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Optimal design of electric vehicle charging stations considering various energy resources

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ABSTRACT

In this paper the optimal design of an Electric Vehicle Charging Station (EVCS) with the goal of minimizing the lifecycle cost, while taking into account environmental emissions, is presented. Different energy sources such as renewable energy technology based and diesel generation are considered, with realistic inputs on their physical, operating and economic characteristics. In order to address the "range anxiety", concern of EV owners regarding the distance the vehicle can travel, the design of an EVCS along highways, as an isolated microgrid, is studied. In another study, the EVCS is assumed to be connected to the grid as a smart energy hub. The charging demand of the EVCS is estimated considering real drive data. Analysis is also carried out to compare the economics of a grid-connected EVCS with an isolated EVCS and the optimal break-even distance for the grid connected EVCS to be a viable option, is determined.

1. Introduction

The global demand for energy has been increasing rapidly, which impose a large burden on the existing energy resources, and adversely impacts the environment and global warming. As governments around the world move toward a green energy economy, Plug-in Electric Vehicles (PEVs) have an increasingly important role to play, because of their contribution to emissions reduction from the transport sector. As stated by the Ministry of Transportation, Ontario, Canada, the province is investing $20 million from its Green Investment Fund to build nearly 500 electric vehicle charging stations (EVCSs) at over 250 locations in Ontario by 2017 [1]. Ontario government is also encouraging investments in renewable energy sources (RES), through the existing Feed-In-Tariff (FIT) program [2]. Thus, there is need to examine the optimal design of EVCS in the presence of RES.

RES combined with PEVs present significant potential in solving environmental and economic problems. Several studies discussed the integration of PEVs with RES in the context of system operations. A multi-year, multi-objective planning model which minimizes Greenhouse Gas (GHG) emissions and system costs over the planning horizon is proposed in Ref. [3], to determine the optimal level of PEV penetration as well as the location, size, and year of installation of renewable Distribution Generation (DG) units. A two-stage stochastic operations model for a microgrid is developed in Ref. [4] to determine the optimal energy scheduling for DGs and distributed energy storage devices. The impact of PEVs on microgrid energy scheduling under various charging schemes is also discussed. In Ref. [5], the expected grid operation cost is minimized while considering the random behavior of PEVs in a stochastic security-constrained unit commitment model. It is concluded that power systems can mitigate the variability of RESs and reduce grid operation costs by smart coordination of the storage capability of PEVs. A conceptual framework and an optimization methodology for designing grid-connected systems that integrate PEV chargers, RES, and Li-ion storage is presented in Ref. [6]. A PEV charging policy, which makes economic charging decisions every 5 min based on real-time market price signal, considering transmission and distribution integration issues and solar PV output, is proposed in Ref. [7]. It is shown that the PEVs provide voltage support to the distribution system and allow increased penetration of distributed solar PV arrays and hence defer distribution network upgrades. The optimal size of local energy storage for a Plug-in Hybrid Electrical Vehicle (PHEV) charging facility and control strategy for its integration with PHEV charging stations and a solar PV system is proposed in Ref. [8]. It provides general guidance and pathways to solve two major technical challenges-local energy storage device

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Nomenclature

x	Index for EVCS supply component options (solar PV, converter, diesel generator, battery energy storage system (BESS), grid connection)
N	EVCS project life, yr
N_x	EVCS component life, yr
i	Annual real interest rate (the discount rate), %
$PWF(i,N)$	Present worth factor
$TNPC$	Total net present cost, \$
AC_x	Total annualized cost of component x, \$/yr
AC_{Cx}	Annualized capital cost of component x, \$/yr
C_{Cx}	Initial capital cost of component x, \$
AC_{Rx}	Annualized replacement cost of component x, \$/yr
C_{Rx}	Replacement cost of component x, \$
$SFF(i,N)$	Sinking fund factor
S_x	Salvage value of component x at the end of the project life, \$
N_{Rx}	Remaining life of component x at the end of the project life, yr
AC_{OMx}	Annual O&M cost of component x, \$/yr
η_{Boiler}	Boiler efficiency
C_{Fuel}	Cost of fuel for boiler, \$/kg
LHV_{Fuel}	Lower heating value of the boiler fuel, kWh/kg
C_{Boiler}	Cost of thermal energy from the boiler, \$/kWh
E_{Grid}	Electricity sold to the grid by EVCS, kWh/yr
E_{EVCS}	Electrical energy demand of the EVCS, kWh/yr
$E_{Thermal}$	EVCS thermal energy demand, kWh/yr
NPC	Net present cost, \$
COE	Levelized cost of energy, \$/kWh

sizing and system control strategies. A mathematical model based on particle swarm optimization and interior point method is formulated to address an economic dispatch problem, taking into account the uncertainties of PEVs and wind generators [9]. An aggregated battery storage model is used in Ref. [10] to investigate the application of PEVs as regulation power providers with high wind power penetrations. It is noted that optimal charge/discharge of PEVs can minimize their energy costs, and provide regulation power for both high and low wind speed days. To optimize the wind capacity in order to minimize the total cost that includes customer interruption cost and annual generation cost, a reliability/cost evaluation model is proposed in Ref. [11]. Different numbers of PEVs are considered to minimize the total distribution system cost. It is concluded that the proposed reliability/cost model can help in planning of distribution systems considering RES and PEVs.

The novel features and contributions of our paper, over and above other papers that have reviewed in the literature, as follows:

- Most of the papers focused on the impact of charging PEVs on the grid, and aspects of EVCS design while neglecting the economic feasibility of this investment.
- There is a need to examine how the EVCS can be operated as an isolated microgrid considering different supply options including renewable energy resources, and as a smart energy hub.
- None of the reported papers examined and compared the economics of a grid-connected EVCS with an isolated EVCS, nor determined the optimal break-even distance for the grid connected EVCS to be a viable option. Moreover, different EVCS configurations are studied in this work considering real drive data of PEVs.

In view of the above discussions, the main objectives of this paper can be outlined as follows:

- Determine the optimal design of an EVCS considering various RES technology options and diesel generation with realistic inputs on their physical, operating and economic characteristics.
- Determine the break-even distance for connection of the EVCS with the main grid and compare that with the cost of an isolated EVCS. Compare the same with an optimally designed EVCS with renewable energy based supply options and grid connected configuration.

The rest of the paper is organized as follows: Section 2 presents the problem definition, Section 3 briefly discusses the system under consideration and different cases considered for optimal EVCS design. The system input data is presented in Section 4. In Section 5 the EVCS design results are presented and discussed. Finally, Section 6 presents the summary and conclusions of this paper.

2. The mathematical model

The mathematical models used herein for the different system configurations are available in HOMER [12]. The model inputs are the EVCS load demand (both electric and thermal), the solar energy availability profile of the region, and the cost and size data of all system components considered. The software then considers different dispatch strategies that yield the minimum project cost for each EVCS configuration. The optimal EVCS design is determined by minimizing the total net present cost (NPC) comprising the capital cost, replacement cost, operation and maintenance (O&M) cost, fuel consumption cost, and cost of purchased power from the grid. Fig. 1 presents the general architecture of EVCS design using HOMER.

It is noted from Fig. 1 that the EVCS design using HOMER comprises the INPUT, MODEL, and OUTPUT modules. The INPUT module develops the information pertaining to all energy supply options, cost data, PEV related data to estimate the charging demand, etc. The MODEL module is a linear optimization to determine the least-cost design option, with significant degrees of flexibility in choosing and applying the constraints. The OUTPUT module provides the optimal EVCS design configuration with associated analytical results.

The objective of minimization of the total NPC is given as follows:

$$TNPC = \sum_{\in x} AC_x \times PWF(i,N) \tag{1}$$

where the total NPC of the EVCS is the total present value of all the component costs, and the present worth factor (*PWF*) is given as follows [13]:

$$PWF_{(i,N)} = \frac{(1+i)^N - 1}{i(1+i)^N} \tag{2}$$

and the total annualized cost of the EVCS is the sum of the annualized costs of each component x. The annualized cost of an EVCS component x comprises the O&M cost, capital, and replacement costs, annualized over the EVCS life, and is given as follows:

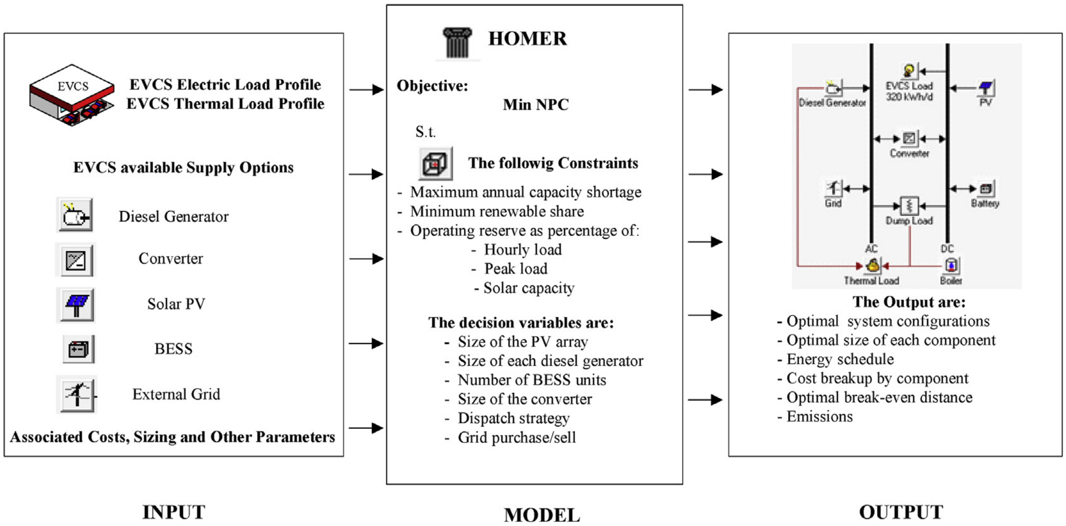


Fig. 1. Architecture of EVCS design using HOMER [12].

$$AC_x = AC_{Cx} + AC_{Rx} + AC_{OMx} \tag{3}$$

where the annualized capital cost of component x is given as follows:

$$AC_{Cx} = \frac{C_{Cx}}{PWF(i, N)} \tag{4}$$

In (3) the annualized replacement cost is calculated as follows:

$$AC_{Rx} = C_{Rx} \times SFF(i, N_x) - S \quad \times SFF(i, N) \tag{5}$$

It is to be noted that the replacement cost of a component may be different from its initial capital cost. The sinking fund factor (SFF) is a ratio used to calculate a series of equal annual cash flows from its future value and is given as follows [13]:

$$SFF(i, N) = \frac{i}{(1+i)^N - 1} \tag{6}$$

Also, noted that the component life can be different from the project life, and the salvage value is the value remaining in a component at the end of the project life and is calculated as follows:

$$S = C_{Rx} \times \frac{N_{Rx}}{N_x} \tag{7}$$

Note that if the EVCS is connected to the grid, electricity purchase and sales need to be accounted for in the annual O&M cost. Finally, the levelized cost of energy (COE) is obtained as follows:

$$COE = \frac{\sum_{\in x} AC_x - C_{Boiler} E_{Thermal}}{E_{EVCS} + E_{Grid}} \tag{8}$$

In (8), the total annualized cost, net of the cost of serving the EVCS thermal load is divided by the total useful electric energy production which comprises the EVCS electrical energy demand and the amount of electricity sold to the grid by the EVCS. Also, in (8) C_{Boiler} is the cost of thermal energy from the boiler (applicable if the boiler is supplying EVCS thermal load) and is calculated as follows:

$$C_{Boiler} = \frac{C_{Fuel}}{\eta_{Boiler}\, LHV_{Fuel}} \tag{9}$$

The technical constraints that are included in the charging station design are as follows:

- The maximum annual capacity shortage is assumed to be 0%, which means that the charging station has to meet the annual load all the time.
- The share of minimum renewables is assumed to be 0%, which means the charging station can be operated without considering any renewable energy resources.
- The operating reserve requirement is determined from the sum of three components:
- 10% of hourly load, which means the system must ensure enough operating reserves to serve up to 10% sudden increase in the load.
- 0% of the peak load, which means the operating reserve requirement is independent of the peak load; however, any p%, non-zero value can also be used, if the operating reserve is expected to cater up to a p% increase in peak load.
- 50% of solar power output, which means the system must ensure enough operating reserve to serve the load even if the PV array output suddenly decreased by 50%.

2.1. The hybrid optimization platform (HOMER)

The Hybrid Optimization platform (HOMER) is a simulation tool developed by the (U.S.) National Renewable Energy Laboratory (NREL) to assist in the planning and design of renewable energy based microgrids. The physical behavior of an energy supply system and its lifecycle cost, which is the sum of capital and operating costs over its lifespan, is modeled using HOMER [12]. Options such as distributed generation (DG) units, stand-alone, off-grid and grid-connected supply systems for remote areas, and other design options, can also be evaluated using HOMER [12]. HOMER is designed to overcome the challenges of analysis and design of microgrids, arising from the large number of design options and the uncertainty in key parameters, such as load growth and future fuel prices. Simulation, and optimization analysis, are the two principal tasks performed in HOMER and used in this work.

Where, on the aspect of simulation, HOMER determines the technical feasibility and lifecycle costs of a microgrid for each hour of the year. In addition, the microgrid configuration and the operation strategy of the supply components are tested to examine how these components work in a given setting over a period of time. The simulation capability of HOMER captures the long-term operation of a microgrid. The optimization component of HOMER depends on this simulation capability.

In the optimization section, HOMER determines the feasible systems with their configurations under the search space defined by the user, sorted by the minimum total net present cost of the microgrid. After the simulation section determines the system configuration of a microgrid, the optimization section calculates and displays the optimal microgrid configuration. HOMER defines the optimal microgrid configuration, which is that configuration with the minimum total net present cost and meeting the modeler's constraints [12].

3. Case studies

Renewable energy technology option, diesel generation, and the option of EVCS being connected to the grid are considered to determine the optimal design of EVCS. Two different cases based on the different supply options are examined, as follows:

3.1. Case-1: isolated EVCS

This case helps address the "range anxiety", which is a common concern of EV owners regarding the distance the vehicle can travel, and EV owners can plan longer trips with more confidence if an EVCS is as readily available as a gas station [1]. Therefore, the design of an EVCS along highways as an isolated microgrid with different supply options such as, solar PV, diesel generation, and battery energy storage system (BESS) is studied and considered as Case-1. The system configuration of Case-1 is presented in Fig. 2, and the EVCS design objective is to minimize the total capital, O&M, replacement and fuel costs, of each component of the system. The decision variables are the size of the diesel generator, solar PV array, battery bank, and converter. The EVCS thermal load is assumed to be served by the boiler, or the waste heat recovery system of the diesel generator, or excess energy from other sources; the optimal supply options is selected by the model.

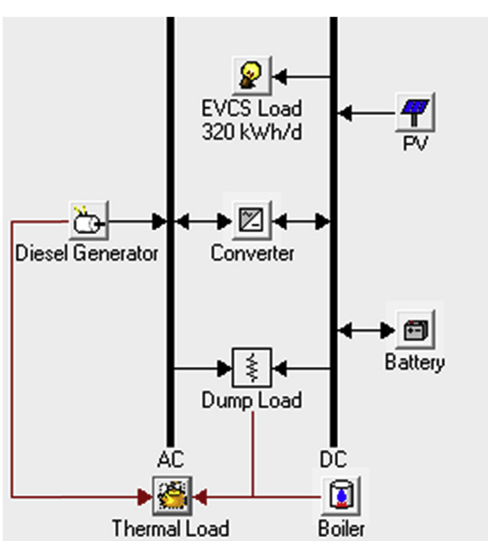


Fig. 2. Available portfolio of energy supply options in Case-1.

3.2. Case-2: Grid connected EVCS as a smart energy hub

In this case, the EVCS is assumed to be connected to the grid as a smart energy hub with different supply options such as solar PV, diesel generation, BESS, and grid. Fig. 3 presents the proposed system configuration. The smart EVCS design objective is to minimize the total cost of capital, O&M, replacement, and fuel costs, associated with each component in the system. The decision variables are the size of the diesel generator, solar PV array, battery bank, and converter. Since the EVCS can purchase and sell power from and to the grid, the model is modified to consider the net costs (purchases minus sales) of the EVCS. The prices offered in the FIT program of Ontario, Canada, are considered for purchase and sell energy from and to external grid [2]. Ontario government is encouraging investments in renewable energy sources, through the existing Feed-in-Tariff (FIT) program [2]. Feed-in Tariffs refer to the prices paid to renewables based energy suppliers for the electricity produced by their generating facility. The pricing structure provides a reasonable return on investment and is differentiated by the project size and technology type. The Feed-in-Tariff is a fixed price for both purchase and sellback power from/to the external grid over the contract duration (typically 20 years). On the other hand, the Time-of-Use (TOU) tariff is applicable to customers only, and is totally different from FIT, and changes during the day with time. We have considered FIT in this work. The optimal EVCS thermal load supply options are determined based on the system configurations assumed in this case. Table 1 presents a summary of all the cases considered in this paper.

4. System input data

4.1. EVCS load

The EVCS load profile is obtained from Drive-4-Data [14], which is a real-world dataset for PEVs maintained by the Waterloo Institute for Sustainable Energy (WISE) at the University of Waterloo. Participating Drive-4-Data drivers have a CrossChasm Technologies C5 Vehicle Datalogger attached to their vehicles, which collects, via wireless-cellular, a minimum of PEVs speed as a function of time, drive cycle and powertrain information, such as vehicle acceleration, and battery SOC. Furthermore, the Datalogger can also provide GPS data, enabling access to the vehicle's driving routes and location which is needed by researchers to determine optimal EVCS locations [14]. In this work the 2013 Chevrolet Volt drive cycles from May 2013 to May 2014 with 16 kWh battery capacity is used to

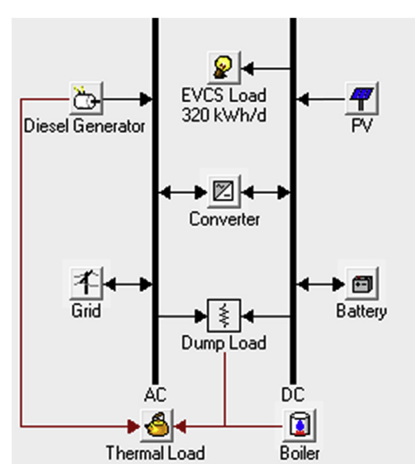


Fig. 3. Available portfolio of energy supply options in Case-2.

Table 1
Summary of cases.

Case	Description of case
1	Isolated EVCS (a) Diesel Based (b) Solar PV with BESS (c) Diesel-Solar PV-BESS Mix
2	Grid Connected EVCS as a Smart Energy Hub (a) Diesel Based (b) Solar PV with BESS (c) Diesel-Solar PV-BESS Mix

generate the PEV charging demand profile. The total number of PEVs assumed to arrive for charging at the EVCS is 20.

Furthermore, NHTS 2009 [15] data for light-duty vehicles is used to distribute the PEV charging demand over the day; with the arrival destination being to buy gas at the gas-station, assuming that PEVs have the same pattern for arriving at the EVCS for charging their vehicles. The normalized hourly distribution of PEVs arriving for charging is presented in Fig. 4.

4.2. Thermal load

The total daily thermal energy demand of the EVCS is assumed to be only 10% of the EVCS electrical energy demand. Thermal load is included in this work to understand how the EVCS can consider the thermal loads to heat the charging station market center, service center, and meet hot water needs of customers, especially in Canadian winters. The value of 10% is assumed in this work to understand the impact of the thermal loads on the operation of EVCS and what supply options can be used to feed this demand. Since data pertaining to thermal loads at EVCSs are still very limited, it is assumed that these loads can be represented as a simple percentage of the electrical demand. However, the developed modeling framework is generic and other realistic % value, from an EVCS, may be used to determine the actual impact and supply options of thermal load. A 24-h Load Scale Factor (shown in Fig. 5) is assumed for the thermal base load and the daily load profile is obtained. Thereafter, the EVCS thermal load profile for each day of the year is obtained by adding daily and hourly noise, by randomly drawing a daily perturbation factor from a normal distribution with a mean of zero and a standard deviation of 15%. In addition, it randomly draws the hourly perturbation factor from a normal distribution with a mean of zero and a standard deviation of 20% [12]. The scaled annual thermal energy demand average is 32 kWh/d with a load factor of 0.41. In this work the thermal load is assumed to be served by the boiler, or by the diesel generator from which waste heat can be recovered, as well as excess energy from other sources.

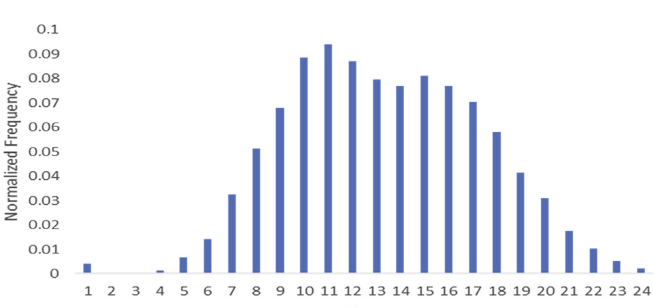


Fig. 4. Arrival of PEVs at EVCS over the day.

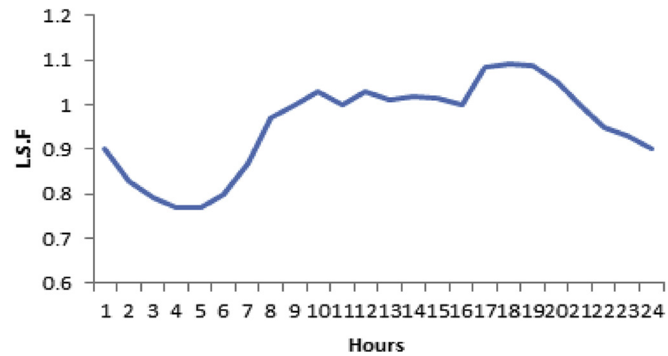


Fig. 5. Load scale factor for hourly thermal load profile of EVCS.

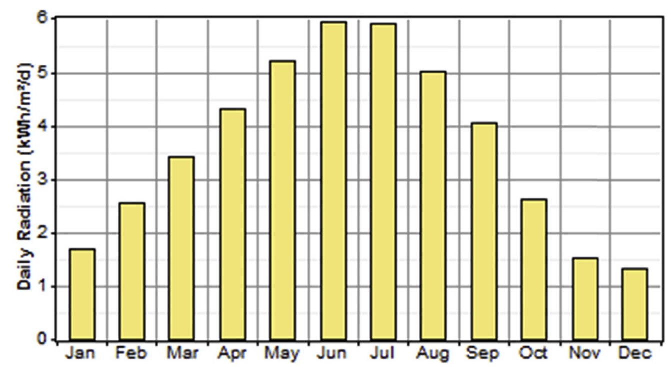


Fig. 6. Solar radiation profile for Waterloo.

4.3. Solar resource

The solar radiation data of Waterloo, Ontario, (43° 39′ N, 80° 32′ W) is considered, which is obtained from the NASA Surface Meteorology and Solar Energy website [16]. The annual average solar radiation for this area is 3.64 kWh/m^2/day. Fig. 6 shows the month-wise average solar radiation profile over a one-year period.

Capital and replacement costs of PV panel include shipping, tariffs, installation, and dealer mark-ups are considered. Some maintenance is typically required on the solar PV panels. A derating factor of 90% reduces the solar PV production by 10% to account for varying effects of temperature and dust on the panels.

4.4. Input data (costs, sizing and other parameters)

In Table 2 the capital cost, replacement cost and O&M cost of each supply option considered, are presented, while the different sizing options and other associated parameters are presented in Table 3.

4.5. Economics

The annual real interest rate is considered to be 6%. The real

Table 2
Cost data of energy supply resources [17].

O&M cost	Replacement cost	Capital cost	Options
$10/year	$7.50/W	$7.50/W	Solar
$2/Battery/year	$75/Battery	$75/Battery	Battery
$100/year	$1000/kW	$1000/kW	Converter
$10/year/km	$20,000/km	$20,000/km	Grid Extension
$0.15/h	$2550	$2550	Diesel Generator (4.25 kW)

Table 3
Data on sizing and others parameters of energy supply resources.

Other information	Life	Options on size and unit numbers	Options
De-rating factor = 90%	20 yrs	1, 10, 50, 100, 150, 200, 300, 500 kW	Solar
Nominal capacity 225 A h	(Lifetime throughput)845 kWh	10, 50, 100, 200, 500, 1,000, 1500	Battery
Can parallel with AC generator.	15 yrs	0, 10, 50, 100, 200, and 500 kW	Converter
Converter efficiency = 90%			
Rectifier efficiency = 85%			
Purchase = $0.12/kWh	–	10, 25, 50, 100, 500, 1000 kW	Grid Connection
Sellback = $0.39/kWh [2]			
Minimum load ratio = 30%	500,000 h	0 to 500 kW	Diesel Generator
Heat recovery ratio = 10%			
Price = $0.70/L	–	–	Diesel Fuel
Density of 820 kg/m^3			
Carbon content 88%			
Sulfur content 0.33%			

interest rate is equal to the nominal interest rate minus the inflation rate. The project life is 25 years.

5. Results and discussions

In this section the different designs of EVCS are examined from the standpoint of economics, emissions, and operational performance. Two cases are considered as mentioned earlier, the isolated EVCS, and a grid-connected EVCS as a smart energy hub. The objective is to determine the optimal design of EVCS while minimizing the lifecycle cost, taking into account environmental emissions and considering various energy supply options.

In Case-1 the EVCS is assumed to be an isolated microgrid fed by diesel generators. Although this may seem to be as unrealistic scenario in a common situation, there are several countries where reliance on diesel as primary energy source is very significant, *i.e.*, Saudi Arabia. In such circumstances, diesel option is a relevant example. However, diesel generator units are very expensive because of their high cost of maintenance, fuel supply, and fuel transportation. In addition, the diesel generators are emission intensive. Therefore, supplying the EVCS with solar PV and BESS sources is also examined; Accordingly, the EVCS is assumed to be supplied by a mixed configuration comprising both diesel and solar PV sources. In Case-2 it is assumed that the EVCS is grid-connected and has the option of drawing/selling-back energy from/to the external grid, while also having its own resources.

5.1. Optimal plan configurations

The optimal EVCS design for each case is obtained from HOMER

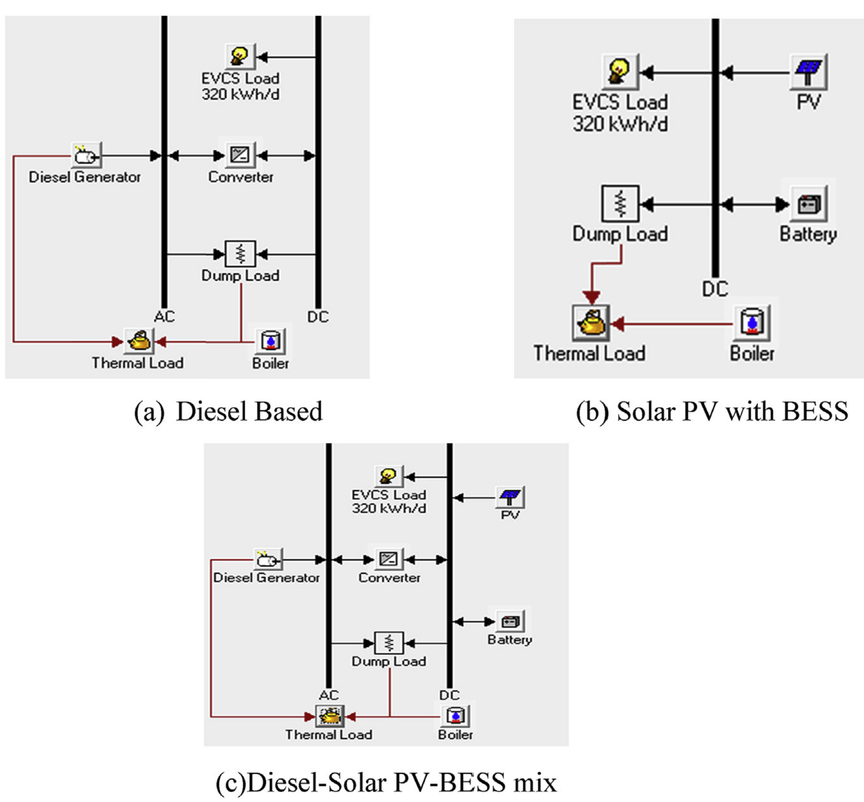
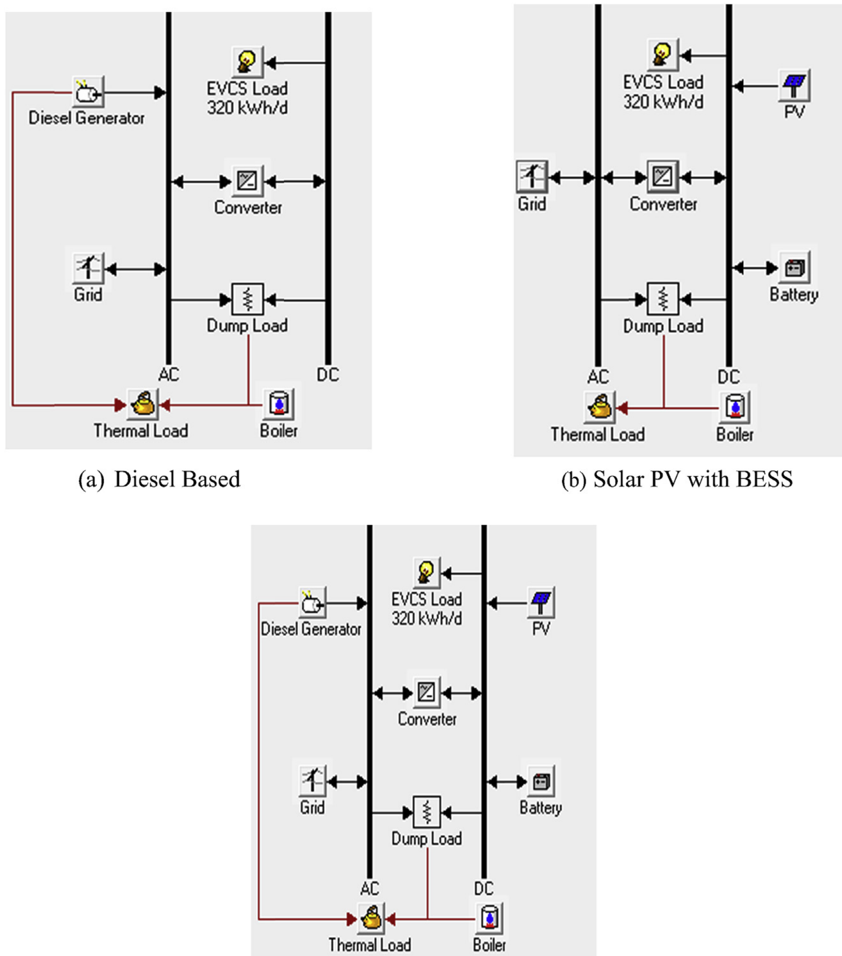


Fig. 7. Optimal EVCS configurations in Case-1: Isolated EVCS.



(a) Diesel Based

(b) Solar PV with BESS

(c) Diesel-Solar PV-BESS mix

Fig. 8. Optimal EVCS configurations in Case-2: Grid connected EVCS.

simulations, using the parameters described in the previous section, and the optimal configurations are shown in Fig. 7 and 8. The corresponding details of the optimal EVCS plans for the two cases are presented in Table 4.

Table 4
Optimal EVCS design.

Component	Case-1			Case-2		
	(a)	(b)	(c)	(a)	(b)	(c)
Diesel, kW	100	0	50	100	0	100
Solar PV, kW	0	300	50	0	250	10
Converter, kW	50	0	50	50	50	50
Battery, numbers	0	1000	500	0	1000	1000
Purchase from grid, kW	0	0	0	50	50	50
Sell to grid, kW	0	0	0	10	10	10

Table 5
Comparison of cost components.

Component	Case-1			Case-2		
	(a)	(b)	(c)	(a)	(b)	(c)
Net present cost, M$	1.617	2.724	0.945	1.020	2.138	0.835
Levelized COE energy, $/kWh	1.075	1.816	0.625	0.675	1.476	0.551
O&M Cost, M$/year	0.118	0.031	0.035	0.071	0.011	0.045

As can be seen from the optimal configurations and design plans, in Case-1, while the diesel dependent EVCS Case-1(a) selects diesel generation to meet its demand, the renewable based EVCS Case-1(b) relies on solar PV, and BESS only. The diesel-solar PV-BESS mix EVCS Case-1(c) opts for a reduced diesel generation capacity and some solar PV capacity.

Case-2(a), the diesel dependent EVCS case selects diesel generation to meet its demand, with ability to drawing/selling energy from/to the external grid, as a smart energy hub. In addition to the grid-connected option the EVCS relies on solar PV, and BESS in Case-2(b). The diesel-solar PV-BESS mix EVCS Case-2(c) opts for a reduced solar PV capacity and drawing/selling energy from/to the external grid.

Table 5 shows the NPC, levelized COE, and the O&M costs for the different cases. It is noted that the NPC and the levelized COE are significantly low in Case-1(c) and 2(c) as compared with Case-1(a) and (b), and 2(a) and (b), and hence are the most favorable designs for isolated and grid-connected EVCS. When the EVCS is based on solar and BESS only, it is noted that the levelized COE is significantly high in both isolated and grid-connected EVCS Case-1(b) and 2(b) because of the large capital cost component. Although in the diesel dependent EVCS the levelized COE is reduced, to 1.075 $/kWh in Case-1(a) and to 0.675 $/kWh in Case-2(a), and it is higher than the diesel-solar PV-BESS mix because of the significantly high cost of fuel in diesel based EVCS, as shown in Figs. 9 and 10(a), and (c). It is

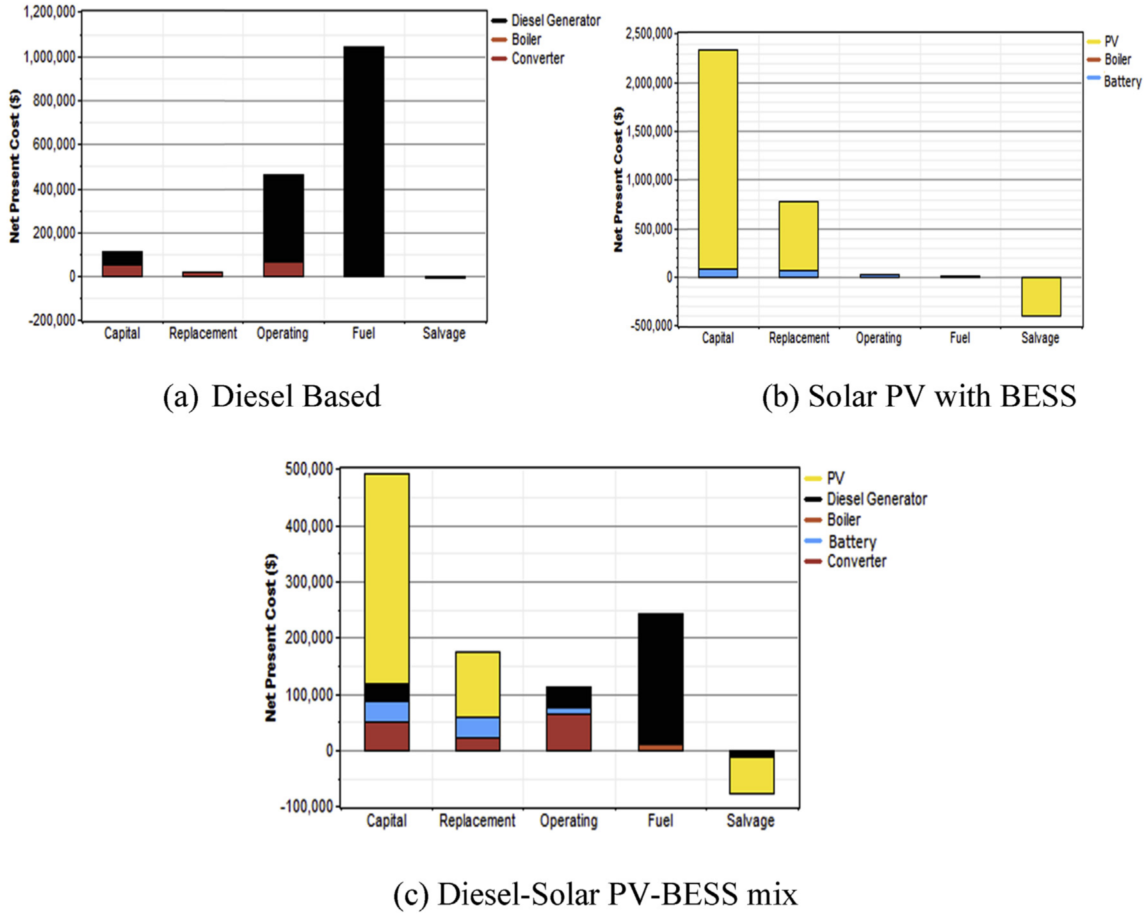


Fig. 9. Optimal cost components for Case-1: Isolated EVCS.

also to be noted that in Case-2 there is a negative O&M cost, which pertains to the revenue earned by the EVCS from selling power to external grid.

Fig. 11 and 12 presents the annual cash flows for the two cases, respectively. It is seen that in the diesel based EVCS (Case-1(a)) Fig. 11, the diesel generator and converter incur a capital cost at the beginning of the project, and converter incurs a replacement cost at year 15, while the system incurs a regular stream of fuel and O&M cost. However, in Case-1(b), the solar PV with BESS based EVCS only incurs an initial investment cost while the replacement cost is sporadically distributed over its lifetime (Fig. 11(b)) and the other costs are negligible. In Fig. 11(c), the cash flow pattern is similar to (b) with an additional regular stream accounting for cost of fuel and O&M arising because of the presence of diesel generator.

The annual cash flow of Case-2 is similar to Case-1, however because of the sellback power to the grid and associated revenue earnings by the EVCS, the O&M cost is significantly reduced (Fig. 12(a)). Also, the system incurs a regular high stream of fuel and O&M cost as compared to Case-1(c), because of the significant increase in diesel generation capacity (Fig. 12(c)).

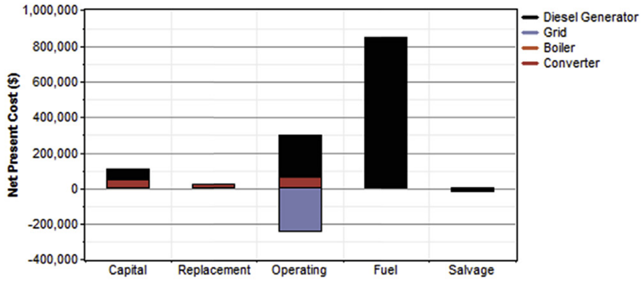
5.2. Optimal production and consumption profiles in various EVCS configurations

Comparisons of electrical energy production and consumption for various cases are presented in Fig. 13 and 14, and Table 6. As shown in Table 6, in the solar PV with BESS based EVCS (Case-1(b) and 2(b)), the total energy produced is much higher than other cases, and the EVCS has to transfer a substantial portion of the energy (excess energy) to resistive heating which can be used to serve a thermal load. This is because, solar PV energy is intermittent and non-dispatchable and the EVCS being fully reliant on these sources, is exposed to these risks. The diesel based EVCS (Case-1(a) and Case-2(a)) relies only on diesel which results in no excess energy, while Case-2(a) has the option of drawing/selling additional energy from/to external grid. In Case-2(c), the solar PV production is significantly reduced as compared with Case-1(c) and its energy contribution is only 8%, and the energy supply in this case mostly depends on diesel and external grid (Fig. 14(c)).

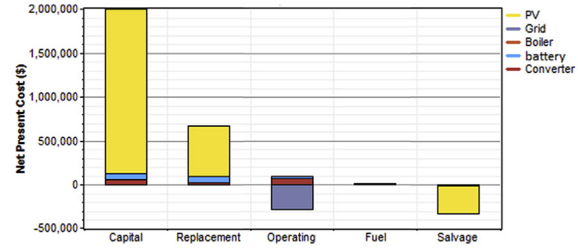
Table 7 presents the optimal operation of battery and converter for the two cases. The difference between the energy charge and discharge of battery, and in and out of converter in each case; is the losses and is reported in Table 6. For example, the BESS charging energy is 30,655 kWh/yr in Case-1(b) and the discharged energy is 26,490 kWh/yr, which implies a total loss of 4.165 MWh/yr. In Case-1(a) and 2(a) the optimal energy transferred from the diesel generator to EVCS through rectifier is presented.

5.3. Optimal energy supply options of EVCS thermal load

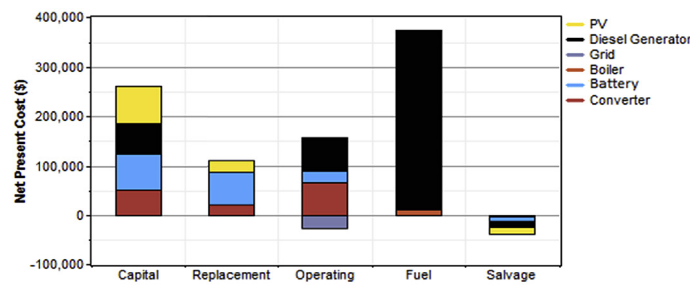
The EVCS thermal load is assumed to be supplied from different supply options which are boiler, waste heat recovery system of diesel generator, and excess energy from other sources. Fig. 15 and 16 and Table 8 presents the supply options used and the percentage of each to meet the EVCS thermal load in each case. It is noted that the EVCS thermal load is fed through the waste heat energy of



(a) Diesel Based

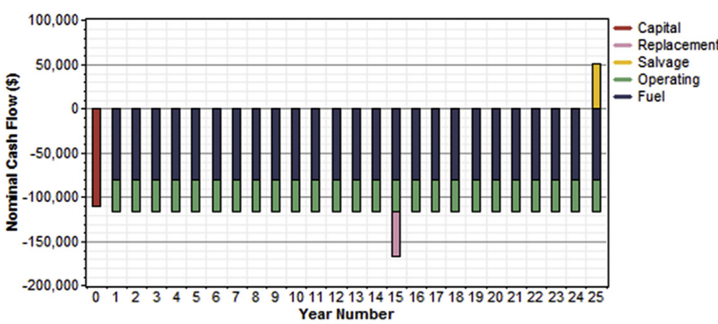


(b) Solar PV with BESS

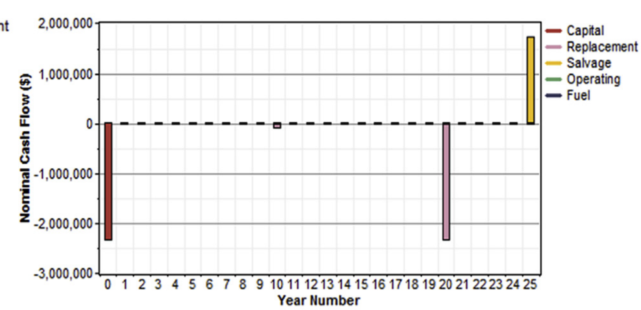


(c) Diesel-Solar PV-BESS mix

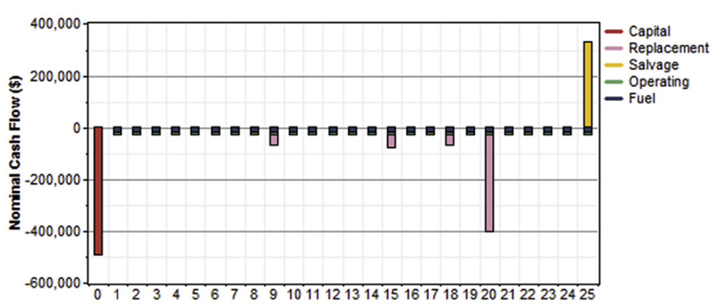
Fig. 10. Optimal cost components for Case-2: Grid connected EVCS.



(a) Diesel Basesd



(b) Solar with BESS



(c) Diesel-Solar PV-BESS mix

Fig. 11. Cash flow for Case-1: Isolated EVCS.

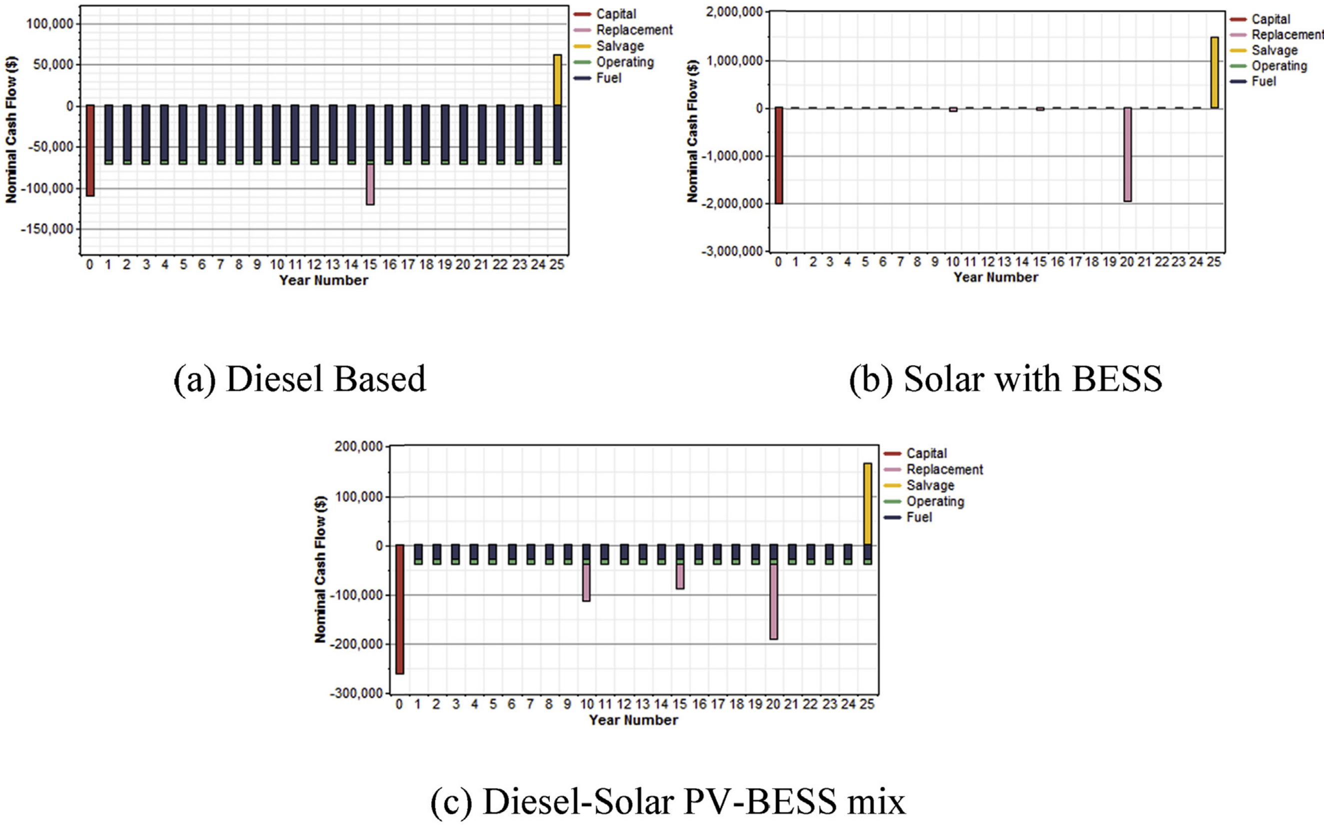


Fig. 12. Cash flow for Case-2: Grid connected EVCS.

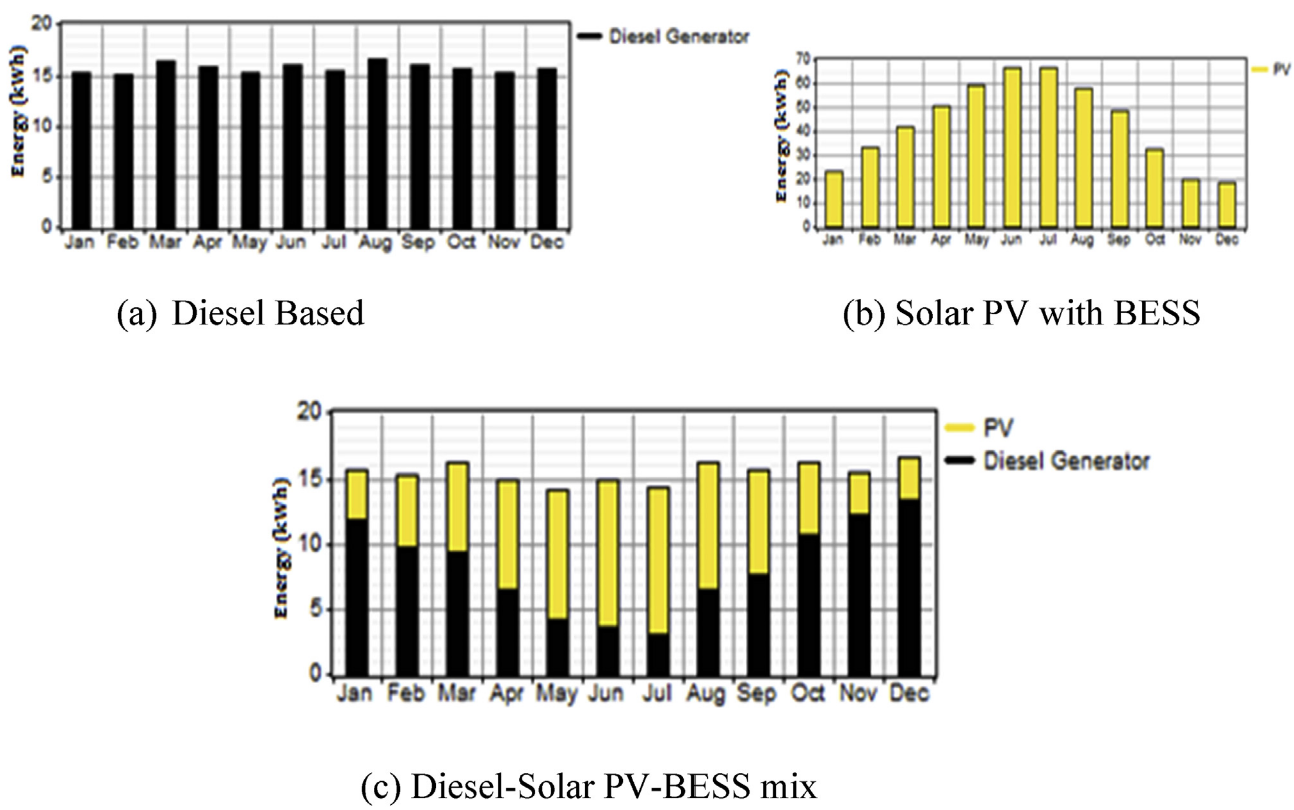
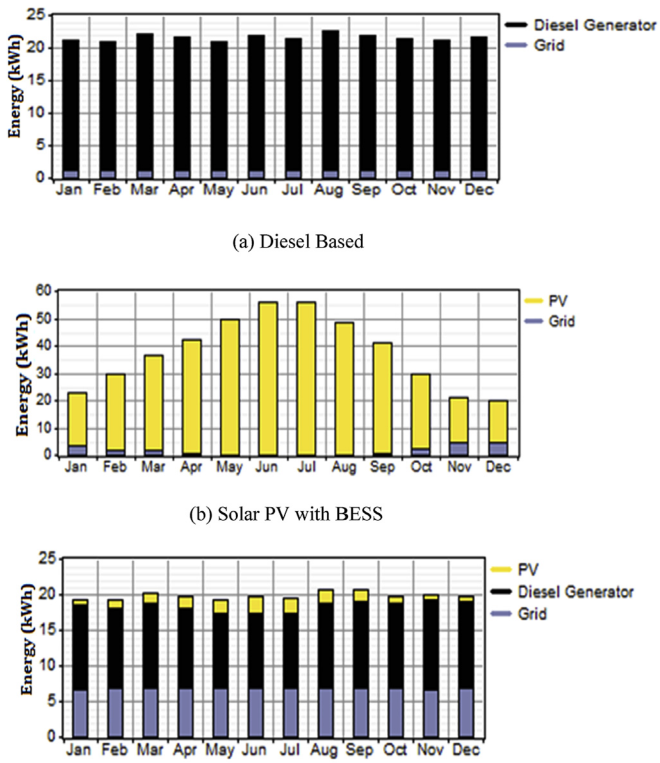


Fig. 13. Power production for Case-1: Isolated EVCS.



(a) Diesel Based

(b) Solar PV with BESS

(c) Diesel-Solar PV-BESS mix

Fig. 14. Power production for Case-2: Grid connected EVCS.

diesel generator in Case-1(a) and 2(a); while the excess energy and boiler are the supply options in Case-1(b) and 2(b). In Case-1(c) and 2(c), waste heat energy of diesel generator and boiler mix is used to supply the EVCS thermal load.

5.4. Effect of distance from grid and the optimal breakeven distance

In this analysis, the distance of the proposed EVCS site is taken into consideration and the optimal plans with all different supply options of the isolated EVCS (Case-1) are determined assuming that the EVCS can draw power from the external grid. Fig. 17 shows that the NPC of diesel based EVCS in Case-1(a), with grid connectivity option, is significantly less when the EVCS is very close to the external grid point of connection (say, zero kilometers). As the grid connectivity distance increases, the NPC increases, but remains lower than the one without external grid option for up to 69.9 kms. Beyond that, it is no longer economical for the Case-1(a) to connect to the external grid. However, in Case-1(b), the break-even distance is significantly increased and is beyond 125 kms, when it is no longer economical to connect to the external grid (Fig. 18). On the other hand, in Case-1(c), the break-even distance is only 36.6 kms (Fig. 19).

5.5. Comparison of environmental emissions from various EVCS configurations

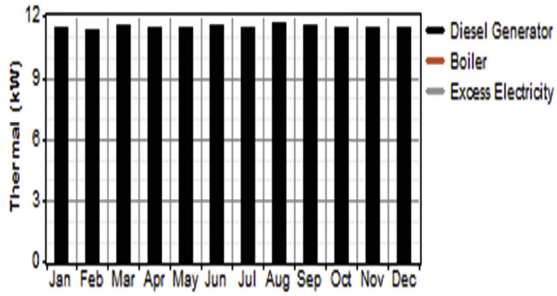
As mentioned before, one of the main objectives of this work is to reduce emissions by using green energy sources. The results presented in Table 9 show that the solar PV with BESS based EVCS in both cases significantly reduces the total system emissions (Case-1(b) and 2(b)) as compared to all others cases. However, although diesel-solar PV-BESS mix emits more than the solar PV with BESS based, it is still quite environmentally friendly when compared to the only diesel based option.

Table 6
Comparison of energy production and consumption.

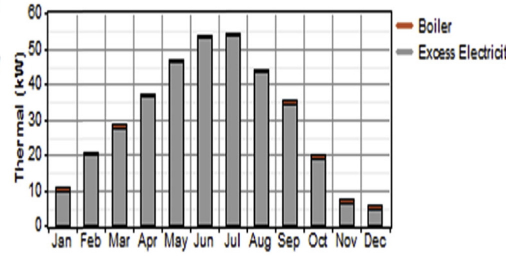
Component	Case-1			Case-2		
	(a)	(b)	(c)	(a)	(b)	(c)
Production, MWh/yr						
Diesel generator	137.387 (100%)	0	71.769 (53%)	178.689 (95%)	0	101.121 (58%)
Solar PV	0	153.386 (100%)	63.326 (47%)	0	216.732 (96%)	12.669 (8%)
Drawn energy from external grid	0	0	0	10.399 (5%)	14.207 (4%)	59.924 (34%)
Renewable energy contribution	0%	100%	47%	0%	96%	8%
Total	137.387	153.386	135.095	189.088	230.939	173.714
Consumption, MWh/yr						
EVCS electrical load energy served	116.779	116.779	116.779	116.779	116.779	116.779
EVCS thermal load energy served	11.680	11.680	11.680	11.680	11.680	11.680
Energy sell back to grid	0	0	0	51.700	63.033	23.898
Excess energy (as resistive heating)	0	32.442	0	0	20.551	0
Losses	20.608	4.165	18.316	20.609	30.576	33.037

Table 7
Optimal operation of battery and converter of EVCS.

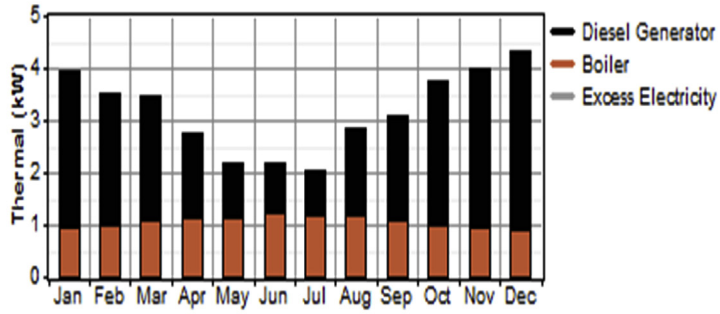
Component (kWh/yr)	Case-1			Case-2		
	(a)	(b)	(c)	(a)	(b)	(c)
Battery energy, charge	–	30,655	52,988	–	76,807	66,509
Battery energy, discharge	–	26,490	45,438	–	66,161	57,244
Inverter energy, in	–	–	–	–	70,032	13,607
Inverter energy, out	–	–	–	–	63,033	12,246
Rectifier energy, in	137,387	–	71,769	137,388	14,207	149,413
Rectifier energy, out	116,779	–	61,003	116,779	12,076	127,002



(a) Diesel Based

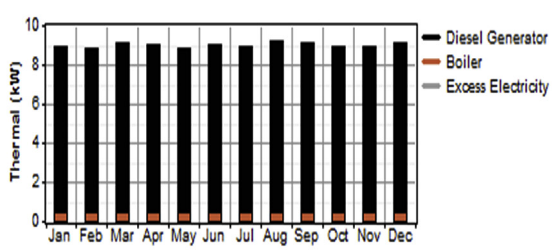


(b) Solar PV with BESS

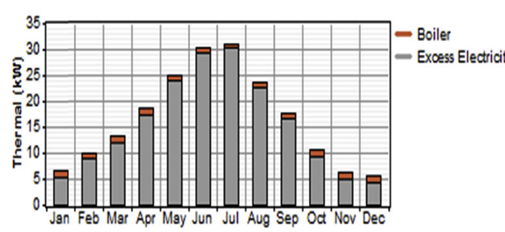


(c) Diesel-Solar PV-BESS mix

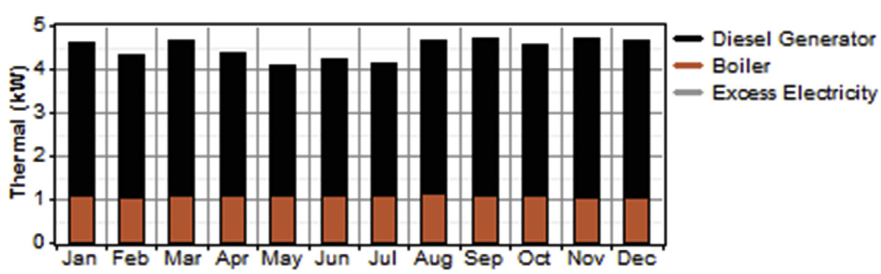
Fig. 15. Optimal supply options of EVCS thermal load for Case-1:Isolated EVCS.



(a) Diesel Based



(b) Solar PV with BESS



(c) Diesel-Solar PV-BESS mix

Fig. 16. Optimal supply options of EVCS thermal load for Case-2: Grid connected EVCS.

Table 8
Optimal EVCS thermal load sources.

Source	Case-1			Case-2		
	(a)	(b)	(c)	(a)	(b)	(c)
Boiler	0	3%	34%	5%	7%	24%
Generator waste heat energy	100%	0	66%	95%	0	76%
Excess energy from other sources	0	97%	0	0	93%	0

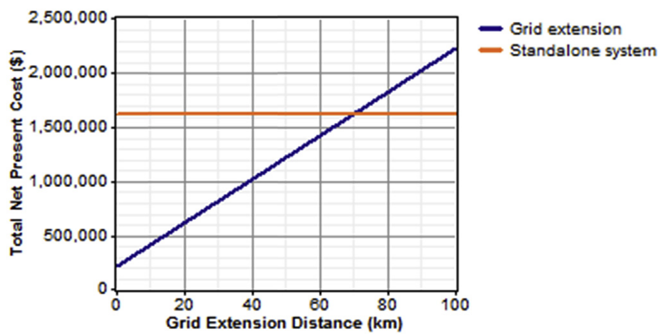


Fig. 17. Variation of NPC with grid connectivity distance for Case-1(a).

6. Summary

This paper presented the optimal design and comparative studies for an isolated EVCS, and a grid connected EVCS as a smart energy hub configuration. Various supply options were included in this study such as diesel based, solar PV with BESS based and diesel-solar PV-BESS mix. Studies were carried out using the HOMER software which provides a very efficient tool for case studies and policy analysis. From the methodology, data, results,

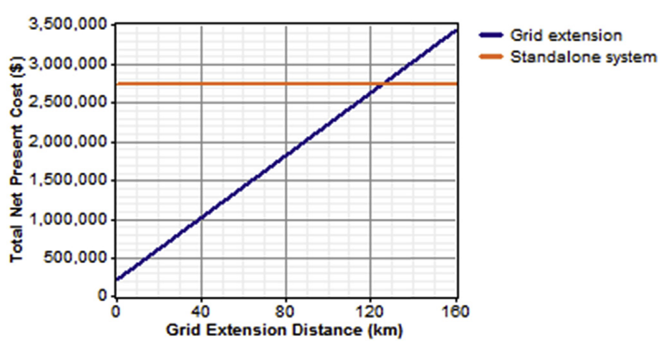


Fig. 18. Variation of NPC with grid connectivity distance for Case-1(b).

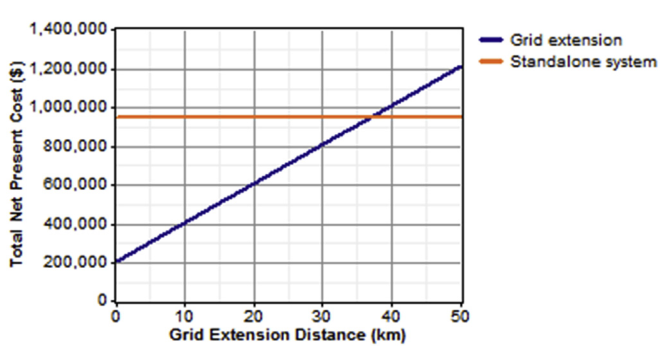


Fig. 19. Variation of NPC with grid connectivity distance for Case-1(c).

Table 9
Case-wise comparison of emissions.

Emissions, kg/yr						
Pollutant	Case-1			Case-2		
	(a)	(b)	(c)	(a)	(b)	(c)
Carbon dioxide	305,589	2417	71,594	223,488	9815	132,613
Carbon monoxide	754	0	169	613	0	264
Unburned hydrocarbons	83.6	0	18.8	67.9	0	29.2
Particulate matter	56.9	0	12.8	46.2	0	19.9
Sulfur dioxide	614	4.94	144	388	12.8	319
Nitrogen oxides	6731	0	1511	5412	25.4	2401

and discussion above, the following conclusions are drawn:

1 Analysis revealed that if the EVCS was located within the city range and could be operated as a smart energy hub with diesel-solar PV-BESS supply mix options, it was the most economically favorable option.
2 In order to allow the EV customers to travel long distances with ease, the feasibility of isolated EVCS along highways was studied in this work and from the analysis it was noted that the diesel-solar PV-BESS mix had the lowest NPC and a fairly small carbon footprint, when compared to a diesel-based EVCS. Although a fully renewable-based EVCS, which had no carbon footprint, was the most preferred, the NPC was higher.
3 Grid connected EVCS as a smart energy hub was considered to examine the feasibility of EVCS located within the city range in a high-density area, considering that the EVCS not only relies on the external grid but had its own resources.
4 Although a solar PV with BESS-based EVCS had no carbon footprint, the NPC was higher and hence not selected.
5 Analysis was also carried out to determine the break-even grid extension distance from the isolated EVCS location.
6 It was noted that the solar PV with BESS based isolated EVCS could benefit the most by grid connectivity, followed by the diesel-based isolated EVCS, because of their high costs.

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Corrigendum

Corrigendum to “Optimal design of electric vehicle charging stations considering various energy resources” [Int. J. Renew. Energy 107 (July 2017) 576–589]

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