Design of Solar-Powered Electric Vehicle Charging System

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***Abstract*— This paper investigates the feasibility of charging electric vehicles (EV) with PV panels at workplaces and residences and declares the suitable PV system capacity in Visakhapatnam. As the penetration of EVs is increasing, need of charging stations with renewable energy to reduce burden on power system and also to mitigate climate change. The work considers charging stations for residential and workplace for its study. The configuration of the charging stations is based on the models proposed by NITI AAYOG, Government of India. Starting with estimation of charging profile of an EV, the work estimates the power requirement of a typical charging station for workplace applications (Only solar PV) and for residential (solar PV with energy storage) with a fixed tilt and azimuth angle. A suitable solar PV system, with and without energy storage, to meet the above desired power is designed, by using SAM software. The appropriate PV system is found for EV charging stations (CS) by analysing the technical and economic performance of different capacities of the solar PV system to meet the expected demand. The study results show the self-consumption, cost of energy (COE), payback period (PBP), and net present value (NPV) based on which the capacity of solar photo voltaic (SPV) system and with or without energy storage is decided and selected depending on its application.**

Keywords*— charging stations, electric vehicles, renewable energy, solar system, storage system.

I. INTRODUCTION

In India, over the next ten years transport electrification is predicting that to be driven by electric vehicles(EVs), to include especially two-wheelers (scooters, motorcycles) and three-wheelers (passenger and cargo). Aside from these four-wheelers are also being electrified and electric buses will be present in notable numbers. Primarily, because of the rising cost of conventional energy sources[1], the use of renewable energy sources such as solar energy is preferring now a days since it is available to a broad audience. Combining both, that is charging an electric vehicle with solar is a better option to minimize the hazard gases emission from burning of fossil fuels and also to reduce the burden on the grid. Under the different business models of EVCS based on its energy requirements and consumption pattern, in this paper, the design of both workplace and residential charging stations was analyzed, and also its technical and economical aspects were determined.

II. LITERATURE SURVEY

A number of studies have been analyzed the design of a charging station based on solar PV arrays and charging circuits [2,3]. For an optimal system, panels are oriented to maximize the revenue [4] and an electric vehicle charging station is implemented with a modern solar technique with level -2 charger [5]. By taking dynamic charging needs of EVs, the optimal power management between solar, grid and BESS with the EVs in the charging station [6].

The EVCS is also designed optimally based on technical and economical aspects using the HOMER GRID software [7] and based on cars, the investment cost, the monthly variation in energy generation, charged annually, and the decrease in carbon dioxide (CO2) emissions with PVsyst 7.2 software [8]. Through a battery management system (BMS), few algorithms are proposed for efficient charging in EVs with solar panels to manage the battery pack [9] and with vehicles initial state of charge and rest time of vehicles and the regional solar pattern at the workplace by considering a local workplace [10]. A time multiplexing method is used as strategy to charge EVs from solar energy by simulation and experiment in charging EVs with different amounts of energy based on priority using Arduino is successful [11]. A high-performance DC-DC boost converter controlled by a PI controller is proposed to alleviate the current state of fast charging and environmental problems. Based on the required preset reference voltage value, different output power levels can be generated by the proposed converter [12] and discussed the different charging technologies [13].

The Hybrid Energy Storage System (HESS) along with a supercapacitor and battery is widely used to charge the Electric Vehicle [15] and in a home solar PV system the electric vehicle battery (EVB) is used as a storage device [14].To study the increase of self-consumption of photovoltaic (PV) power a model was developed by vehicle-to-grid (V2G) technology and smart charging of electric vehicles (EVs) [16] and based on a similar principle as the F1-score in machine learning a study uses a novel score, called self-consumption-sufficiency balance (SCSB), which conveys the balance between self-sufficiency (SS) and self-consumption (SC) [17]. A solar carport architecture is proposed which will provide a three-port interface with solar panels, electric car and the utility grid to create a absolute power flow between the three ports [18] and PV chargers are investigated and compared based on converter topology, system architecture, and bidirectional power capability for V2G operation [19]. As a Gaussian mixture model, modeling the charging probability of electric vehicles, and this Gaussian mixture model enables capturing the charging profiles, extensively with a few parameters and therefore it enables estimating the charging probability effectively for individual parameter intervals [20] and inspects

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how different factors affect the charging profile of particular EVs based on actual data [21]. An assisted approach for EV charging in dc microgrids [22] and an efficient energy management approach that is adaptable with the standard dc fast charger so called CHAdeMO [23]. Developing a charger with a bidirectional DC-DC converter is proposed by a sepic converter [24] and an isolated unidirectional dual bridge (IUBD) DC/DC converter [25].

Stored high-pressure air is used to blow over the surface of PV panels, to cooling the panels and to removing the dust presented and mainly to increase the output power [26]. To fulfill the climate and energy targets, determining the minimum penetration levels that allows. For a case study of Portugal in 2050 to reduce carbon dioxide emissions, using an smart charging approach show that a 100% renewable energy-based electricity supply is possible with certain photovoltaics and electric vehicle combinations [27].

In the available literature discussed above, the following issues have not been investigated:

1. Design of solar based electric vehicle charging station with standard Indian requirements.
2. Techno-economic evaluation for analysing its performance.

The present work attempts to address the above two issues.

In this work, a solar based Electric vehicle charging system can be used either for residential/commercial purposes. This system which is considered in this work has been adopted from the "handbook of electric vehicle charging infrastructure implementation" [29].

The objectives of this proposed work are: To design an EV charging system using a PV System (without and with storage): 1. Residential 2. Workplace and to analyze the techno-economic performance under uncontrolled and controlled charging scenarios.

III. METHODOLOGY

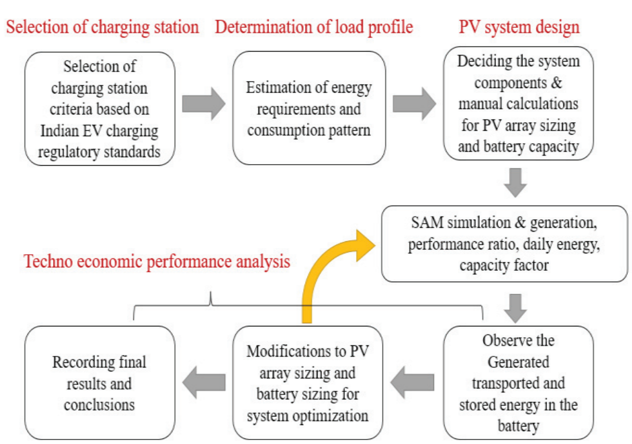

Fig. 1. Methodology to design an EV charging system with PV

The methodology to fulfill the above objectives and to investigate the above issues which are not discussed in the previous works is shown in figure 1.

Depending on location and requirements, electric vehicles can be charged in many ways. Also, different types of infrastructure for charging EVs designed for different applications. Based on available EV models and electric vehicle supply equipment (EVSE), with specifications and standards for EV chargers in the market and the electricity grid characters will vary among the states and countries.

Commonly, an area required to set up a 1kWp solar PV system is of about 10 sq m. The system can be designed as a roof over the charging facility, to maximize space utilization or it can be arranged on the roof by the owner's choice.

The energy requirements will decide the system capacity. Based on the specifications of the inverter and module, the system components like the number of modules and storage capacity are decided.

After observing the results for different capacities of the solar system for both the EVCS business models, the optimal PV system is suggested.

IV. APPROACH

This section involves a detailed explication of the selection of charging stations, determination of energy consumption pattern, and PV system design.

A. Selection Of Charging Station

In general, the EV charging infrastructure based on its ownership and use. It can be categorized as public, semi-public, and private. Both the workplace and residential charging stations come under the private charging station.

The MoHUA’s suggested that for all the new buildings, the building bye-laws ask 20% of parking spaces for charging infrastructure.

EV charging implies the battery pack to supply the direct current (DC). A converter is required to provide DC power to the battery as electricity distribution systems supply alternate current (AC) power. Since the applications are residential and workplace, for both the parking time of vehicles which doesn't require fast chargers and sufficient to charge with slow chargers to install an economical EV charging station.

B. Determination Of Load Profile

For planning the EV charging infrastructure, it is a must to consider the charging demand as well as constraints on the power supply. The planning process is to evaluate the EV charging demand, which depends on the vehicles that are getting charged in the charging station. At the same time, to achieve EV adoption targets availability of EV charging infrastructure is also necessary.

An EV charging demand assessment can be utilized as input data to decide the EV chargers number required in the charging station and to analyse grid capacity. It is generally acquired that the charging of EVs of a large population will have two major effects on the grid; it will increase the load on local distribution networks and it will increase the overall

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power load needed. Anyway, the uncontrolled charging of a large number of EVs could raise the peak demand significantly. To attenuate these concerns, controlled charging of EVs may need to be accomplished.

Normally there are two ways to explore the travel patterns and charging behaviour of a large number of EVs. One procedure would be to conduct a EV trial and use the outcomes from that trial to inform and conclude charging patterns and power demand forecast. The second method would be to design a fleet of EVs and use the results of the model as a representation of the power demands of the EVs.

C. *Design Of Pv System*

Designing the PV system requires selecting the number of modules, strings, and modules per string. Then based on the chargers type suitable converters are used. Excess or unused capacities will increase the cost of the project since required and enough equipment is needed to be selected and implemented. Two aspects are vital while designing the PV system. They are 1. Technical aspects and 2.Economical aspects.

D. *Technical aspects*

Technical aspects should be discussed from both the input and output sides.

The input side technical aspects consist of location and weather files which indicate the latitude and longitudes of the system placed. Module parameters and inverter parameters are needed to be selected based on power requirements. System design is done based on the minimum and maximum limitations values.

The output side technical aspects consists annual energy, it is the amount of electricity supplied by the overall system, energy yield is the ratio of AC electric output to the DC capacity, performance ratio is the measure of a solar system's is the ratio of annual electric generation output AC in kWh to its nameplate capacity in DC kW by considering the solar resource at the location where system's implemented and shading and soiling of the array into consideration, the capacity factor is defined as the output electricity to the system DC capacity in a year, self-consumption is the amount of load that is supplied by the system, self-sufficiency is the amount of system generation supplied to the load and renewable fraction is similar to the self-consumption but compared with the actual load and the power from the grid. The renewable fraction is considered in this work because in the case of the residential case the self-consumption is not feasible since the load is supplied by the storage system.

E. *Economical aspects*

Economical aspects should be discussed from both the input and output sides.

The input side economical aspects consist of installation costs which consist of the battery, inverter, module, the remaining equipment, Grid interconnection, labour, installation, Permitting and environmental studies, Engineering and developer overhead the operation and maintenance costs consist of fixed costs, maintenance costs and replacement costs, the degradation represent the decrease in value of project capital, financial parameters is about the project's tax rates, financial and debt structure, and other parameters to analysis. Electricity rates will determine in such a way that should be based on the state tariffs also based on this tariff the system bill with and without the system is calculated to determine the bill savings.

The output side economical aspects consist of COE is the cost of electricity delivered to the grid that is expressed in cents per kilowatt-hour, the payback period the time in years, installation costs, operating and maintenance costs, income taxes, debt-related costs, incentives and depreciation, the net capital cost is the total installed cost, net present value is a evaluation of a project's commercial feasibility that includes both cost and revenues (or savings for commercial and residential projects).

For reliable power supply, the generated electricity for EV charging is typically allowed through solar photovoltaic (PV) supported by stationary energy storage. If the demand in power can only be partially met through the respected location’s electricity generation and energy storage, the owner needs to organize for a backup electricity supply source, either by a new metered connection or through an existing grid connection. Net metering or net billing allows the withdrawal the produced electricity from the total electricity consumed on-site using renewable energy in a billing period. Apart from these three segments of the approach to achieve the objectives two more important sections involves are storage system and electricity rates.

1) *Storage system*

The energy storage system is essential since it will be used to produce the surplus power, supply the peak demand, to utilize it when the system or grid is absent. Not only the energy capacity to supply the load but also the power capacity of the battery pack is crucial to minimize grid dependency. Another consideration for the power capacity of the energy storage system is to get the subsidies from the government norms if it is within their ranges. Its dispatch is one more important segment to maximize the supply to load from the local generation. The dispatch of the battery is done carefully based on ToU and power requirements.

2) *Electricity Rates*

The specific quantity of money framed by the seller for the supplying the electrical energy to grid or various consumers is known as electricity tariff. Especially the tariff is the method of billing a consumer for consuming power. The tariff includes the total cost of consuming and supplying electricity with a reasonable cost [31]. As above mentioned, if the system is connected to the net metering, the tariff rewarded by SECI to vendors and it will be fixed by MNRE depending on conditions of the market. The charges are distributed based on the time, and it is distributed by daily hours and yearly months.

V. RESULTS & DISCUSSIONS

- The configuration of the SPV system is designed based on SAM software.

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- The present work considers a private charging system capable of charging two 2-Ws and two 4-Ws.
- The fixed tilt angle of the panels is 20^0 and the azimuth angle is 180^0.
- The solar system capacity is considered as 10kW by considering two factors: based on the peak demand and based on the sun hours.
- Along with the 10kW system different capacities are selected to find the suitable system. The system design is shown in the table 5.
- The energy storage capacity of the vehicles is:
    1. For 4-wheeler = 26kWh
    2. For 2-wheeler = 3.6kWh

  Since the total energy storage capacity is 58kWh.
- The charging profile of the EV is collected from the measurement of the charging current of EVs when they are charged from 20% to 100% SoC as shown in figure 2, Yokogawa makes a power analyser cw.240 is used for measurements.

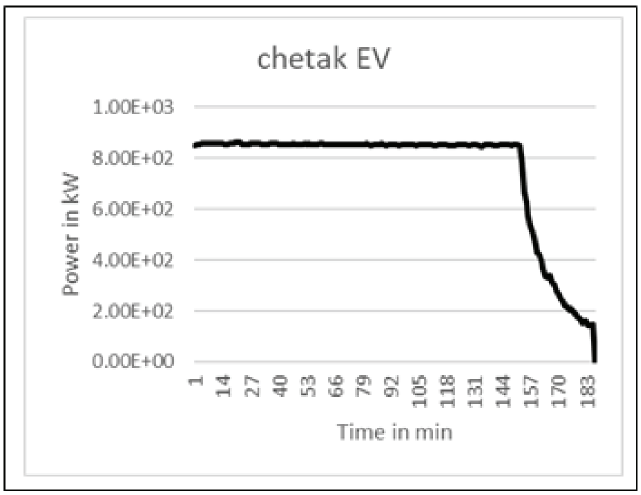

Fig. 2. Charging profile of a chetak EV

- Both the uncontrolled and controlled charging profile is designed based on each vehicle charging profile and its battery capacities respectively and is shown in table 1.
- The installation costs, operation & maintenance costs, and financial parameters are tabulated in 2 & 3, where installation costs are about the one-time investment, and O & M costs are all about the yearly investment of the project. The financial parameters will address the project debt percentage, tax, and loan time.
- Based on the time of use the electricity rates are varying. This is to increase the income. Totally all the yearly hours are distributed by 8 periods. Since the distribution system has peaks from 6am – 10am and 6pm – 10pm it is separated and given high value compared to the normal hours to increase the income.

TABLE I. CONTROLLED AND UNCONTROLLED PROFILES AT EVERY HOUR

CHARGING PROFILES		
Time in hours (WP/RE)	**Controlled Profile (kW)**	**Uncontrolled profile (kW)**
9 am/5 pm	9	11.68
10 am/6 pm	9	11.68
11 am/7 pm	9	11.68
12 am/8 pm	10	11.68
1 pm/9 pm	8	10.22
2 pm/10 pm	7	10.22
3 pm/11 pm	6	-

TABLE II. INSTALLATION COSTS

INSTALLATION COSTS			
Module:	0.39$/Wdc	Battery:	187$/kWh
Inverter:	0.09$/Wdc	Permitting and environmental studies	1% of DCC
Balance of equipment (BoE):	0.06$/Wdc	Engineering and developer overhead	3% of DCC
Labour and installation (L & I):	0.02$/Wdc	Grid interconnection	0.5% of DCC

TABLE III. OPERATION AND MAINTENANCE COSTS, FINANCIAL PARAMETERS

O & M COSTS	
Fixed cost = 640$/year (with battery) = 385$/year (without battery)	Replacement cost (only battery) = 187$/kWh
Financial parameters	
Analysis period = 25yrs	Loan term = 10yrs
Federal income tax rate = 15%	Debt percent = 100% of CC

- And the months march, April, may, and September, October, November, December is having high generation and low generation respectively when compared to the remaining months. The pictorial representation of the electricity charges is shown in the figure 3.
- And based on the period distribution the prices are tabulated in the table 4.

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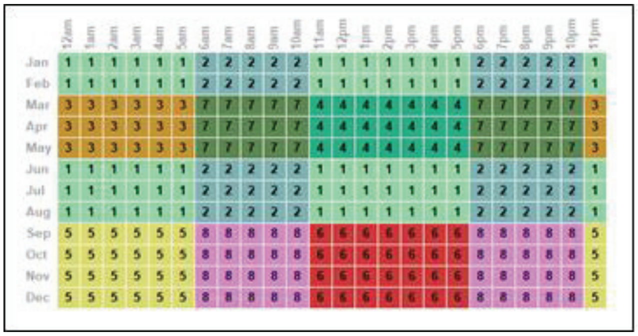

Fig. 3. Electricity charges distribution based on hours and months

TABLE IV. SELLING AND BUYING ELECTRICITY PRICES BY ABOVE PERIOD DISTRIBUTION

ELECTRICITY PRICES		
Period/price	Sell ($)	Buy ($)
1	0.035	0.064
2	0.036	0.064
3	0.039	0.064
4	0.037	0.064
5	0.033	0.064
6	0.032	0.064
7	0.038	0.064
8	0.034	0.064

TABLE V. SYSTEM DESIGN

SYSTEM DESIGN						
S/m capacity/ parameters	10kW	12kW	15kW	20kW	25kW	30kW
DC capacity	10.5	12.6	15	21.6	25.2	32.4
AC capacity	10	12	15	20	25	30
No. of modules	35	42	50	72	84	108
No. of strings	5	6	5	8	7	9
No. of modules/ string	7	7	10	9	12	12

- After all the simulations done for the different capacities of the solar system for workplace and residential controlled and uncontrolled charging stations, the results are tabulated and found the optimal system.

VI. CONCLUSIONS

- Based on the number of vehicles estimated in the charging station the load profile of the charging station is determined.
- By considered the different capacities of solar system from 10kW to 30kW, the suitable PV system is suggested based on the self-consumption, cost of energy, net present value, payback period.
- The optimal system is declared separately based on application, charging profile and battery capacity, by considering the cost of energy(COE), payback period(PBP), net present value(NPV) independently for the workplace and residential.

TABLE VI. COMPARISON OF DIFFERENT FACTORS FOR DIFFERENT CAPACITIES OF THE SOLAR SYSTEM FOR WORKPLACE-UNCONTROLLED CHARGING STATION

WORKPLACE (Uncontrolled)					
Cap/para	SC (%)	COE ($)	NPV ($)	NCC ($)	PBP (yrs)
10kW	51	2.46	4472	6335	5.4
12kW	61	2.38	5356	7602	5.4
15kW	72	2.44	6486	9050	5.4
20kW	89	2.37	8340	13033	5.7
25kW	90	2.37	9064	15205	6
30kW	93	2.3	10430	19549	6.4

TABLE VII. COMPARISON OF DIFFERENT FACTORS FOR DIFFERENT CAPACITIES OF THE SOLAR SYSTEM FOR WORKPLACE-CONTROLLED CHARGING STATION

WORKPLACE (Controlled)					
Cap/para	SC (%)	COE ($)	NPV ($)	NCC ($)	PBP (yrs)
10kW	67	2.46	5568	6335	4.8
12kW	77	2.38	6417	7602	4.9
15kW	84	2.43	7323	9050	5.1
20kW	92	2.37	8748	13033	5.6
25kW	93	2.32	9468	15205	5.8
30kW	95	2.82	10541	19549	6.4

TABLE VIII. COMPARISON OF DIFFERENT FACTORS FOR DIFFERENT CAPACITIES OF THE SOLAR SYSTEM FOR A RESIDENTIAL-UNCONTROLLED CHARGING STATION WITH A 60KWH BATTERY

RESIDENTIAL (60kWh Battery) (Uncontrolled)					
Cap/para	SC (%)	COE ($)	NPV ($)	NCC ($)	PBP (yrs)
10kW	63	7.97	-1745	18260	19.8
12kW	57	6.9	265	19528	14.3
15kW	59	6.25	2209	20976	11.6
20kW	73	5.17	7900	24958	8
25kW	63	4.79	8296	27130	8.5
30kW	65	4.29	9909	31474	8.5

TABLE IX. COMPARISON OF DIFFERENT FACTORS FOR DIFFERENT CAPACITIES OF THE SOLAR SYSTEM FOR A RESIDENTIAL-UNCONTROLLED CHARGING STATION WITH A 60KWH BATTERY

RESIDENTIAL (60kWh Battery) (Controlled)					
Cap/para	SC (%)	COE ($)	NPV ($)	NCC ($)	PBP (yrs)
10kW	73	7.98	-966	18260	16.9
12kW	66	6.9	930	19528	13.1
15kW	68	6.25	3353	20976	10.4
20kW	85	5.18	10782	24958	7.1
25kW	73	4.79	9599	27130	8
30kW	75	4.31	11194	31474	8

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TABLE X. COMPARISON OF DIFFERENT FACTORS FOR DIFFERENT CAPACITIES OF THE SOLAR SYSTEM FOR A RESIDENTIAL-UNCONTROLLED CHARGING STATION WITH AN 80KWH BATTERY

Residential (80kWh Battery) (Uncontrolled)					
Cap/para	SC (%)	COE ($)	NPV ($)	NCC ($)	PBP (yrs)
10kW	68	9.67	-4801	22450	-
12kW	72	8.45	-2758	23717	21.6
15kW	79	7.52	-542	25166	15.5
20kW	94	5.98	5405	29148	7.9
25kW	82	5.58	8504	31320	8.9
30kW	84	4.87	10635	35664	8.7

TABLE XI. COMPARISON OF DIFFERENT FACTORS FOR DIFFERENT CAPACITIES OF THE SOLAR SYSTEM FOR A RESIDENTIAL-CONTROLLED CHARGING STATION WITH AN 80KWH BATTERY

Residential (80kWh Battery) (Controlled)					
Cap/para	SC (%)	COE ($)	NPV ($)	NCC ($)	PBP (yrs)
10kW	79	9.67	-3551	22450	-
12kW	83	8.42	-807	23717	16.1
15kW	88	7.49	1439	25166	12.9
20kW	97	5.87	11211	29148	7.5
25kW	95	5.5	11460	31320	8
30kW	96	4.54	12772	35664	8

- By selecting the PV system capacities of 12,15,20,25,30 kW with the 10kW system the comparisons declare the suitable system for both workplace and residential.
- The negative NVP indicates that the project is infeasible since from the comparisons the infeasible system is not at all taken into consideration for implementation.
- Hence every system capacity is feasible from table 6 & 7, the optimal system for the workplace EVCS without battery is a 15kW PV system with 72% and 84% SC for uncontrolled and controlled charging systems respectively, because to achieve 10% more SC, the system capacity should be doubled there by the NCC should also increase by two times and since there is a noticeable change in COE.
- By comparing tables 8 & 9 with 10 & 11 respectively, it is clear that the 80kWh battery is better at supplying the load than the 60kWh battery.
- Hence from the table 10 & 11, the optimal system for the residential EVCS with an 80kWh battery is a 20kW PV system because the SC is highest and PBP is lowest for that capacity.

VI. SIMULATION RESULTS

- From the SAM software, the profiles are checked to note the battery SoC from the profiles section.
- From figure 4, it is clearly shown that daily the battery is charged up to 94% of Soc and discharged up to 17% since the maximum and minimum State of Charge given to SAM are 95% and 15% respectively.

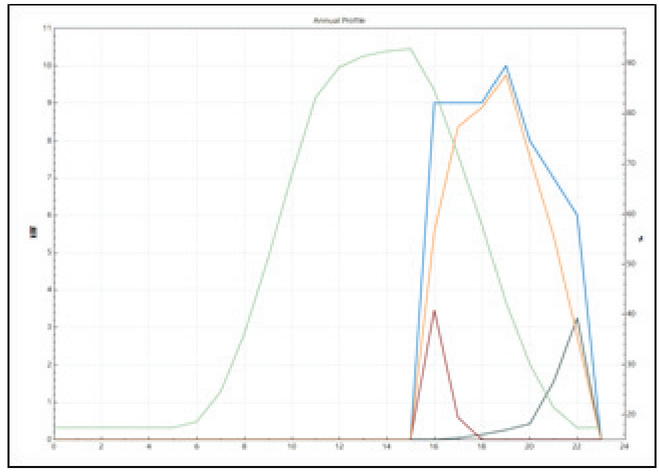

Fig. 4. Simulation results from the profiles section from the SAM software of the residential controlled charging station with 80kWh battery

Blue – charging station Load, Orange – Battery to load, Maroon – System to load, Dark green – Grid to load, Light green – Battery SoC

TABLE XII. SELF-CONSUMPTION OF SYSTEM FOR DIFFERENT CAPACITIES FOR WORKPLACE AND RESIDENTIAL CHARGING SYSTEM

SELF CONSUMPTION						
Capacity (kW)/ Application	**Workplace**		**Residential 60kWh**		**Residential 80kWh**	
	C	**UC**	**C**	**UC**	**C**	**UC**
10	67.5	51.3	73.6	63.3	79.6	68.7
12	77.2	61.7	66.2	57.1	83.9	72.3
15	84.4	72.7	68.8	59.3	88.8	76.5
20	92.2	86.7	85.7	73.8	97.6	94.5
25	93.8	90.1	73.6	63.5	95.0	82.7
30	95.3	93.6	75.7	65.4	96.0	84.9

- From table 12, the self-consumption is the factor which implies the load share within the system for workplace and with system and battery for residential by excluding the grid.
- And it is clear that the self-consumption is not increased rapidly with the capacity, since in this work, the suitable capacity is selected for which system the highest self-consumption is obtained.
- In the table 13, the comparison is done with different parameters to know more about the system technical and economical aspects to decide the appropriate system.

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TABLE XIII. COMPARISON AMONG DIFFERENT PARAMETERS FOR DIFFERENT SYSTEM CAPACITIES

Comparison among different parameters for different system capacities						
Parameter /System capacity	**10kW**	**12kW**	**15kW**	**20kW**	**25kW**	**30kW**
AR (m^2)	57.08	68.5	81.5	117.43	137	176
AE (kWh)	16895	20233	24483	35499	41506	53451
EY (kWh/kW)	1607	1604	1631	1642	1645	1648
BE (%)	92.9	92.3	93.5	93.5	93.2	91.4
Grid %	20.2	15.9	10.9	2.11	4.68	3.62
System %	3.54	4.25	5.13	7.39	8.62	11.1
Battery %	76.29	79.87	83.92	90.49	86.71	85.27
SC	79.66	83.98	88.84	97.64	95.05	96.08
CF	18.3	18.3	19	18.7	18.8	18.8
PR	0.79	0.79	0.8	0.81	0.81	0.81
COE (cents/kWh)	9.67	8.42	7.49	5.87	5.5	4.84
NPV ($)	-3551	-807	1439	11211	11460	12772
NCC ($)	22450	23717	25166	39148	31320	35664
PBP (yrs)	-	16.1	12.9	7.5	8	8

ASSUMPTIONS

The assumptions that are made in this work are;

- It is considered that two 2-Ws and two 4-Ws of EVs are in the parking slot.
- Uncontrolled charging means that the vehicle is charging with a level 1 charger at a 3-pin socket and controlled charging means that the vehicle is charging with a type 2 charger.
- Controlled charging taken in this work is just an assumption profile and can be made better using real-time techniques.
- Daily the load is the same irrespective of the weekends and holidays.
- The uncontrolled charging profile of 4-W is followed by the 2-W profile.
- Every vehicle is getting charged at min 20% SoC in the charging station.
- Only AC chargers are considered not DC and fast chargers hence we use an inverter.

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