Optimal Design of Electric Vehicle Charging Stations Integrated with Renewable DG

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Abstract--**Electrification of the transportation sector is a crucial step toward achieving a sustainable society. It will lead to several advantages, such as: reduce consumption of oil, reduce emissions and integrate renewable energy resources into the grid. Deployment of electric vehicle charging stations (EVCS) is essential to encourage large adoption of Electric Vehicle (EV) as it will reduce 'range anxiety' concern regarding the distance the EV could travel before the battery runs out. In this work, an optimal design of an electric vehicle charging station that integrates renewable distributed generation (DG) will be designed for cost and emission reduction. Both an isolated microgrid EVCS and an EVCS connected to the grid were studied in different cases, where energy sources such as PV, wind, and diesel generator are considered to supply the EVCS demand. The model was designed using HOMER software and designed based on realistic input data in terms of physical, operational and economic characteristics.**

Index Terms— **Charging station, Electric vehicle, Microgrid, Renewable energy sources.**

I. Introduction

GLOBALIZATION has made people travel more, live far from their work and consume goods from all around the world. This has led to more use of transportation, which has been found to consume 62.3% of the oil in the world in 2011, producing emissions of 6892 Mt of CO_2 [1]. Efforts must be done to reduce oil dependence, decrease energy consumption and lessen the environmental impact of the transportation system. One feasible solution to address the challenges linked to the transportation sector is to electrify that sector [2].

An electric vehicle is a promising solution to ensure a sustainable transportation system as it provides lots of benefits. From an economical point of view, it costs more to purchase an EV than internal combustion engine vehicle (ICEVs). However, the high efficiency of an electric motor reduces the operation cost compared to the ICEVs. From an environmental point of view, the high efficiency of the electric motor will reduce the total CO_2 emissions even within an electricity system with a high fraction of fossil fuel generation. From the point of view of the electric grid, it can also play an important factor in the integration of renewable energy into the existing electricity system [3]. The electric vehicle (EV) does not affect the grid as it still has a low market right now. However, the International Energy Agency has set a target to have over 20 million EVs on the road by 2020 [4]. With this growth of the EV market, it is expected that it will affect the performance and efficiency of the electric grid. Extra investment in the generation and transmission capacity will be required, due to an increase of peak loads under simple charging strategy [3]. Another impact of EV on electric distribution networks are: power quality issues, transformer and line saturations and increase on electrical losses [1, 3, 4, 5]. For that, to integrate a high penetration of plug-in electric vehicle (PEVs) into grid safely network reinforcements, embedded generation and EV charge management strategy which is called as coordinate charging are required. The lack of accurate PEV charging data has led to a lack of robustness in coordinate charging. This could improve more in the years to come when the penetration of the PEVs will increase to a high level. Until then uncoordinated charging PEVs need to be accommodated. The option of upgrading the infrastructure to accommodate the uncoordinated PEVs is costly and will take time. Also, supplying the uncoordinated PEVs through conventional generation will lead to a shift in the emissions from the transportation sector to the generation sector. For that, it is important to consider the renewable DG as a source to accommodate the growth of uncoordinated PEV loads [6].

Several contributions have been presented in the literature in the area of combining renewable energy resources (RES) with PEVs. A survey conducted in [7] shows that if renewable energy was offered in EVCS, there will be a 433% increase in the usage of these stations by EV drivers. The benefit of adopting renewable generation at EVCS was confirmed in [8] through simulation. In [6] an algorithm has been designed to accommodate high penetrations of PEVs through renewable DG. The algorithm helped the local distribution companies (LDC) to plan for the location, size, and year of installation of renewable DG units while minimizing the costs and emissions and enabling higher percentages of PEV integration. In [9] a grid-connected solar powered EVCS with V2G was designed and tested experimentally. It has proved in this work that the EVCS produces enough electric energy to charge EV on a sunny day, and it is capable of balance load demand in the local grid during cloudy days. A similar study in [9] was proposed in [10] but with wind energy. In [11] a grid-tied PV-Wind EVCS for stadiums was proposed and analyzed in terms of cost, validity, and usefulness. It was found that the system was profitable and capable of reducing the CO_2 emissions. Similar work has been done to design a PV-wind charging station for small Tuk-Tuks in [12]. However, the system was isolated from the grid, and the diesel generation has not been considered as an option. In [13] an optimal design of EVCS was studied while different generation options were considered such as PV, diesel generation, and storage batteries. However, the wind was not considered as an option. Two cases have been studied in term of economics and environmental impacts. Those two cases were isolated EVCS and grid-connected.

It is clear that this area of research still needs more studies and investigation. The work that will be discussed in this paper will be an improvement to what was done in [13]. The main contribution of this work will be as follow:

1. Wind energy will be considered as a source option
2. The penalties in the CO_2 emission will be accounted for in the optimization problem

The paper is organized as follows: Sections II and III present the problem definition and the system modeling, respectively. Section IV explains the system sizing and input data. Section V introduces case studies, and Section VI presents the results and discussion, followed by the conclusions in the last section.

II. Problem definition

The objective of this work is to design an EVCS that ensures supplying the load while minimizing the cost and the system emissions. The work presented in this paper will be done using The Hybrid Optimization Of Multiple Electric Renewables platform (HOMER), which is a simulation tool to help in the designing, planning and evaluating of a renewable energy microgrid [14].

The system architecture consists of three elements: input, model, and output. The input is comprised mainly of the EVCS electric and thermal load profile, EVCS available supply options and the associated sizing, costs and other parameters of the components. The model will be run in HOMER for the purpose of minimizing the net present cost (NPC) and emissions. The following constrains will be considered:

- The maximum annual capacity shortage fraction is set to 0%, which imply that the annual load will be met all the time.
- The minimum allowable value of the annual renewable fraction is set to 0%, which imply that the charging station can operate without renewable resources.
- The operation reserve is determined from the addation of four values to ensure that the electricity will be supplied even if the load demand suddenly increases or renewable generation suddenly decreases:
  1. 10% of hourly load, to ensure serving up to 10% unexpected increase in the load.
  2. The reserve requirement is independent of the peak load as the percentage is assumed to be 0%
  3. 50% of wind turbine power output will be added to the operation reserve, which means the system must ensure enough operating reserve to supply the load even if the wind turbine output unexpectedly decreased by 50%.
  4. 50% of solar power output, which means the system must ensure enough spare capacity operating to supply the load even if the PV array output unexpectedly decreases 50%.

The decision variable will be the size of the renewable energy resources and the amount of energy purchased from or sold to the grid.

The output of the proposed algorithm consists of the optimal system configuration, the optimal size of each component, energy scheduling, cost breakup by component, optimal break-even distance, and emissions. As the problem is multi-objective, normally there will be no unique solution to the problem [15]. In this work comparison between different scenario will be mentioned and it will be left open to the owner of the EVCS to decide the solution that will fit their requirements.

A. System Costs

The objective of this project is to minimize the total net present cost (NPC) which is the present value of all the costs that afford within the project lifetime minus the present value of all the income that it gains over its lifetime. All the system configuration in the optimization results is ranked based on the value of the NPC.

B. System Emissions

Reducing emissions is one of the prime objectives of this work. This will be taken care off by introducing emission penalties. The Canadian Federal Climate-change Plan mentioned that the penalties on carbon emissions will start at \$15 per ton of carbon and reach up to \$65 by 2018 [16]. For that, in the analysis of this paper, four specific carbon dioxide emission penalties of \$15/ton, \$30/ton, \$45/ton and \$65/ton will be considered.

III. System modeling

A. EVCS load

The EVCS load profile used in this paper is similar to that used in [13], which is a real load obtained from Drive-4-Data [17]. Where Drive-4-Data is an initiative by Waterloo Institute for Sustainable Energy (WISE) at the University of Waterloo, that motivate an EV driver to attach Datalogger to their vehicle to collect data such as, PEVs speed as a function of time, drive cycle and powertrain information, such as vehicle acceleration, battery SOC and the vehicle's driving routes and location. The PEV charging demand profile was generated from 2013 Chevrolet Volt drive cycles from May 2013 to May 2014 with 16 kWh battery capacity. Where 20 PEVs assumed to arrive for EVCS. The daily load profile of EV charging is shown in Fig. 1.

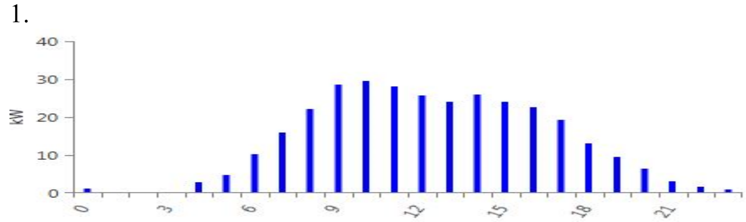

Fig. 1. PEVs arrival at EVCS over the day.

B. Thermal load

The thermal energy demand is considered in this work to be 10% of the EVCS electric energy demand. Thermal load is used in EVCS in cold countries to heat facility services available at the charging station. The thermal load will be supplied by the boiler, or by recovered waste heat from the diesel generator and the excess energy from renewable resources.

C. Solar resource

This study is made based on data for Waterloo, Ontario. The solar radiation profile over a one-year period was taken from NASA Surface Meteorology and Solar Energy website for Waterloo, Ontario, (43° 39' N, 80° 32' W) [18]. The solar radiation profile is shown in Fig. 2. The annual average solar radiation for this region is 3.64 kWh/m^2/day.

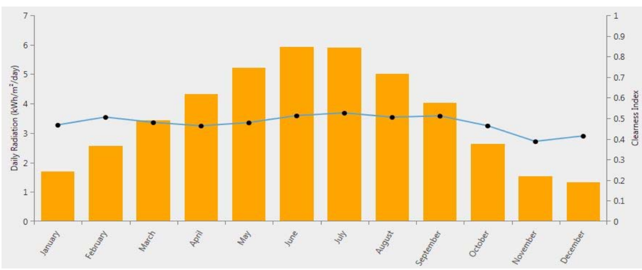

Fig. 2. Solar radiation profile

D. Wind resource

Wind resources are also taken from NASA Surface Meteorology and Solar Energy website [18] for Waterloo, Ontario. The annual average wind for this area is 5.08 m/s Fig. 3 shows the wind speed profile over a one-year period.

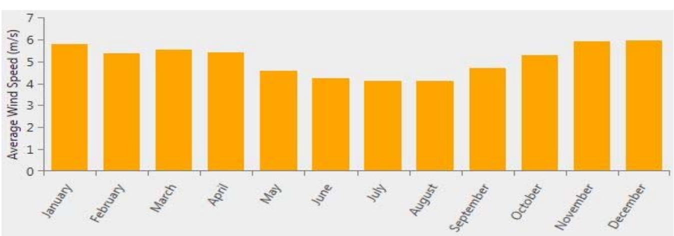

Fig. 3. Wind speed profile

IV. SYSTEM SIZING AND INPUT DATA

A. Sizing Strategy

The main aim of the hybrid system is to supply the load continuously with the required power. Since the hybrid system consists of wind and solar which depends on the weather conditions, a storage system should be provided to supply the load with required power during severe weather conditions. When the power generation by both wind turbine and PV array is insufficient to supply the load and the storage is depleted, the diesel generators will be used.

B. Component costs and sizing option

The sizing options together with other associated parameters of the supply components are showed in Table 1, while the costs are presented in Table 2. [19]

Table 1 Sizing options and other parameters

Options	Options on size and unit numbers	Life	Other information
Solar	1, 10, 50, 100, 150, 200, 300, 500 kW	20 years	De-rating factor =90%
Wind (10kW)	0,1,10,50,100,500 unit	15 years	Weibull distribution with K=1.83
Battery	10, 50, 100, 150, 200, 500, 1,000, 1500 unit	(Lifetime throughput) 845 kWh	Nominal capacity 225 Ah
Converter	0, 10, 30, 50, 100, 200, and 500 kW	15 years	Converter efficiency = 90% Rectifier efficiency = 85%
Grid Extension	10, 25, 50, 100, 500, 1000 kW	-	Purchase= $0.12/kWh Sellback= $0.39/kWh [20]
Diesel Generator	0 to 500 kW	500,000 h	Minimum load ratio = 30% Heat recovery ratio = 10%
Diesel Fuel	-	-	Price = $0.70/L Density of 820 kg/m3 Carbon content 88% Sulfur content 0.33%

Table 2 Costs of energy supply resources

Options	Capital cost	Replacement cost	O&M cost
Solar	$3000/kW	$3000/kW	$10/year
Wind	$7900/turbine	$9000/turbine	$30/year
Battery	$75/Battery	$75/Battery	$2/Battery/year
Converter	$1000/kW	$1000/kW	$100/year
Grid Extension	$20,000/km	$20,000/km	$10/year/km
Diesel Generator (4.25 kW)	$2550	$2550	$0.15/h

C. Economics

The project life is 25 years, while the annual real interest rate is set to be 6%.

V. CASE STUDIES

Table 3 shows the case studies that will be considered for analysis.

Table 3 Cases studies summary.

Case	Description of case
1	Diesel dependent EVCS
2	Renewable-based EVCS
3	Diesel-renewable mixed EVCS
4	EVCS connected to external grid

VI. RESULTS AND DISCUSSION

A. Comparison of various cases

1) Optimal EVCS configurations and cost components

The optimal EVCS design shown in Fig. 4 was obtained from HOMER for the different cases shown in Table 3. The detailed analysis of the optimal EVCS is presented in Table 4 for each case. It is clear from Table 4 that while the diesel-dependent EVCS (Case-1) required 50 kW of diesel capacity, the renewable-based EVCS (Case-2) completely depended on solar PV, wind, and battery storage generation. The diesel renewable mixed EVCS (Case-3) reduced diesel generation capacity to 25 kW, battery string and renewable capacity. In Case-4, it is realized that when the EVCS have the option of withdrawing energy from the grid, it depends on the grid to an elevated level.

Diesel-renewable mixed EVCS was found to be the most economical option from the islanded option, as it is shown in Table 5. Since, in most of the time, an external grid will be available for connection with the islanded EVCS then this option can be considered. However, the connectivity distance should be considered. This will be discussed in the sensitivity analysis. It can be realized from Table 5 that the levelized cost have the highest value in Case-1, while it reduces in Case-2 to 0.4471 $/kWh, which is higher than Case-3. Fig. 5, 6 and 7 can explain this variation in cost. As it is shown in Fig. 5 the fuel of the diesel generator plays a major factor in increasing the cost of the system as the system is dependent on the diesel generator only. In the renewable based EVCS, the fuel has a minor effect, while the major cost comes from the capital cost as there is a need to install the components of the system, this is clearly shown in Fig. 6. While in the Diesel-Renewable mix EVCS both the fuel and the capital cost will contribute in raising the cost as is shown in Fig.7; however, the cost will be lower than both previous cases. In Case-4, as is shown in Fig. 8, the significant cost component is the operation cost which is mainly due to the power purchased from the grid.

Figs. 9-12 show the annual cash flows for all EVCS configurations, respectively. The diesel based EVCS (Case-1) in Fig. 9 shows that at the beginning of the project the diesel generator and the inverter incur a capital cost, while in year 15 the inverter will incur a replacement cost. The system will also require a regular stream of fuel and operation & maintenance costs. While in renewable based EVCS (Case-2) the system will incur an initial investment cost that is higher than Case-1 due to the cost of renewable components. Inverter and wind generators will require a replacement cost at year 15 and 20 respectively while other costs will play a minor effect. Case-3 will have the same pattern as in Case-2, with an addition of regular stream accounting for the fuel and operation cost. Case-4 will require a small investment cost at the beginning as the system will already be existing and the cost of operation will be distributed through the system, while in year 15 an additional cost will be present which is the cost of replacing the inverter.

Table 4 Optimal EVCS design

Component	Case-1	Case-2	Case-3	Case-4
Diesel, kW	50	0	25	0
Solar PV, kW	0	100	50	0
Wind, kW	0	100	10	10
Converter, kW	50	10	30	30
Battery, numbers	0	1500	150	10
External grid, kW	0	0	0	1000

Table 5 Comparison of cost component

Items	Case-1	Case-2	Case-3	Case-4
Net present cost, M$	0.897	0.687	0.542	0.313
Levelized cost of energy, $/kWh	0.5859	0.4471	0.350	0.193
Operating cost, M$/year	0.0628	0.0113	0.0245	0.0213

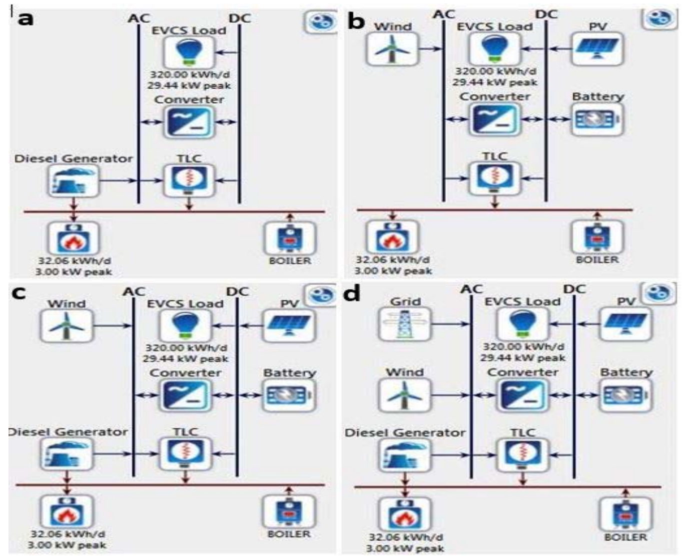

Fig. 4. Optimal EVCS configurations (a) Case-1, (b) Case-2, (c) Case-3, (d) Case-4.

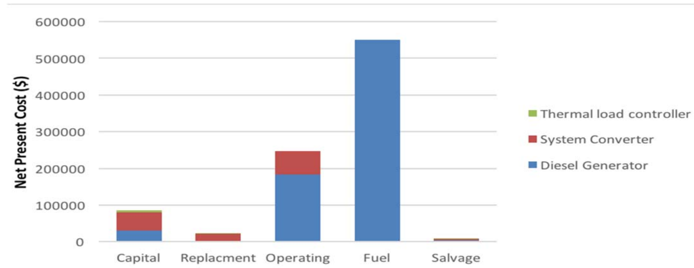

Fig. 5. Cost component for Case-1

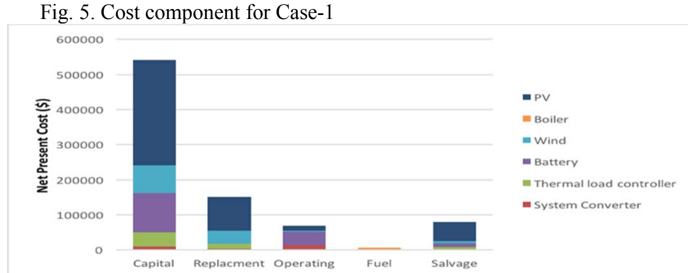

Fig. 6. Cost component for Case-2

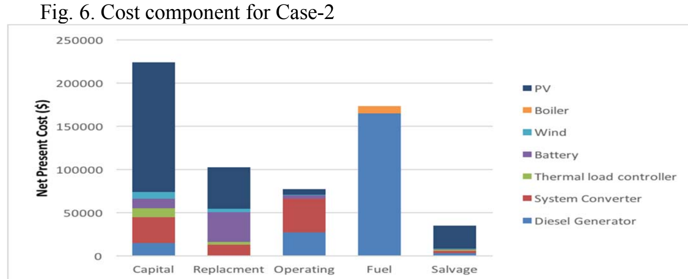

Fig. 7. Cost component for Case-3

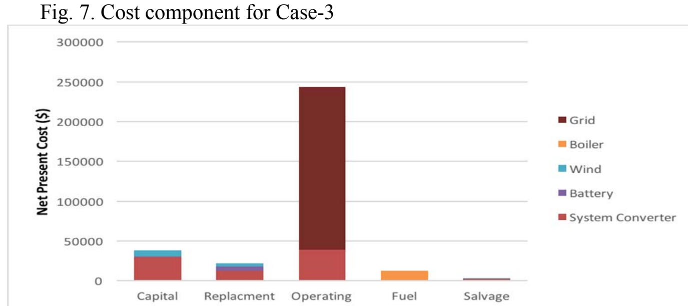

Fig. 8. Cost component for Case-4

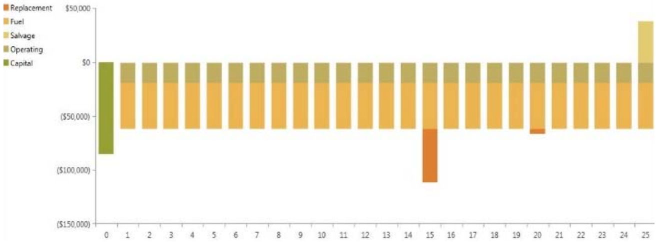

Fig. 9. Case-1 cash flow

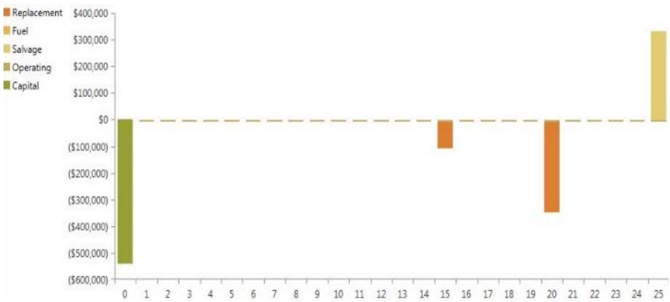

Fig. 10. Case-2 cash flow

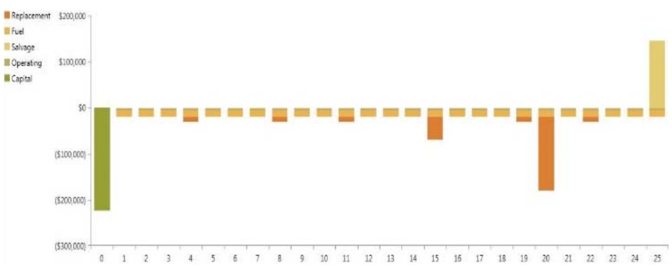

Fig. 11. Case-3 cash flow

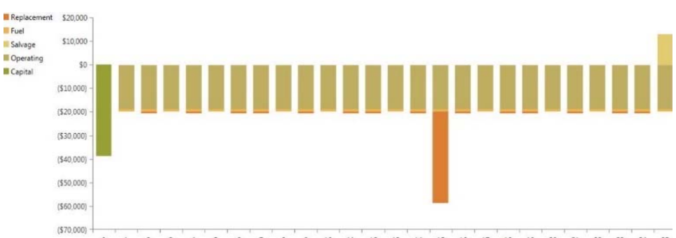

Fig. 12. Case-4 cash flow

2) *Production profiles in various EVCS Configurations*

The electric energy production and consumption for the four different EVCS configuration have been considered and presented in Table 6 and Figs. 13-16. It is clear from Table 6 that renewable based EVCS (Case-2) has the highest production amount as well as the highest excess energy dump to dump load. This is expected due to the intermittent and non-dispatchable characteristics of the renewable energy. Therefore, relying on only renewable energy to operate the EVCS is a risk, and the capacity needs to be higher. It can be realized in the diesel-renewable based EVCS (Case-3) both the production and the excess energy have been reduced. This is due to the availability of the diesel generator and the storage source. In Case-4 there is no excess energy as the EVCS sells all excess energy back to the grid. However, it is clear from Fig. 16 that the renewable energy contribution has been reduced dramatically as compared to Case-2 and 3 as per Fig. 14 and 15.

Table 6 Production and consumption in varies EVCS configurations

Component	Case-1	Case-2	Case-3	Case-4
Production, MWh/yr				
Diesel generator	174.436 (100%)	0	59.399 (44%)	0
Solar PV	0	138.085 (63%)	69.042 (51%)	0
Wind	0	79.394 (37%)	7.939 (6%)	7.939 (6%)
External grid	0	0	0	135.139 (94%)
Renewable energy contribution	0%	100%	57%	6%
Total	174.436	217.497	136.381	143.079
Consumption, MWh/yr				
EVCS electrical load energy served	116.800	116.800	116.800	116.800
EVCS thermal load energy served	11.7	11.7	11.7	11.7
Energy sold back to grid	0	0	0	3.580
Excess energy to dump load	37	91	1.7	0

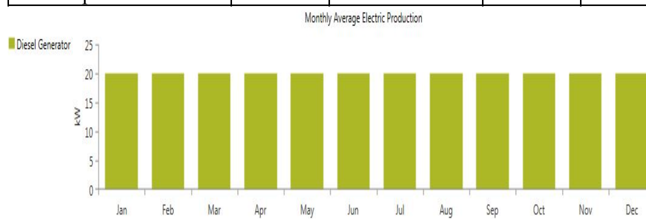

Fig. 13. Case-1 power production

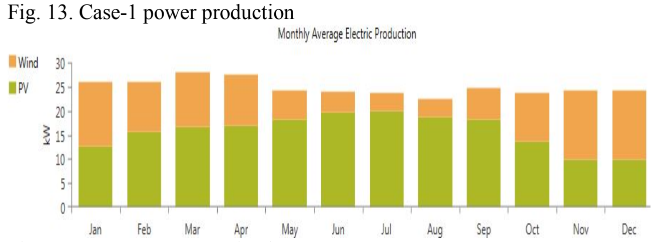

Fig. 14. Case-2 power production

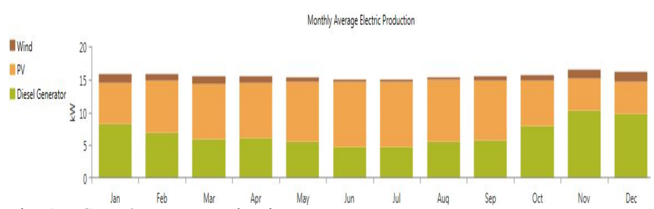

Fig. 15. Case-3 power production

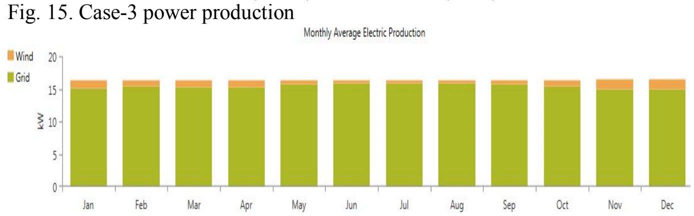

Fig. 16. Case-4 power production

3) *Effects of EVCS configurations on environmental emissions*

As one of the main goals of this work is to lessen the emission of the system, it makes sense to expect that the renewable based EVCS (Case-2) will have the lowest emission. This is shown in Table 7. While Case-3 emits more than renewable based EVCS, it will still have lower emission than diesel-based EVCS.

Table 7 Comparison of emission

Pollutant	Case-1	Case-2	Case-3	Case-4
Emissions, kg/yr				
Carbon dioxide	159351	1947	50133	86847
Carbon monoxide	995	0	298	0
Unburned hydrocarbons	44	0	13	0
Particulate matter	6	0	2	0
Sulfur dioxide	322	4	101	368
Nitrogen oxides	935	0	280	176

B. Sensitivity analysis

1) Effect of CO_2 penalty in the NPC and the share of renewable energy

As it was mentioned in section 3, the penalty on carbon dioxide emission was studied. Fig.17 shows that as the penalty on CO_2 increases the NPC increases. The renewable energy fraction stays unchanged for a small amount of penalty below \$30/ton. However, as the penalty increases above \$30/ton amount the fraction of renewable energy increase until it reaches 84% of renewable fraction at a penalty of \$45/ton where it stays unchanged even for higher penalty.

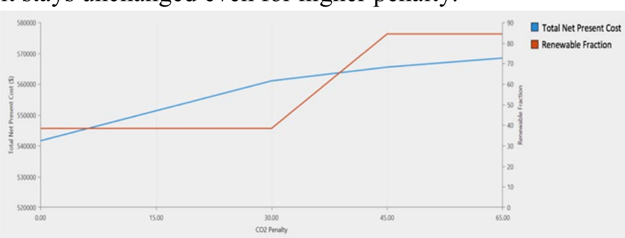

Fig. 17. Effect of CO_2 penalty in the NPC and renewable fraction

2) Optimal break-even distance

As it has been shown in previous analysis that from the island EVCS, Case-3 was the most economical. If we assume that this case may be connected to the external grid due to the availability and reliability of grid connection, then the distance of the EVCS will play a key role in the NPC. Fig. 18 shows that the NPC with a grid connectivity option increases as the distance increases between the grid and the point of connection but it has a lower cost compared to the one without an external grid option for up to 17.9 km in this case.

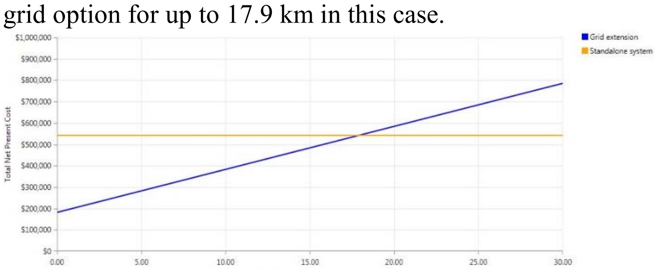

Fig. 18. Effects of grid connectivity distance in NPC

VII. Conclusion

An optimal design configuration for EVCS was discussed in this paper. Various supply options were considered such as: PV, wind, diesel generator and battery. The analysis has been done using HOMER software with different case studies. The results indicate that the most economical islanded EVCS is the diesel renewable mix. Although this option has higher emission than the renewable based EVCS, still the emission is lower than the diesel based EVCS. It has also shown that as the penalties in the emission increase that will lead to an increase in the percentage of renewable energy used in the system. The possibilities of relying on the external grid have been studied in this paper, and it was shown that with this option the excess of generated energy from renewable resources can be sold back to the grid. Analysis has been made to find the breakeven extension distance.

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