Table 4 mainly due to the increased share of RER based generation.

Table 5. Pollutants emitted in grid-PV case

Quantity	Value	Units
Carbon Dioxide	431,133	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	1,869	kg/yr
Nitrogen Oxides	914	kg/yr

5.3 Grid-PV-Battery

In Grid-PV-Battery case, the COE of this system reduced significantly and found to be ₹4.62/kWh. The NPC of the system is also reduced to ₹ 85.6 million. Figure 8. shows the cost summary of Grid-PV-Battery case. This reduction in COE and NPC is mainly due to electricity purchased from the grid decreases significantly on yearly basis and generation from the PV system increased significantly. The surplus power supplied back to grid also a factor for reduced COE and NPC in this case. Also the pollutants emitted reduces significantly in this case (Table 6) because dependency on grid is reduced which is the main source of pollutants. The power outage is 0 kWh in Grid-PV-BESS case as the maintenance and faults mainly occurs on grid network and in this case the grid dependency is very low.

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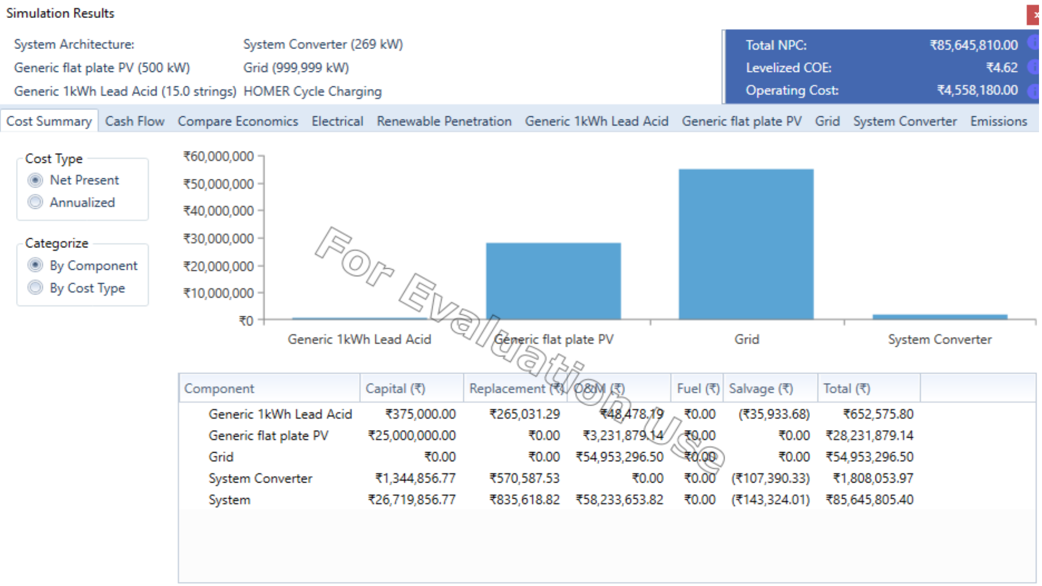

Component	Capital (₹)	Replacement (₹)	O&M (₹)	Fuel (₹)	Salvage (₹)	Total (₹)
Generic 1kWh Lead Acid	₹375,000.00	₹265,031.29	₹48,478.19	₹0.00	(₹35,933.68)	₹652,575.80
Generic flat plate PV	₹25,000,000.00	₹0.00	₹3,231,879.14	₹0.00	₹0.00	₹28,231,879.14
Grid	₹0.00	₹0.00	₹54,953,296.50	₹0.00	₹0.00	₹54,953,296.50
System Converter	₹1,344,856.77	₹570,587.53	₹0.00	₹0.00	(₹107,390.33)	₹1,808,053.97
System	₹26,719,856.77	₹835,618.82	₹58,233,653.82	₹0.00	(₹143,324.01)	₹85,645,805.40

Fig. 8. Cost summary for Grid-PV-BESS case

Table 6. Electricity purchased/sold from/to the grid across the year

Month	Energy purchased (kWh)	Energy sold (kWh)	Net Energy purchased (kWh)	Peak demand (kW)	Energy charges
Jan	62936.692022	14359.824417	48576.867605	278.909574	₹390,297.46
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Mar	55160.281627	15915.893140	39244.388487	262.261352	₹330,416.35
Apr	49766.915978	14097.734231	35669.181747	249.245082	₹299,026.34
May	51692.433290	12028.802909	39663.630381	260.225193	₹319,746.22
Jun	52130.509006	9058.052882	43072.456124	273.925686	₹333,210.38
Jul	61414.537634	7047.012646	54367.524988	284.545299	₹405,237.22
Aug	63859.380739	7875.840399	55983.540339	270.758101	₹419,450.22
Sep	56475.003706	14455.741592	42019.262114	253.754691	₹344,729.93
Oct	52133.717591	15276.145016	36857.572575	244.888857	₹311,469.52
Nov	58653.316902	14839.827911	43813.488991	281.875786	₹358,633.82
Dec	65971.665337	11435.146784	54536.518553	281.296860	₹421,778.64
Annual	682172.240721	149807.892188	532364.348533	284.545299	₹4,250,878.06

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Table 7. Pollutants emitted in grid-pv-battery case

Quantity	Value	Units
Carbon Dioxide	431,133	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	1,869	kg/yr
Nitrogen Oxides	914	kg/yr

6. CONCLUSIONS

PV energy and electric vehicles are critical components in reducing CO2 emissions and fossil fuel usage. Despite the fact that electric vehicles are more cost-effective and ecologically benign than gasoline cars, their adoption is limited for a variety of reasons. The most visible of these reasons are the charging scheduling of electric vehicles and the efficient design of dedicated charging facilities. If the charging facility and underground metro station relies exclusively on the central grid to fulfil the load requirement, the distribution system will be overburdened, which is undesirable. This would put a lot of strain on the main grid, which could happen during peak demand hours, resulting in higher operational costs and more greenhouse gas emissions. In this context, creating a specialised charging station in parking of a metro station can reduce reliance on the main grid while also allowing for more efficient load scheduling for electric vehicles and underground metro station. In this thesis, a comparison is made between three cases viz. grid only, Grid-PV-BESS, and Grid-PV is made for a case study of a Metro Station. The load of the metro station consist of a charging station of EVs and other auxiliary load like lighting load and UPS load etc. From the simulation, it is found that grid only mode has highest COE i.e. ₹7.9/kWh and highest NPC ₹ 133 million. In Grid-PV-BESS case the COE is ₹4.62/kWh and NPC is ₹85.6 million. In the third system, i.e. Grid-PV system, the COE and NPC is least i.e. 4.59/kWh and ₹85 million. The pollutants emitted from the system is highest in case of grid only case, and least in Grid-PV case.

From the above discussion it is concluded that, Grid-PV system is best suited for fulfilling the electricity demand of lighting load for an Underground Metro Station. In the coming years, with the technological advancements, the cost of PV system and other power electronics converter system will decrease and fossil fuel based electricity generation cost will increase. So, it is suggested that Grid-PV based configuration is best suited for the particular case study.

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IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified ⁜ Impact Factor 7.105 ⁜ Vol. 9, Issue 5, May 2022
DOI: 10.17148/IARJSET.2022.9554

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