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Optimal planning and design of hybrid renewable energy systems for microgrids

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ABSTRACT

This paper presents a technique for the optimal planning and design of hybrid renewable energy systems for microgrid applications. The Distributed Energy Resources Customer Adoption Model (DER-CAM) is used to determine the optimal size and type of distributed energy resources (DERs) and their operating schedules for a sample utility distribution system. Using the DER-CAM results, an evaluation is performed to evaluate the electrical performance of the distribution circuit if the DERs selected by the DER-CAM optimization analyses are incorporated. Results of analyses regarding the economic benefits of utilizing the optimal locations for the selected DER within the system are also presented. The electrical network of the Brookhaven National Laboratory (BNL) campus is used to demonstrate the effectiveness of this approach. The results show that these technical and economic analyses of hybrid renewable energy systems are essential for the efficient utilization of renewable energy resources for microgrid applications.

1. Introduction

Renewable energy is regarded as an appealing alternative to conventional power generated from fossil fuel [1,2]. This has led to increasingly significant levels of distributed renewable energy generation being installed on existing distribution circuits. Although renewable energy generation has many advantages, circuit problems can arise due to the intermittency and variability of the renewable energy resources.

A hybrid renewable energy system, consisting of two or more renewable energy sources used together, mitigates the intermittent nature of renewable energy resources, improves the system efficiency, and provides greater overall balance to the energy supply. However, hybrid renewable energy systems have received limited attention due to the complexities involved in achieving optimal planning and design. Conventional approaches can sometimes result in renewable energy combinations that are over-sized or not properly planned or designed [3].

A microgrid is a group of interconnected loads and Distributed Energy Resource (DER) generation that acts as a single controllable entity with respect to the grid, but with the capability to connect and disconnect from the main grid. Microgrids are increasingly being considered to enhance a local grid's reliability, resiliency, quality, and efficiency. Furthermore, microgrids increase the effectiveness of renewable energy and help implement net-zero buildings, campuses, and communities [4]. For these reasons, techniques for the optimal planning and design of hybrid renewable energy systems for microgrids are studied in this paper.

The technical and economic analyses of hybrid renewable energy systems for microgrids are essential for the efficient utilization of renewable energy resources. Several software tools are introduced and compared to analyze the electrical, economical, and environmental performance of hybrid renewable energy systems [5–14]. A survey of recent studies in this field shows that various hybrid renewable energy systems have been investigated using the Hybrid Optimization of Multiple Energy Resources (HOMER) [15–38]. However, there are not many comparable studies that utilize the Distributed Energy Resources Customer Adoption Model (DER-CAM). The survey also shows that in some cases, the DER-CAM is the preferred tool for hybrid renewable energy system design modeling, mainly due to the robust and flexible three-level optimization algorithm, hourly time step, and other scale considerations, but particularly due to the several successful applications with modeling microgrid systems [5,39,40]. Thus, the DER-CAM is selected for this study.

The DER-CAM is a tool that was developed by Lawrence Berkeley National Laboratory (LBNL) to help optimize the selection and

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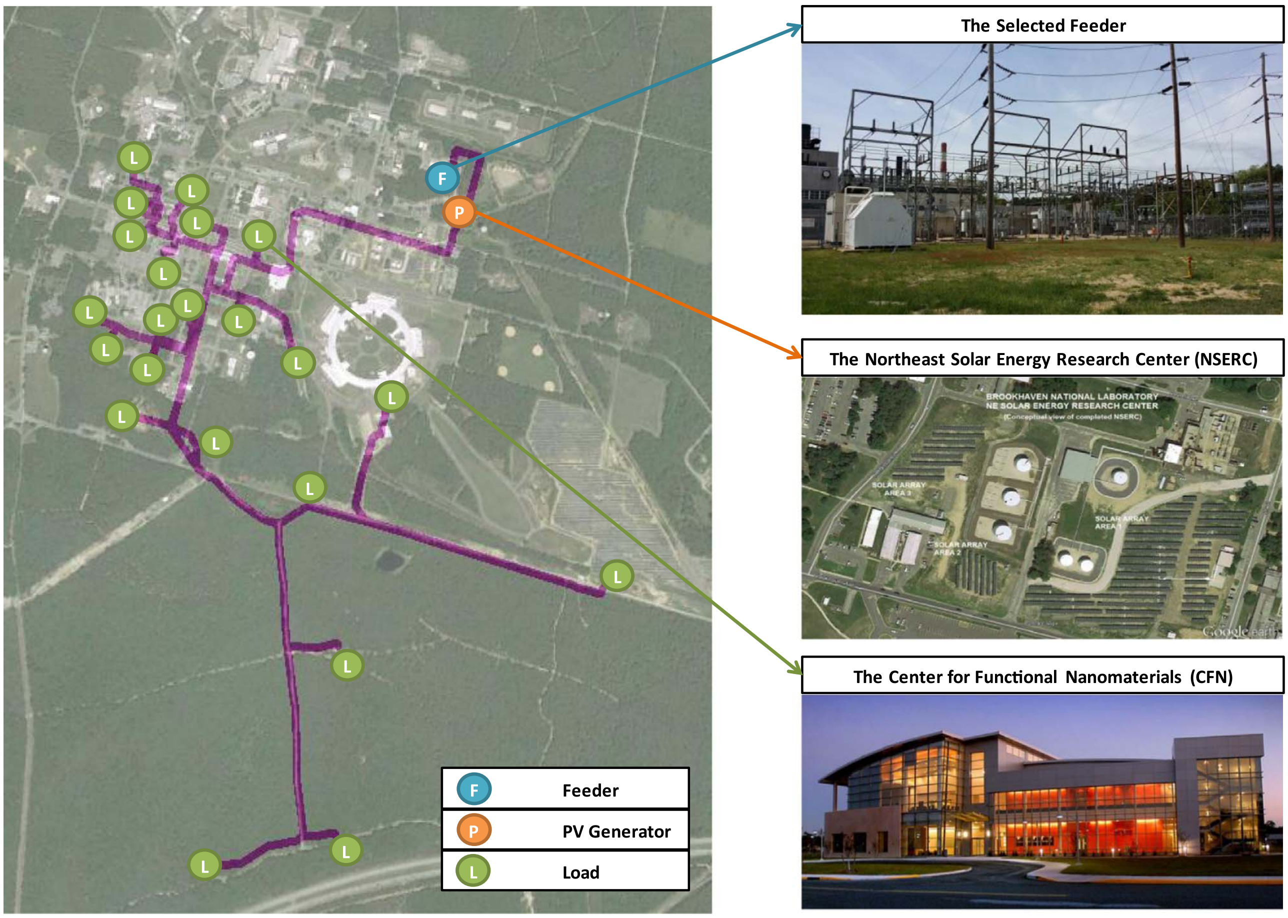
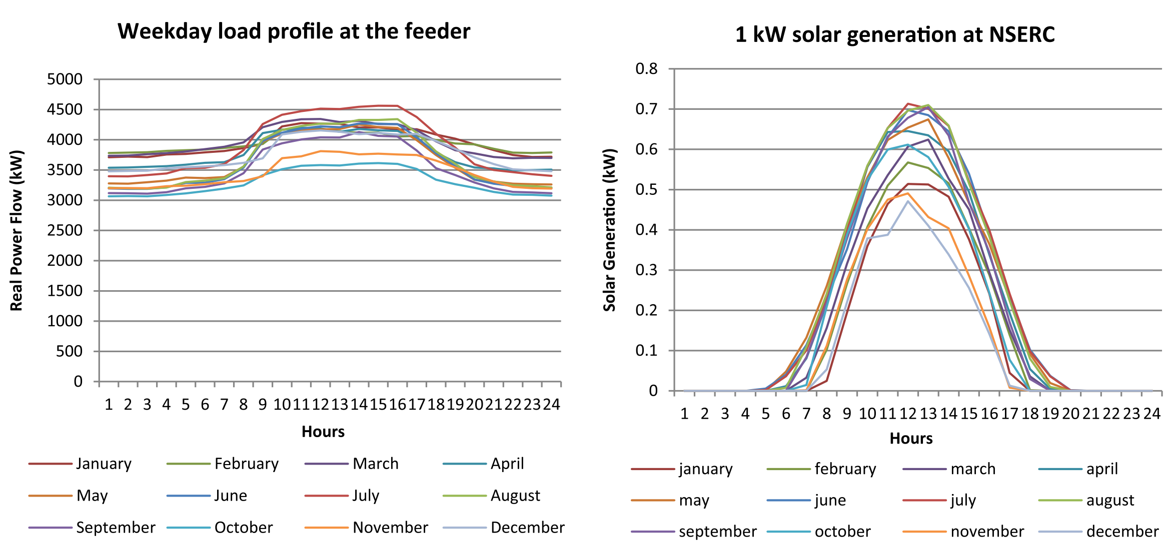


Fig. 1. the selected feeder for the simulation.



(a) Weekday load profile at the feeder (b) 1 kW solar generation at NSERC

Fig. 2. Key input data into DER-CAM. (a) Weekday load profile at the feeder, (b) 1 kW solar generation at NSERC.

operation of distributed energy resources on a utility distribution system [41]. The main objective of the DER-CAM is to minimize either the annual costs or the CO_2 emissions of providing energy services to the modeled site, including utility electricity and natural gas purchases, plus amortized capital and maintenance costs for any DER investments. The key inputs into the model are the customer's end-use energy loads, energy tariff structures and fuel prices, and a user defined list of preferred equipment investment options. The program then outputs the optimal DER and storage adoption combination, and an hourly operating schedule, as well as the resulting costs, fuel consumption, and CO_2 emissions.

However, the focus of the DER-CAM model is primarily to perform an economic analysis that does not in any way take into consideration the electrical distribution circuit performance that will result from the implementation of the microgrid. Further research is required to develop an integrated analytical tool that will combine the economic

Table 1
The annual costs and CO_2 emissions savings by the investment for the Non-microgrid case.

	Reference case (no investment)	Non-microgrid Case (investment)	Reduction
Total Annual Energy Costs ($)	$4,073,282	$3,929,580	***- $143,702***
Total Annual CO_2 emissions (kg)	16,656,949 kg	15,547,613 kg	***- 1,109,336 kg***

optimization capabilities of the DER-CAM model together with an electrical system performance modeling and analysis tool for a more complete and comprehensive analysis of DER and microgrid applications. For example, it is possible that the cost-optimized configuration of DER will not provide an acceptable electrical performance on the distribution circuit; this could result in adverse impacts, such as voltage violations. In this study, further analysis is performed to include an evaluation of the electrical performance of the distribution circuit after the development of a microgrid based on the output of the DER-CAM analytical tool.

Furthermore, the optimum physical placement of DER within the microgrid is vital in order to obtain the full benefits from the microgrid and improve both the efficiency and reliability of the system [42,43]. Therefore, this paper also analyzes the economic benefit of the optimal location of DER in the system in conjunction with the optimized economic and environmental outputs from a DER-CAM analysis. The results will show how the microgrid performance can be further enhanced by properly locating DER.

This paper presents a technique for the optimal planning and design of hybrid renewable energy systems for microgrid applications. Section 2 presents the DER-CAM results on the optimal size, type, and operation schedules for DER adoption for a sample microgrid. It also shows an estimate of the total annual energy costs and total annual CO_2 emissions when the selected DERs are adopted. In Section 3, the electrical performance of the distribution circuit is evaluated using Distribution Engineering Workstation (DEW) software after the initial development of a microgrid based on the output of the DER-CAM analytical tool. In addition, the effects of varying the locations of the DER within the system are compared in Section 4. Finally, the findings of the study are summarized in Section 5.

2. Economic and environmental performance evaluation of hybrid renewable energy systems using DER-CAM

2.1. Site selection

One representative feeder on the Brookhaven National Laboratory (BNL) campus electrical network was selected for the study because it includes large research and office buildings as well as the 0.5 MW Northeast Solar Energy Research Center (NSERC) solar PV research array, as shown in Fig. 1. The NSERC has been supplying a maximum of 518 kW-dc of solar generation directly into the BNL distribution system since May of 2014. The total load on this feeder typically ranges between 2.5 MW and 5.5 MW. The NSERC solar PV array is the only non-emergency generation on the feeder. The largest single facility load on the feeder is the Center for Functional Nanomaterials (CFN), which is a mix of research facilities, laboratories, and offices. The remainder of the loads on the feeder consists of small industrial buildings (pumps, air conditioning, ventilation, lighting, etc.), small research laboratories, and office and administration buildings.

The major buildings, operating units, and research facilities that are supplied by this feeder, in most cases, are metered at their service entrance. In some of the larger facilities such as the CFN, the entire facility is metered, but individual feeders within the facility may also be tracked for the purpose of energy usage monitoring. Most of the meters at BNL are part of an Advanced Metering Infrastructure (AMI) system. However, not all of the parameters that can be measured by these devices are gathered and stored by the AMI system at this time. At present, load data are collected and stored automatically by the AMI system, typically every 15 min. Several of the older buildings on the site may still be monitored by manual energy meters; these load data are recorded manually, typically on a monthly basis.

As previously mentioned, the BNL NSERC is also connected to this feeder. The NSERC is a research and test facility specifically developed for evaluating and commercializing innovative new technologies that will advance the use of solar energy, particularly in the northeast, and facilitate integration into the electric grid. The NSERC currently has a 518 kW grid-connected solar photovoltaic research array available for field-testing equipment under actual northeastern weather conditions, and is fully instrumented with research-grade monitoring equipment to provide high resolution (1sec), time-stamped data sets for research purposes.

2.2. Key inputs to DER-CAM

The load profile at the feeder and a normalized 1 kW solar generation profile at NSERC are used as inputs for DER-CAM as shown in Fig. 2(a) and (b), respectively. Furthermore, the standard commercial PSEG-LI electric rate is used as input for the local energy

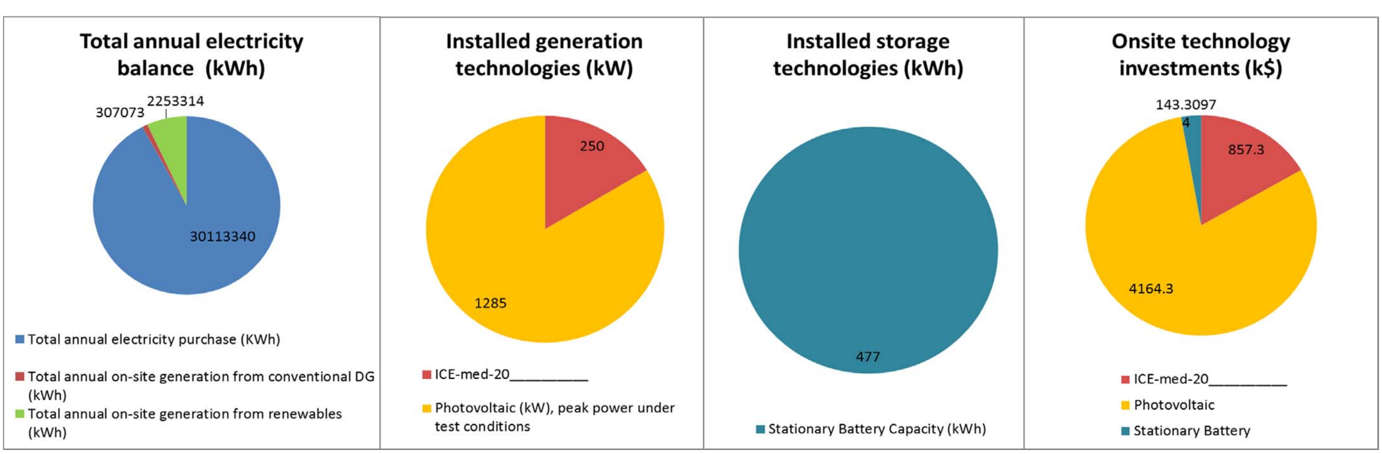


Fig. 3. DER-CAM investment results for the Non-microgrid case.

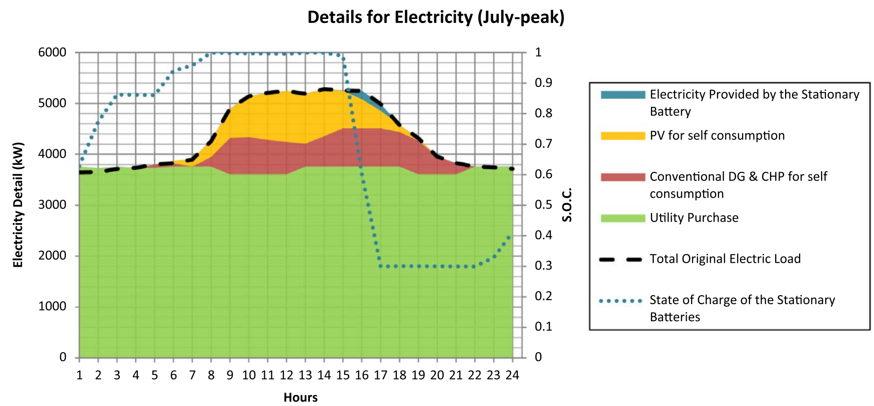


Fig. 4. the detail electricity operation during peak day in July for the Non-microgrid case.

Table 2
The annual costs and CO_2 emissions savings by the investment for the Microgrid case.

	Reference case (no investment)	Microgrid case (investment)	Reduction
Total annual energy costs ($)	$4,073,282	$4,233,259	***+ $159,977***
Total annual CO_2 emissions (kg)	16,656,949 kg	10,731,794 kg	***- 5,925,155 kg***

tariff structure [44]. The reference data provided by DER-CAM are used for the fuel and equipment investment prices.

A multi-objective approach was used in this study by considering the minimization of both the annual costs and CO_2 emissions. Every optimization run in the multi-objective study is a tradeoff between the cost and environmental functions. A weighting factor is input to the DER-CAM to indicate the user's preference for minimizing cost (weighting factor=1.0) or emissions (weighting factor=0.0). The weighting factor used will impact the DER combination recommended by the DER-CAM. The program also considers the relative investment cost of each DER being considered and factors this into the recommended mix. For example, even though the costs of utility-scale energy storage investments continue to decrease, it still remains an expensive technology. Consequently, in this study energy storage, which is relatively higher in cost than the other DER options selected, would typically not be economically viable when cost minimization options alone are being evaluated (weighting factor=1.0). For illustrative purposes in this study, a weighting factor of 0.75 is used, indicating that 75% weight is given to minimizing annual costs and 25% weight is given to minimizing CO_2 emissions. Two cases are simulated:

Non-microgrid case – most economical and environmental solution for the BNL campus to operate with a supply of utility power and without being a microgrid.

Microgrid case – most economical and environmental solution for the BNL campus to operate as a microgrid, including island mode.

2.3. DER-CAM results and discussions

2.3.1. Non-microgrid case results

Table 1 shows the annual energy cost and CO_2 emission savings, by investment, for the Non-microgrid case. The optimal technology adoption reduces the total annual energy cost by $143,702 and the total annual CO_2 emissions by 1,109,336 kg. Fig. 3 shows the DER-CAM investment results for the Non-microgrid case. DER-CAM suggests an optimal mix of 1285 kW PV generation and 250 kW diesel generation together with a 477 kW stationary battery at the selected site.

Fig. 4 shows the detailed hourly electricity operating schedule during the peak day in July for the Non-microgrid case. The base load is supplied by utility power purchase and the increase load above the base load is supplied by PV and diesel generation. The stationary battery is charged during non-peak time and then supplies the stored electrical energy back to the system during the peak operating time.

2.3.2. Microgrid case results

The microgrid is a group of interconnected loads and DER generation that acts as a single controllable entity with respect to the grid, but with the capability to connect and disconnect from the grid. To simulate the Microgrid case in DER-CAM, we select one peak day,

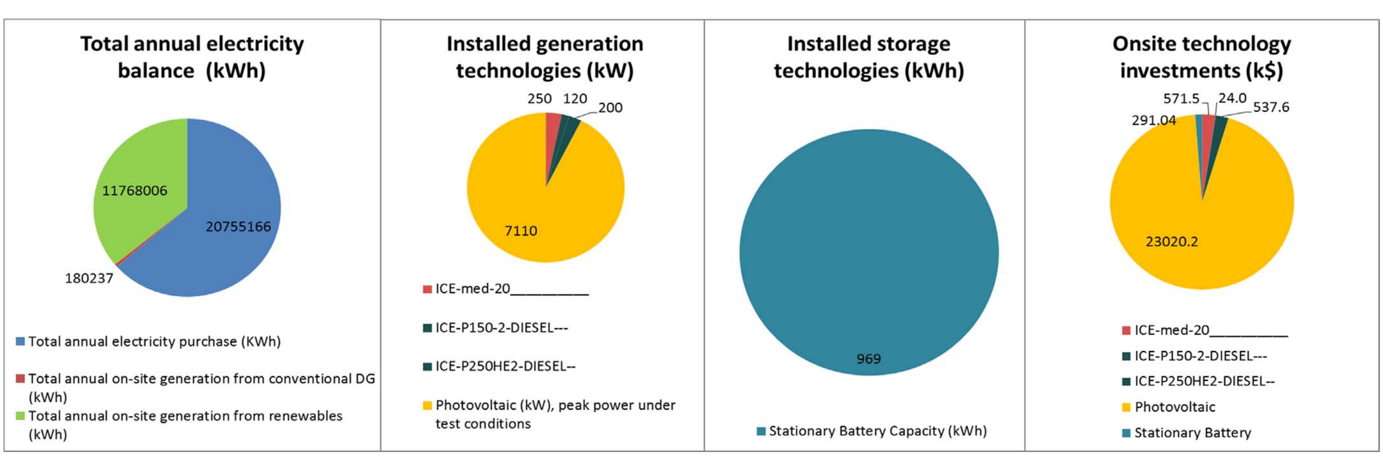


Fig. 5. DER-CAM investment results for the Microgrid case.

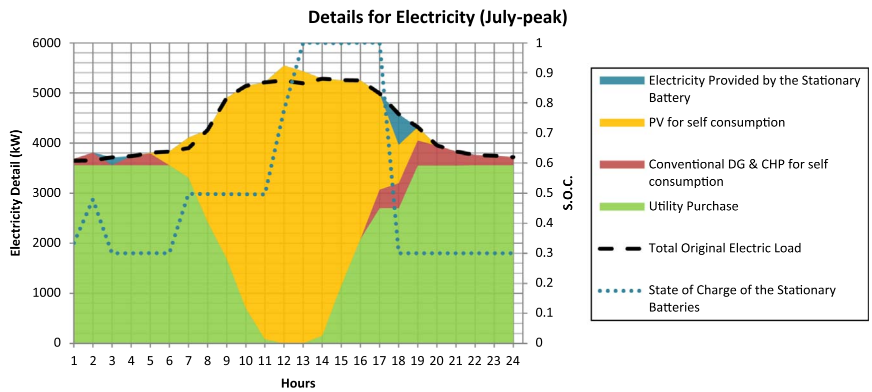


Fig. 6. The detail electricity operation during peak day in July for the Microgrid case.

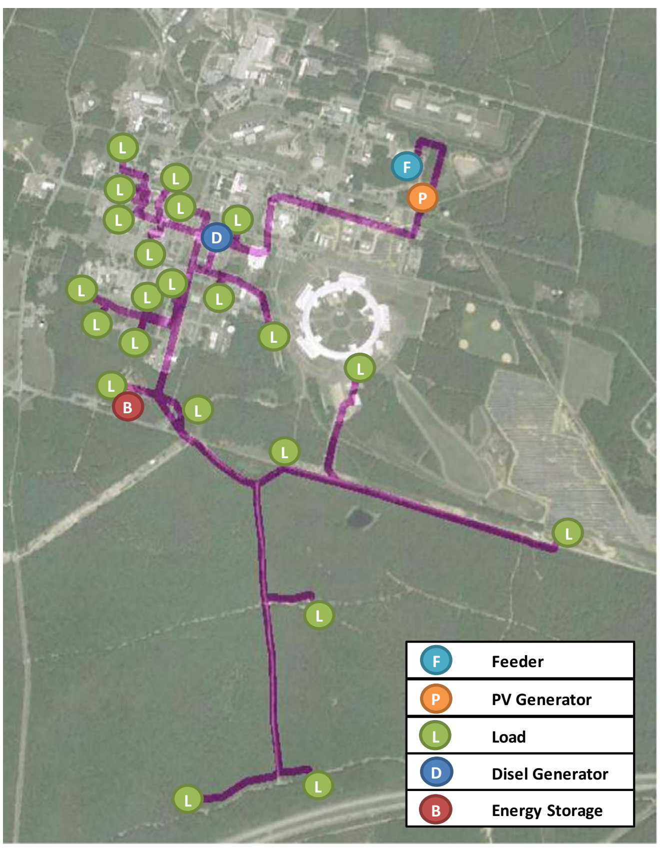


Fig. 7. DER adopted location at the selected feeder.

as in the previous case, but then assume that the supply of electricity from the utility is unavailable. Therefore, all the electricity required by the microgrid on the peak day has to be supplied from the local DG. Table 2 shows the annual energy cost and CO_2 emissions savings, by investment, for the Microgrid case. The adoption of microgrid technology increased the total annual energy cost by $159,977; however, the total annual CO_2 emissions are reduced by 5,925,155 kg. Although the microgrid has the potential to benefit the environment tremendously, the overall economic challenge must be overcome before its full potential can be realized.

Fig. 5 shows the DER-CAM investment results for the Microgrid case. DER-CAM suggests an optimal mix of 7110 kW PV generation and 570 kW diesel generation together with a 969 kW stationary battery at the selected site.

Fig. 6 shows a detail hourly electricity operating schedule during the peak day in July. This is the result of grid-connected operation. The PV generation period partially coincides with the peak demand on that day. At the time of peak demand, the microgrid's on-site generation covers the entire load demand; during the remainder of the afternoon, local DG charges the stationary battery. When PV generation is insufficient to meet the microgrid's load demand, the local diesel generation, utility purchase, and the stationary battery are used to make up for any difference.

2.3.3. 3.3. Discussions

The results show that DER-CAM can provide information on the optimal size, type, and operation schedules for DER adoption based on specific site load and price information, and performance data for available equipment options. The model also provides an estimate of the total annual energy costs and total annual CO_2 emissions when the selected DERs are adopted. In this study, DER-CAM can offer the ability to increase the effectiveness of renewable energy and to help implement net-zero buildings, campuses, and communities.

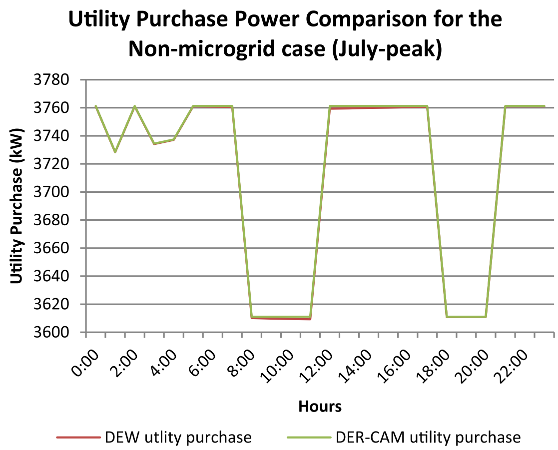
However, the focus of this model is primarily to perform an economic analysis that does not take into consideration the electrical distribution circuit performance that will result from the implementation of the microgrid. Further research is required to develop an integrated analytical tool that will combine the economic optimization capabilities of the DER-CAM model together with an electrical system performance modeling and analysis tool for a more complete and comprehensive analysis of DER and microgrid applications. For example, it is possible that the cost-optimized configuration of DER will not provide acceptable electrical performance on the distribution circuit and this could result in adverse impacts such as voltage violations. Therefore, further analysis is performed in the next section to evaluate the electrical performance of the distribution circuit after the development of a microgrid based on the output of the DER-CAM analytical tool.

3. Electrical performance evaluation of hybrid renewable energy systems using DEW

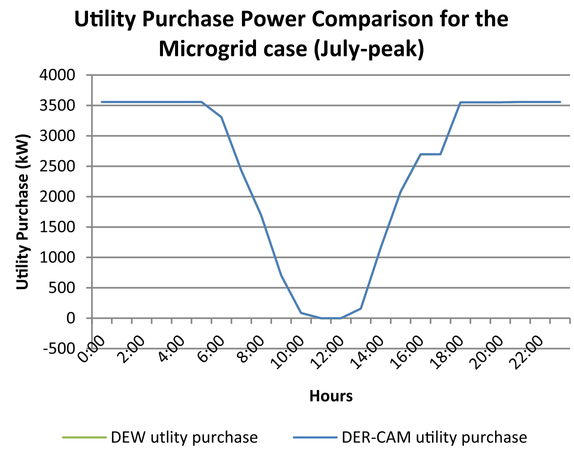
3.1. DER adoption for electrical performance evaluation

Fig. 7 shows the developed DEW model using the selected feeder to evaluate the electrical performance of the cost-optimized configuration of DER obtained from the DER-CAM. The circuit model is derived from actual data. It is a 13.8 kV, Y-connected circuit that supplies power to several major buildings, operating units, and research facilities. The time-varying loads are estimated from averaged hourly AMI measurements, hourly customer kWh load data, and monthly kWh load data processed by load research statistics to create hourly loading estimates for each customer [45,46].

Initially, the selected DERs from the DER-CAM analysis are randomly placed in the developed DEW model without any power

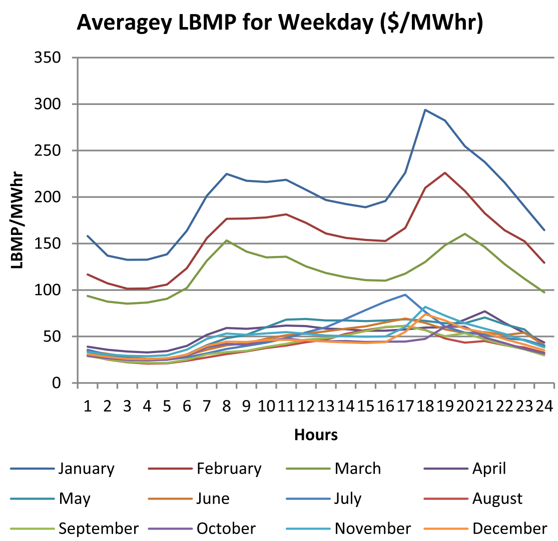


(a) utility purchase power comparison for the Non-microgrid case

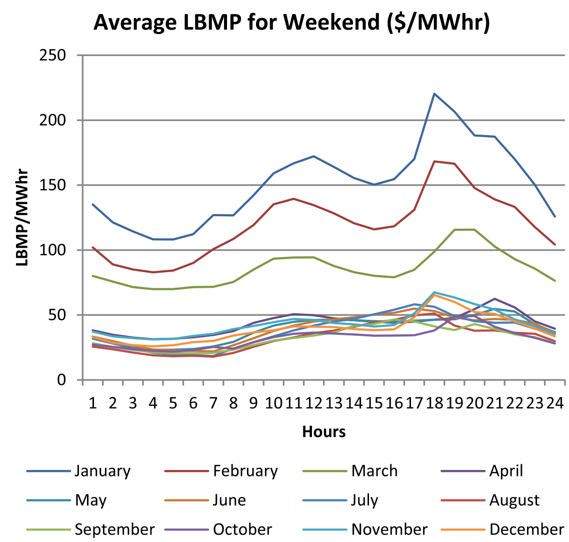


(b) utility purchase power comparison for the Microgrid case

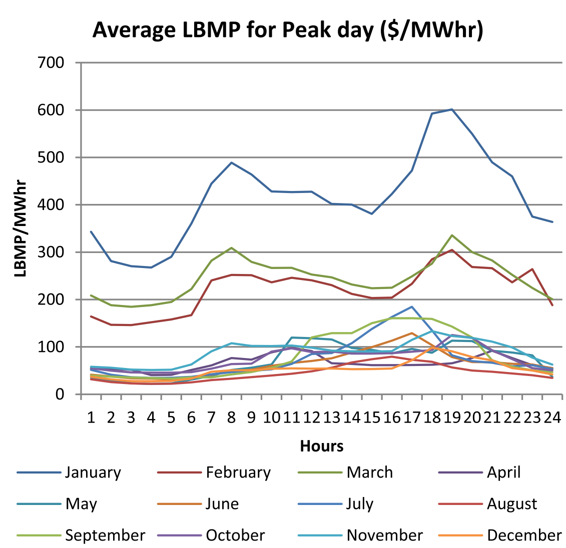
Fig. 8. Utility purchase power comparison between DER-CAM and DEW results for the Non-microgrid and Microgrid case during peak day in July. (a) utility purchase power comparison for the Non-microgrid case, (b) utility purchase power comparison for the Microgrid case.



(a) Average LBMP for weekday

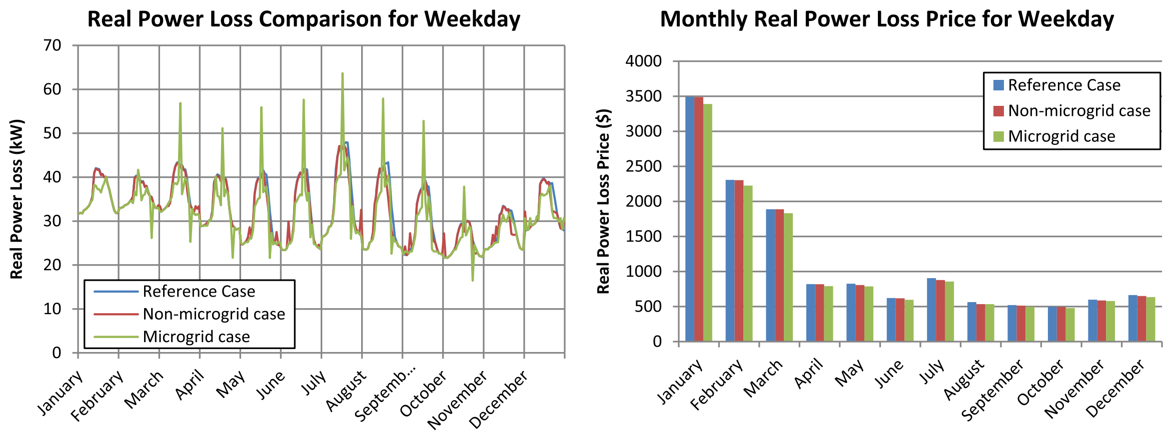


(b) Average LBMP for weekend



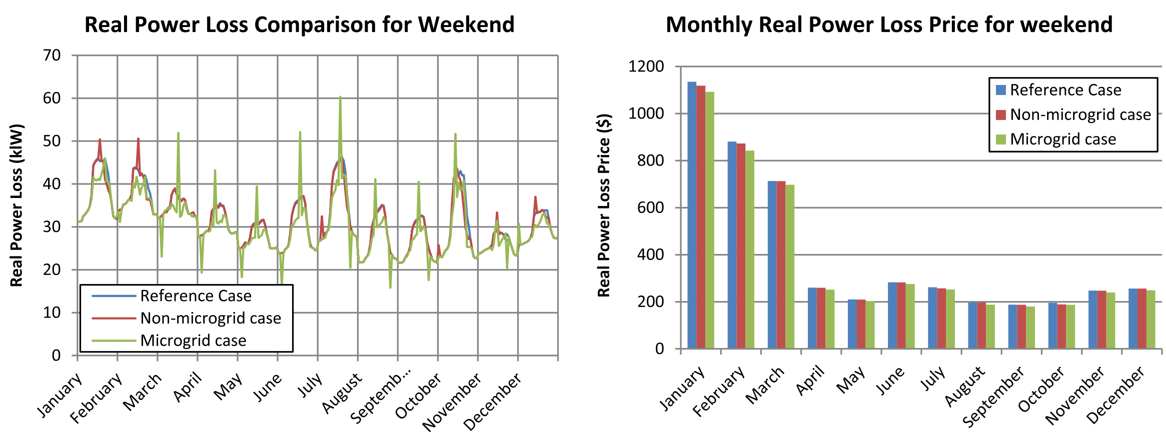
(c) Average LBMP for peak day

Fig. 9. The hourly LBMP for the long island load zone in New York area [49]. (a) Average LBMP for weekday, (b) Average LBMP for weekend, (c) Average LBMP for peak day.



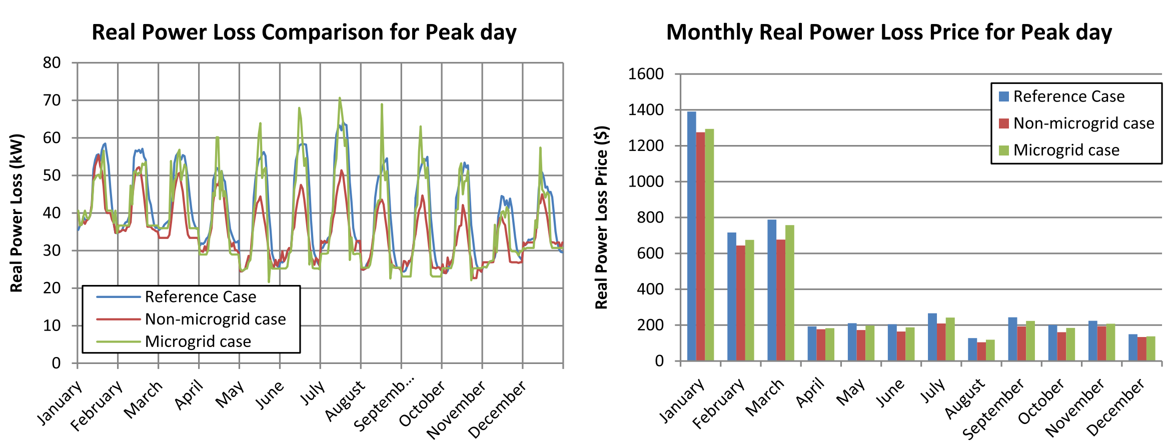
(a) Real power system loss for weekday (b) Monthly real power system loss price for weekday

Fig. 10. Real power system loss comparison for weekday. (a) Real power system loss for weekday, (b) Monthly real power system loss price for weekday.



(a) Real power system loss for weekend (b) Monthly real power system loss price for weekend

Fig. 11. Real power system loss comparison for weekend. (a) Real power system loss for weekend, (b) Monthly real power system loss price for weekend.



(a) Real power system loss for peak day (b) Monthly real power system loss price for peak day

Fig. 12. Real power system loss comparison for peak day. (a) Real power system loss for peak day, (b) Monthly real power system loss price for peak day.

system violations, such as voltage and overloading violations [47,48]. The NSERC has been supplying a maximum of 518 kW-dc of solar generation directly into this feeder, and there are plans to expand the solar array in the near future at the same location. Therefore, the location of PV generation is fixed at the current NSERC location. The initial locations of energy storage and diesel generator are also shown in Fig. 7.

Furthermore, the DER-CAM-suggested hourly electricity operating schedules of PV generators, diesel generators, and energy storage are applied into the circuit to evaluate the electrical performance. Results show that there are no changes in power system violations after adopting the recommended DERs. Fig. 8 shows the utility electricity purchase comparison between DER-CAM and DEW results. The results show that the power purchased from the utility is almost identical. This means that the DER-CAM-suggested operating schedule of DERs works well and purchasing more or less power from the utility was

Table 3
Number of day for each month.

	Weekday number	Weekend number	Peak day number
January	20	8	3
February	17	8	3
March	18	10	3
April	19	8	3
May	20	8	3
June	17	10	3
July	20	8	3
August	18	9	3
September	18	9	3
October	20	8	3
November	18	9	3
December	19	9	3

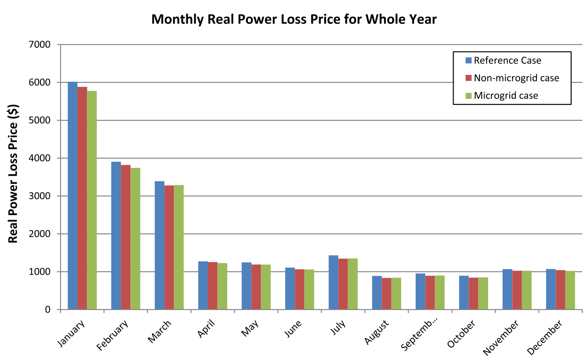


Fig. 13. Monthly real power loss price for whole year.

not required. However, the DEW results show a little lower utility power purchase because it includes the power system loss reduction benefits provided by DER adoption, which were not considered by the DER-CAM. Thus, the economic benefit resulting from power system loss reduction will be added into the DER-CAM economic performance results in the next section.

3.2. Economic performance evaluation of power system loss reduction by DER adoptions

The hourly Location Based Marginal Prices (LBMP) for the Long Island load zone in the state of New York is used to calculate the economic benefits of power system loss reduction by DER adoptions, as shown in Fig. 9 [49]. Average LBMP of all weekdays and weekends except peak day during the month is used for weekday and weekend calculation. Average LBMP of three peak days during the month is used for the peak day calculation. In these figures (Fig. 9(a), (b), and (c)), a much higher LBMP is observed in the first three months of the year (January, February, and March) than for the other remaining months of the year.

Figs. 10 through 12 show the real power system loss comparison for weekday, weekend, and peak day, respectively. Each figure includes real power system loss for the specific day and at their monthly price. The number of days shown in Table 3 is assumed to calculate the monthly power system loss. The monthly power system loss is calculated by multiplying the specific day with its number in Table 3. The cost is then calculated by multiplying the monthly power system loss with the LBMP in Fig. 9.

In these figures, the Microgrid case shows the most power system loss reduction during the winter season, however, it increases the loss during the summer season when PV generation is at its peak. This is a result of some redundancy in the PV generation. Although the Microgrid case has increased losses during peak generation time, the overall power system loss reduction benefit is the greatest in the Microgrid case for weekdays and weekends. The Non-microgrid case is the most beneficial for peak day operation. Furthermore, the first three months have higher real power system loss prices compared to other months because of the higher LBMP in these months.

Fig. 13 shows the monthly real power system loss price for the whole year, which is the sum of the values in Fig. 10 (b), Fig. 11 (b), and Fig. 12 (b). It shows that the first three months have higher real power system loss prices than other months, similar to that observed in the previous figures. It also shows that the Microgrid case shows the most power system loss cost reduction. The Non-microgrid case is also able to reduce the cost more than the reference case. Table 4 shows the total economic performance evaluation of power system loss reduction by DER adoptions. The Non-microgrid case reduces the cost from power system loss by $777 and the Microgrid case reduces the cost from power system loss by $977. More DER investments show greater cost reduction in real power system loss. The annual energy cost by combining DER-CAM results with power system loss reduction is reduced by $144,479 in the Non-microgrid case but still increases by $159,000 in the Microgrid case.

After completing the electrical performance of the hybrid renewable energy systems by applying the DER-CAM investments, the Microgrid case still shows an economic disadvantage. However, one of the biggest benefits of the microgrid application is to enhance a local grid's reliability, resiliency, power quality, and efficiency. This study shows that the Microgrid case is able to improve efficiency and shows how much economic benefit is obtained from this. In the future, further analysis would be required to estimate the other microgrid benefits (reliability, resiliency, and quality) to encourage more microgrid applications. In the next section, this paper will continue to investigate how much economic benefit can be garnered from the optimal location of DERs in conjunction with the optimized economic and environmental outputs from DER-CAM analysis.

4. Economic performance evaluation of the optimal placement of DER

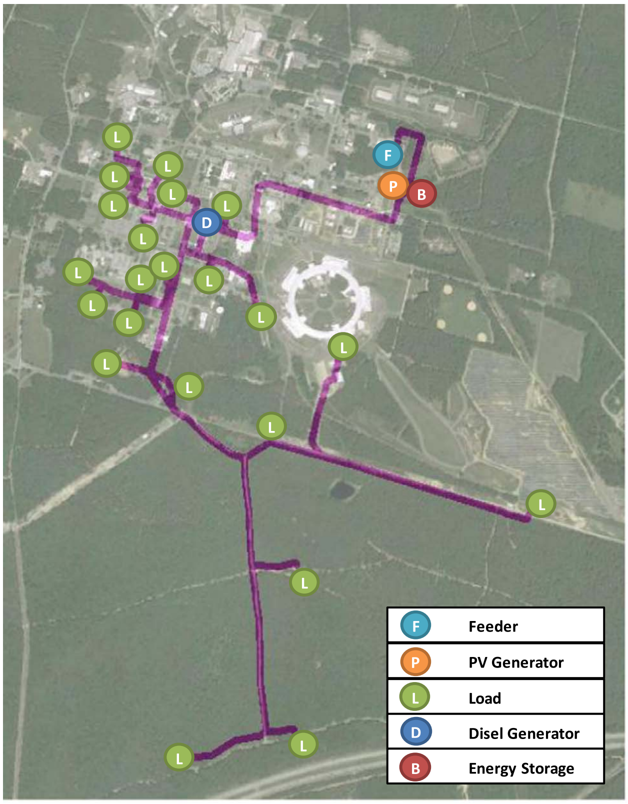
4.1. Optimizing DER placement

Initially, the selected DERs from the DER-CAM analyses are randomly placed in the developed DEW model without making any power system design violations such as voltage and overloading, as described in the previous section. In this analysis, the combination of DERs among the selected locations is varied in order to try to optimize the locations where the DERs are deployed and quantify the resulting economic benefits. Again, the location of the PV generation remains fixed at the current NSERC location. Four different combinations of microgrid cases are then simulated:

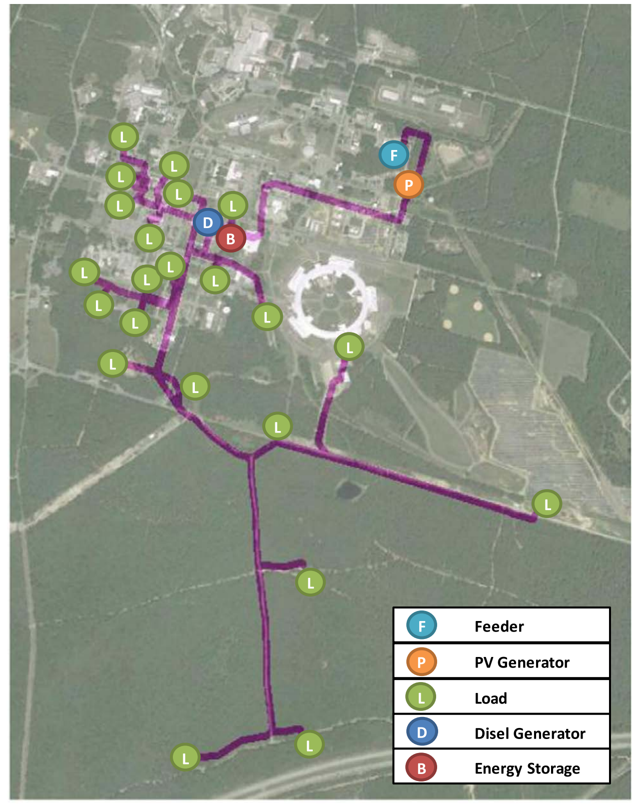
Microgrid case – initial selection as shown in Fig. 7 (reference case).

Table 4
Economic performance evaluation of power system loss reduction by DER adoptions.

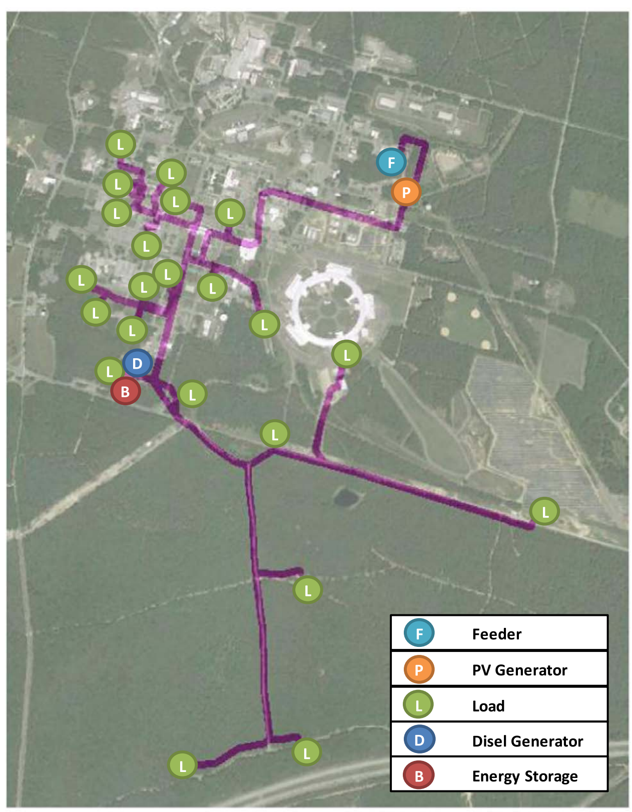
	Reference case	DER-CAM results	Reduction	Power system loss reduction	Total reduction
Non-microgrid case	$4,073,282	$3,929,580	***- $143,702***	***- $777***	***- $144,479***
Microgrid case		$4,233,259	***+ $159,977***	***- $977***	***+ $159,000***



(a) DER placement for Microgrid-PV case

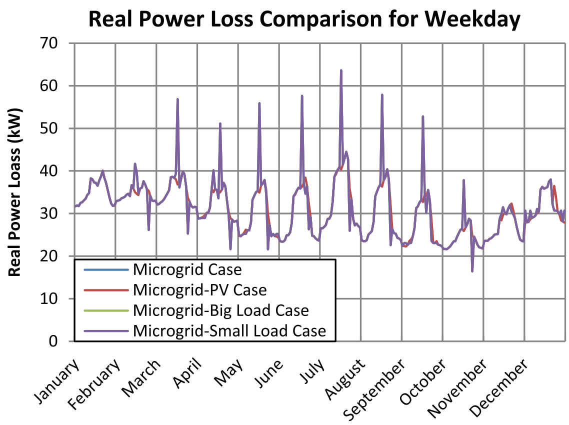


(b) DER placement for Microgrid-Big Load case

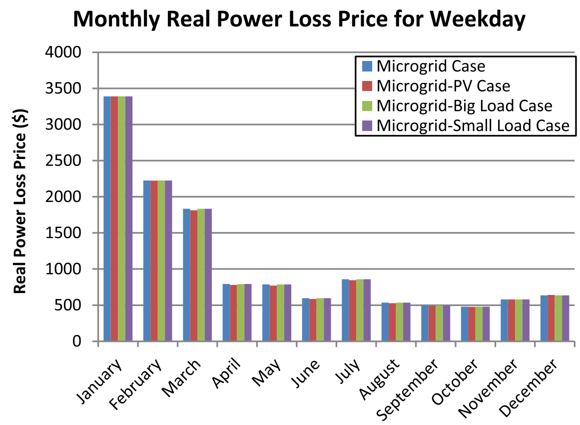


(c) DER placement for Microgrid-Small Load case

Fig. 14. DER placement at the selected feeder. (a) DER placement for Microgrid-PV case, (b) DER placement for Microgrid-Big Load case, (c) DER placement for Microgrid-Small Load case.

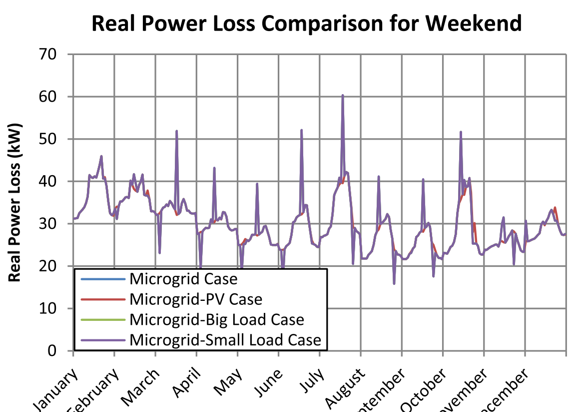


(a) Real power loss comparison for weekday

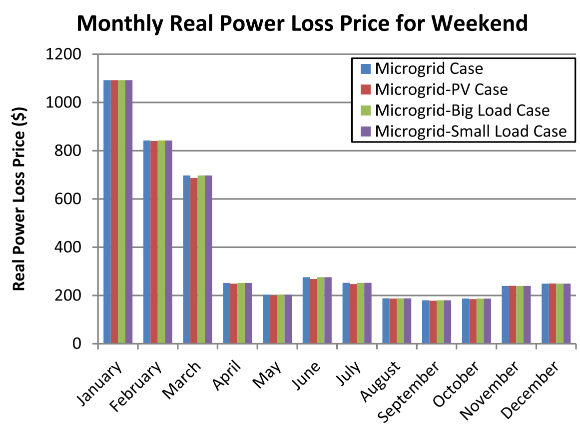


(b) Monthly real power loss price for weekday

Fig. 15. Real power system loss comparison of the optimal plcaement of DER for weekday. (a) Real power loss comparison for weekday, (b) Monthly real power loss price for weekday.

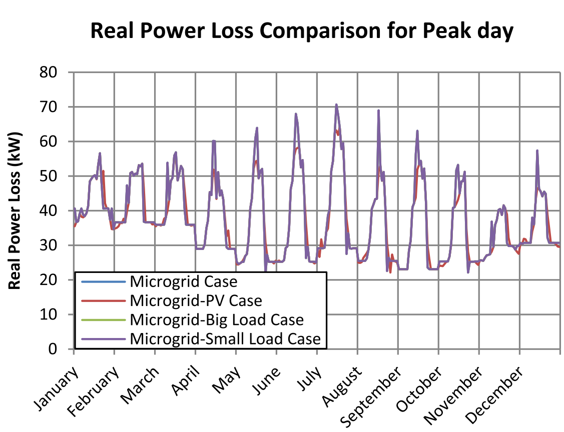


(a) Real power loss comparison for weekend

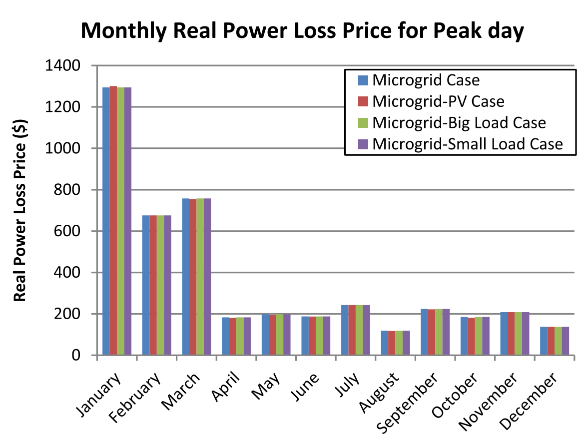


(b) Monthly real power loss price for weekend

Fig. 16. Real power system loss comparison of the optimal plcaement of DER for weekend. (a) Real power loss comparison for weekend, (b) Monthly real power loss price for weekend.



(a) Real power loss comparison for peak day



(b) Monthly real power loss price for peak day

Fig. 17. Real power system loss comparison of the optimal plcaement of DER for peak day. (a) Real power loss comparison for peak day, (b) Monthly real power loss price for peak day.

Microgrid-PV case – energy storage is located where the PV generation is located as shown in Fig. 14 (a).

Microgrid-Big Load case – energy storage and diesel generator are located where the big load is located as shown in Fig. 14 (b).

Microgrid-Small Load case – energy storage and diesel generator are located where the small load is located as shown in Fig. 14 (c).

The detailed locations of DER for each case are shown in Fig. 14. The Microgrid-PV case is selected to observe the effects when the storage is located close to the charging source. The energy storage is mainly charged by PV generators according to the DER-CAM suggested hourly electricity operating schedule. The Microgrid-Big Load case is selected to show the effects when minimizing the power delivery losses. The Microgrid-Small Load case is selected to compare the results with the Microgrid-Big Load case.

4.2. Economic performance evaluation of the optimal placement of DER

Figs. 15 and 16 show the real power system loss comparison for different combinations of DERs for weekday, weekend, and peak day, respectively. Each figure includes the real power system loss for the specific day and at their monthly price. The monthly real power loss price is calculated in same way as described in the previous section. The first three months have higher real power system loss prices than the other months because of higher LBMP in these months, as was noted in the previous analysis.

The overall power system loss reduction benefit is the greatest in the Microgrid-PV case. This shows that the greatest system benefit is obtained when the energy storage is located closest to the charging source. There is not much difference noted between the Microgrid-Big Load and Microgrid-Small Load cases. The reason for this in the case of the selected circuit is that it is physically so small that the delivery loss effect is negligible. However, the case where the DERs are located close to the big load shows a little more benefit than the case where the DERs are located close to the small load. The trend that the loss increases during peak generation time is not found in the Microgrid-PV case analysis. This is because the redundant PV generation is used to charge the energy storage completely.

Fig. 18 shows the monthly real power system loss price for a whole year, which is the sum of the values in Fig. 15 (b), Fig. 16 (b), and Fig. 17 (b). Again, this analysis shows that the first three months have higher real power system loss prices compared to other months such as observed in the analyses in previous sections. It also indicates that the Microgrid-PV case shows the greatest power system loss price reduction. However, the other cases analyzed are not able to reduce the power system loss significantly compared to the Microgrid case. Table 5 shows the total economic performance evaluation of power system loss reduction for various combinations of DERs. The Microgrid-PV case reduces the cost from power system loss by $1111, which is the annual energy cost achieved by combining DER-CAM results with power system loss reduction increases by $158,866. The improvement in the other cases was found to be nearly the same. Therefore, this study shows that energy storage located closest to the PV generator in this selected circuit is the most beneficial configuration and the location of the diesel generator has a negligible effect in this case, because of its small size.

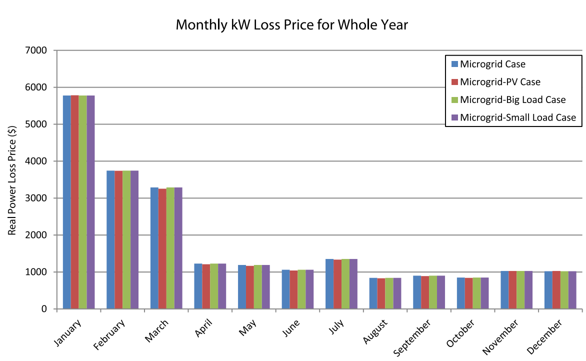


Fig. 18. Monthly real power loss price of the optimal placement of DER for whole year.

5. Conclusions

Techniques for the optimal planning and design of hybrid renewable energy systems were investigated for configuring an example power distribution grid as a microgrid. First, the DER-CAM tool is used to help optimize the selection and operation of distributed energy resources on a utility distribution system. Then, an evaluation is conducted to determine the electrical performance of the distribution circuit after development of a microgrid based on the output of the DER-CAM analytical tool. This study also analyzes the economic benefits of the optimal location of the selected DERs within the system. These technical and economic analyses of hybrid renewable energy systems are essential for the efficient utilization of renewable energy resources for microgrid applications.

The results of the analyses show that DER-CAM can provide information on the optimal size, type and operational schedules for DER adoption based on estimates of the total annual energy costs and total annual CO_2 emissions. It demonstrates the capability of optimization analyses in order to increase the effectiveness of renewable energy integration and to help implement net-zero buildings, campuses, and communities.

Further analysis was performed using DEW to develop an integrated analytical tool that combines the economic optimization capabilities of the DER-CAM model together with an electrical system performance modeling and analysis tool for a more complete and comprehensive analysis of DER and microgrid applications. In the power system demonstration example analyzed, results show that the adopted DERs are able to improve the efficiency of the system, and the economic benefits of the enhancements are quantified.

Finally, this paper demonstrates the increased economic benefits of the optimal location of DERs in conjunction with the optimized economic and environmental outputs from DER-CAM analysis. It was shown that the energy storage, when located closest to the PV generator in this selected circuit, is the most beneficial configuration, and the location of the diesel generator has a negligible effect because of its small size.

After completing the electrical performance of the hybrid renewable energy systems by applying the DER-CAM investments, the Microgrid case still shows economic disadvantages. However, the biggest benefits of adopting the microgrid application, i.e., enhancement of a local grid's reliability, resiliency, power quality, and efficiency, are not quantified in this analysis. This study shows that the microgrid application is able to improve the efficiency of a system. However, addressing the increased application-specific value provided by these other important benefits remains a challenge that must be addressed by future studies: how to weigh these grid-related microgrid benefits including reliability, resiliency, and quality improvements, against the economic disadvantages when the customer considers the microgrid investment options.

Table 5
Economic performance evaluation of power system loss reduction of the optimal palcement of DER.

	Reference case	DER-CAM results	Reduction	Power system loss reduction	Total reduction
Microgrid case	$4,073,282	$4,233,259	*+ $159,977*	*- $977*	*+ $159,000*
Microgrid-PV case				*- $1,111*	*+ $158,866*
Microgrid-big load case				*- $978*	*+ $158,999*
Microgrid-big load case				*- $977*	*+ $159,000*

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