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Comparative Life Cycle Cost Analysis of Hardening Options for Critical Loads

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Abstract: In order to determine the most cost effective alternative among hardening options of power systems, the direct monetary benefits should be evaluated above all other things. Therefore, this paper presents a life-cycle cost model which describes total monetary costs experienced in annual time increments during the project with consideration for the time value of money. In addition, to minimize the risks associated with estimated cost errors due to uncertainties of input data, the stochastic input data are considered. Using the Monte Carlo method, the probabilities and cost ranges in the case studies can be predicted, in turn resulting in better decisions in the selection of hardening options which are cost effective.

Keywords: Monte Carlo method; cost benefit analysis; emergency power supplies; microgrids

1. Introduction

Due to two destructive storms, tropical storm Irene and the October snowstorm in 2011, more than 800,000 customers in the state of Connecticut lost power for over a week, resulting in monetary and intangible economic losses [1]. These major power outages point towards the vulnerability of the existing power system to extreme weather conditions. Moreover, the possibility of widespread outages may significantly increase due to abnormal changes in weather because distribution systems are not typically designed to withstand extreme weather events, such as hurricanes and ice storms. Thus power system hardening methods are of growing concern, placing pressure on electric utilities by state governments to harden the power system in order to cope with storms and bolster preparedness and response.

Three classifications of hardening options are undergrounding (UG), emergency generators (EGs), and microgrid systems. Frequent outages can be the fault of falling trees, wind, debris, or ice which can cause extensive damage to overhead lines. Typically, electricity transmission between generation and customers is through overhead power lines. Therefore, an underground system is a simple solution to this problem by merit of burying lines to prevent damage and disconnection [2]. A second method, EG which is generally fueled by fossil fuels and located close to electricity demand with minimal losses as a standby power source, has been employed for a long time where outages are more prevalent so that the supply of electrical power to the critical loads is constant, even in the case of a power system failure [3]. Finally, microgrid systems can harden the power system. A microgrid system is a small power system employing distributed generators, such as combined heat and power (CHP) or renewable power sources with reduced carbon emissions, in order to entirely supply a local load demand inside of the microgrid itself [4].

The purpose of this paper is to find a suitable approach capable of comparing the life cycle cost (LCC) among several hardening options which must provide continuous and steady power to critical loads of the towns during a long term power outage by catastrophic storms. Therefore, one of the most important requirements from the utility company is that the hardening option candidates should be more reliable, utilizing generation resources among many distributed generation systems. For example, due to tropical storm Irene and the October snowstorm in 2011, power outages lasted more than two weeks. Considering this requirement, the battery energy storage system (BESS) is typically used with distributed generation to compensate an intermittence of renewable sources like short-term power balancing, rather than be used as the independent power supplier without a renewable source for a long-term islanding operation. For this reason, BESS was excluded as a hardening option candidate due to the lack of capability in supplying power continuously for a few weeks, irrespective of its cost and availability. Additionally, photovoltaics (PV) and wind turbines were not considered as hardening options since their generated power is highly dependent on intermittent factors, whereas the fuel cell (FC) and micro-turbine (MT) as hardening options are able to generate stable emergency power to critical loads, such as schools, police stations, nursing home, hospitals, etc., as long as the external natural gas can be provided. Ultimately, FC and MT are selected as hardening options in a microgrid because of their suitability for the long-term power outage preparation, as well as the potential for modular construction and the fact that they may be more easily sited in a downtown district due to better sound characteristics.

Direct monetary benefits should be evaluated above other factors when determining the most cost effective hardening methods for power systems. When estimating the direct monetary benefits, LCC is a useful tool to optimize the cost of acquiring, owning and operating physical assets over their lives by attempting to identify and quantify all of the significant costs involved in that life, using the present value technique [5,6]. In power system applications, LCC has been applied to long-term vs. short-term energy storage [7], electric power generation [8], and renewable energy sources [9–11].

There are several prior studies on hardening power systems [3,12–15]. Multiple utility services and EG sets were considered to ensure continuity of electrical power to essential loads [3], but addressed some of the basic factors consisting of these emergency power systems rather than an economic consideration. Various tactics and strategies for hardening power systems based on Florida hurricane data in 2004 and 2005 were discussed in [12], but focused more on identifying the characteristics of poles that are likely to fail during extreme weather. Collaborative research efforts related to hardening efforts by Florida utilities were addressed to improve preparations for future storms in [13], but only UG was considered as a hardening option. Important considerations that should be evaluated when developing a flood mitigation strategy for electrical substations were proposed in [14], but the hardening methods are limited in detecting floods and building future substations with environmental immunity. Several simulation tools and models for stand-alone electric generation hybrid systems, such as a PV generator and/or wind turbines and/or diesel generators with energy storage are reviewed and compared in [15], but did not address the economic analysis approaches for calculating LCC. None of the papers used stochastic input data to compare LCC in hardening options of power systems, such as UG, EG, and microgrids, especially for storm preparedness.

In this paper, a comparative study of three hardening options for critical loads is performed through the use of LCC analysis [16]. From the proposed LCC model, total costs experienced in annual time increments during the project with consideration for the time value of money can be estimated. In addition, by considering the variation of critical input data, better decisions for the direction of a project can be carried out. For such a reason, the Monte Carlo method is used for forecasting the range of possible outcomes in the stochastic model.

2. Methodology

In order to provide a cost analysis of hardening options, the four steps shown in Figures 1 and 2 in detail, were followed, along with three assumptions:

- only electric loads are considered;
- microgrid distributed generation sources are running all of the time; and
- all generators are assumed to have a single interconnection point.

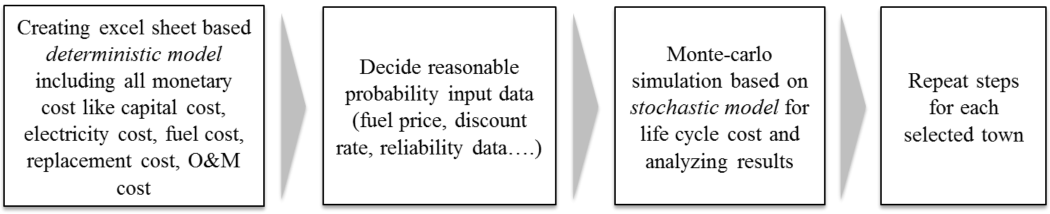


Figure 1. Procedure of cost analysis. O&M: operating and maintenance.

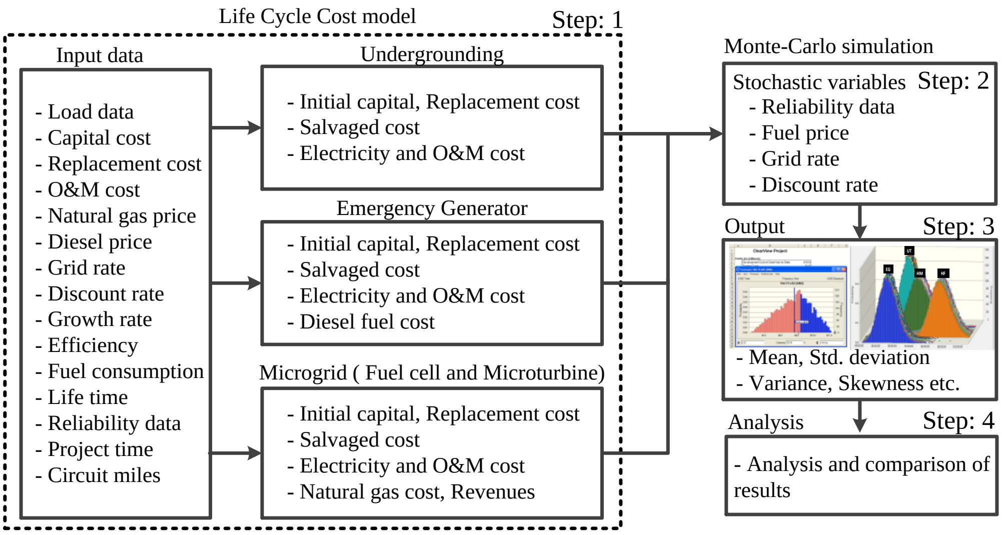


Figure 2. Approach for estimating life cycle cost (LCC) of hardening options.

The main reason to assume the microgrid generators operate all of the time is to assess the benefit of selling electricity as excess power from the microgrid. If the total cost of electricity generation is cheaper than that of utility grid electricity, the economical values can be added. In the LCC analysis, if the peak load is changed to 50% load, then the operational cost will be reduced, but the initial capital cost will be the same. Since the portion of the capital cost is larger than the operating and maintenance (O&M) cost, the main results of LCC analysis will be similar to that of various load conditions.

In the first step, an excel spreadsheet based on the deterministic model is created through several formulas and assumptions for each operating system. In the second step, the deterministic model obtained in the previous step must be extended to a stochastic model. The input data, which includes the uncertainty of future values, such as fuel price, grid rate, and annual interest rate, needs to be defined in this step. In the third step, a Monte Carlo simulation is executed to get the range of possible outcomes from the input data's minimum and maximum forecasted values and to analyze the critical factors affecting the total cost of power system hardening. Finally, Steps 1–4 are repeated for each selected town.

An assumption which is made is that reliability data concerning hardening options such as grid rate (buying and selling), natural gas price, diesel price, and annual net discount rate (discount rate − growth rate) are selected randomly from the predefined probability distributions. The probability density function of these inputs, with their mean and variance, can be defined as:

$$f(x) = f\left(x|\mu, \sigma^2\right) \quad (1)$$

Since deriving exact probabilistic LCC formulas with multiple random variables may be complicated, a Monte Carlo simulation is applied to estimate the probabilistic LCC. As the number of trials approaches infinity, the simulation output approaches the probabilistic LCC formula.

3. Formulas for Estimating Life Cycle Cost

3.1. Net Present Cost

The total net present cost (NPC) describing the time value of money is used to quantify LCC. The net discount rate can be defined as:

$$r_{\text{net}} = f\left(r_{\text{d}}|\mu_{\text{rd}}, \sigma^2_{\text{rd}}\right) - f\left(r_{\text{g}}|\mu_{\text{rg}}, \sigma^2_{\text{rg}}\right) \quad (2)$$

LCC is the total monetary cost of installing and operating a power system for the duration of its entire life and can be defined as:

$$C_{\text{NPC}} = C_{\text{ic}} - C_{\text{svg}} + \sum_{y=1}^{Y_{\text{P}}} \frac{C_{\text{oa}}(y)}{(1 + r_{\text{net}})^y} \quad (3)$$

where:

$$C_{\text{svg}} = C_{x\text{REP}}\left(\frac{1}{1+r_{\text{net}}}\right)^{Y_{\text{P}}}\left(1 - \frac{Y_{rx}}{Y_x}\right)$$
$$C_{\text{oa}}(y) = C_{\text{el}}(y) + C_{\text{rv}}(y) + C_{\text{f}}(y) + C_{\text{OM}}(y) + C_{\text{re}}(y)$$

The annual operating cost (C_{oa}) consists of the electricity cost (C_{el}) to feed local loads, revenue (C_{rv}) from selling power, fuel cost (C_{f}) to operate distributed generators, O&M cost (C_{OM}), and replacement cost (C_{re}) [9].

3.2. Energy Production

The amounts of annual energy production from energy sources need to be evaluated firstly to estimate the annual cost relating to the electricity, revenue, fuel, and O&M costs. Figure 3 shows the power flow diagram of three hardening options during normal and outage conditions. The formulas of the annual energy production from hardening options are as follows.

3.2.1. Undergrounding

UG will always run to support critical loads during normal conditions with much better reliability of the power system while UG cannot provide any power during the outages:

$$E_{\text{g}} = P_{\text{l}} \times \left(T_{\text{y}} - f\left(T_{\text{fu}}|\mu_{\text{fu}}, \sigma^2_{\text{fu}}\right)\right) \quad (4)$$

3.2.2. Emergency Generator

For the EG option, critical loads are supported by the over-head power system during normal conditions and by the EG during outages:

$$E_{\text{g}} = P_{\text{l}} \times \left(T_{\text{y}} - f\left(T_{\text{fg}}|\mu_{\text{fg}}, \sigma^2_{\text{fg}}\right)\right) \quad (5)$$

$$E_{\text{e}} = P_{\text{l}} \times \left(f\left(T_{\text{fg}}|\mu_{\text{fg}}, \sigma^2_{\text{fg}}\right) - f\left(T_{\text{fe}}|\mu_{\text{fe}}, \sigma^2_{\text{fe}}\right)\right) \quad (6)$$

3.2.3. Microgrid

To simplify the microgrid formulas, we assume that T_{fd2}, which represents the interruption hours by failures of microgrids during grid outages, is zero, i.e., $T_{\mathrm{fd}} = Tf_{\mathrm{d1}}$ since the probability of T_{fd2} is very small:

$$E_{\mathrm{g}} = P_{\mathrm{l}} \times f\left(T_{\mathrm{fd}} | \mu_{\mathrm{fd}}, \sigma_{\mathrm{fd}}^2\right) \tag{7}$$

$$E_{\mathrm{gb}} = (P_{\mathrm{l}} - P_{\mathrm{d}} \times R_{\mathrm{d}}) \times \left(T_{\mathrm{y}} - f\left(T_{\mathrm{fg}} | \mu_{\mathrm{fg}}, \sigma_{\mathrm{fg}}^2\right) - f\left(T_{\mathrm{fd}} | \mu_{\mathrm{fd}}, \sigma_{\mathrm{fd}}^2\right)\right) \tag{8}$$

$$E_{\mathrm{d}} = P_{\mathrm{d}} \times R_{\mathrm{d}} \times \left(T_{\mathrm{y}} - f\left(T_{\mathrm{fg}} | \mu_{\mathrm{fg}}, \sigma_{\mathrm{fg}}^2\right) - f\left(T_{\mathrm{fd}} | \mu_{\mathrm{fd}}, \sigma_{\mathrm{fd}}^2\right)\right) + P_{\mathrm{l}} \times f\left(T_{\mathrm{fg}} | \mu_{\mathrm{fg}}, \sigma_{\mathrm{fg}}^2\right) \tag{9}$$

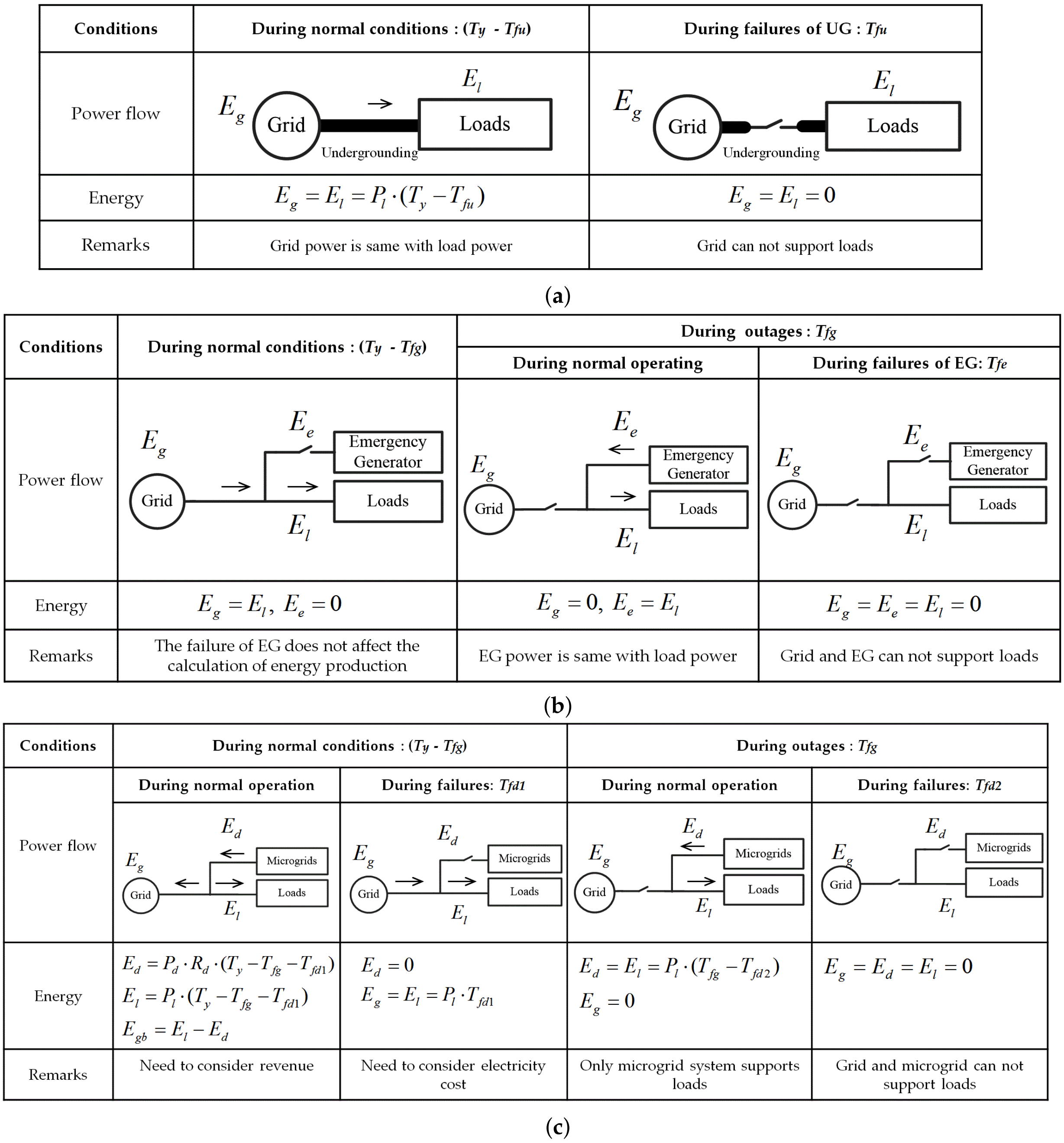


Figure 3. Power flow diagram for calcuating energy production: (**a**) undergrounding (UG); (**b**) emergency generator (EG); and (**c**) microgrid (MG).

3.3. Annual Operating Cost

Using Equations (4)–(9), the annual operating cost (C_{oa}) of hardening options can be calculated as follows.

3.3.1. Undergrounding

The annual operation cost of the UG option is comprised of the electricity and O&M costs:

$$f\left(C_{oa}|\mu_{oa},\sigma_{oa}^2\right) = C_{el}(y) + C_{OM}(y) \tag{10}$$

where:

$$\begin{aligned} C_{el}(y) &= E_g \times f\left(C_{bg}|\mu_{bg},\sigma_{bg}^2\right) \\ C_{OM}(y) &= C_{uOM}L_{ug} \end{aligned}$$

3.3.2. Emergency Generator

The annual operation cost of the EG option is comprised of the electricity, fuel, O&M, and replacement costs:

$$f\left(C_{oa}|\mu_{oa},\sigma_{oa}^2\right) = C_{el}(y) + C_f(y) + C_{OM}(y) + C_{re}(y) \tag{11}$$

where:

$$\begin{aligned} C_{el}(y) &= E_g \times f\left(C_{bg}|\mu_{bg},\sigma_{bg}^2\right) \\ C_f(y) &= (E_e \times F_{ds}/\eta_e) \times f\left(C_{ds}|\mu_{ds},\sigma_{ds}^2\right) \\ C_{OM}(y) &= E_e \times C_{eOM} + L_{oh} \times C_{ohOM} \end{aligned}$$

3.3.3. Microgrid

The annual operation cost of the MG option is comprised of the electricity, revenue from selling power, fuel, O&M, and replacement costs:

$$f\left(C_{oa}|\mu_{oa},\sigma_{oa}^2\right) = C_{el}(y) + C_{rv}(y) + C_f(y) + C_{OM}(y) + C_{re}(y) \tag{12}$$

where:

$$\begin{aligned} C_{el}(y) &= E_g \times f\left(C_{bg}|\mu_{bg},\sigma_{bg}^2\right) \\ C_{rv}(y) &= E_{gb} \times f\left(C_{sg}|\mu_{sg},\sigma_{sg}^2\right) \\ C_f(y) &= \left(E_d \times F_{ng}/\eta_d\right) \times f\left(C_{ng}|\mu_{ng},\sigma_{ng}^2\right) \\ C_{OM}(y) &= E_d \times C_{dOM} + L_{oh} \times C_{ohOM} \end{aligned}$$

4. Case Study

Three hardening options were evaluated using the proposed LCC model for selected two towns (A and B) with several critical facilities, such as hospitals, police stations, schools, nursing homes, and emergency shelters, where the microgrid configuration in Figure 4 exists.

Critical facilities will depend on many factors, such as location, state of the distribution network, distance to substation, availability of gas, etc. We consider four hardening options for critical loads: FC, MT, UG, and EG systems. For microgrid options, FC and MT systems which are fueled by natural gas are considered. This is because the preferences of photovoltaic or wind power systems are highly dependent on intermittent factors, such as weather, location, and season.

For Town A, the total power of critical loads, which has FC systems consisting of four parallel 400 kW units, MT systems consisting of nine parallel 65 kW units, and four parallel 200 kW units, for a total of 1222, 1600, and 1385 kW, respectively. For UG systems, the distance between substations to the critical load is 8.8 miles, whereas Town B has critical loads of 4455 kW, FC systems consisting of

12 parallel 400 kW units, and MT systems consisting of four parallel 65 kW units and 22 parallel 200 kW units. For UG systems, the distance between substations to the critical load is 4.4 miles. Regarding to available power capacities of microgrid options, we selected the minimum number of commercial distributed generator (DG) units, even though the total power of FC and MT are higher than the actual load. Additionally, it is worthwhile to indicate that the overall power system capacity of critical facilities in Town B is much higher than that of Town A.

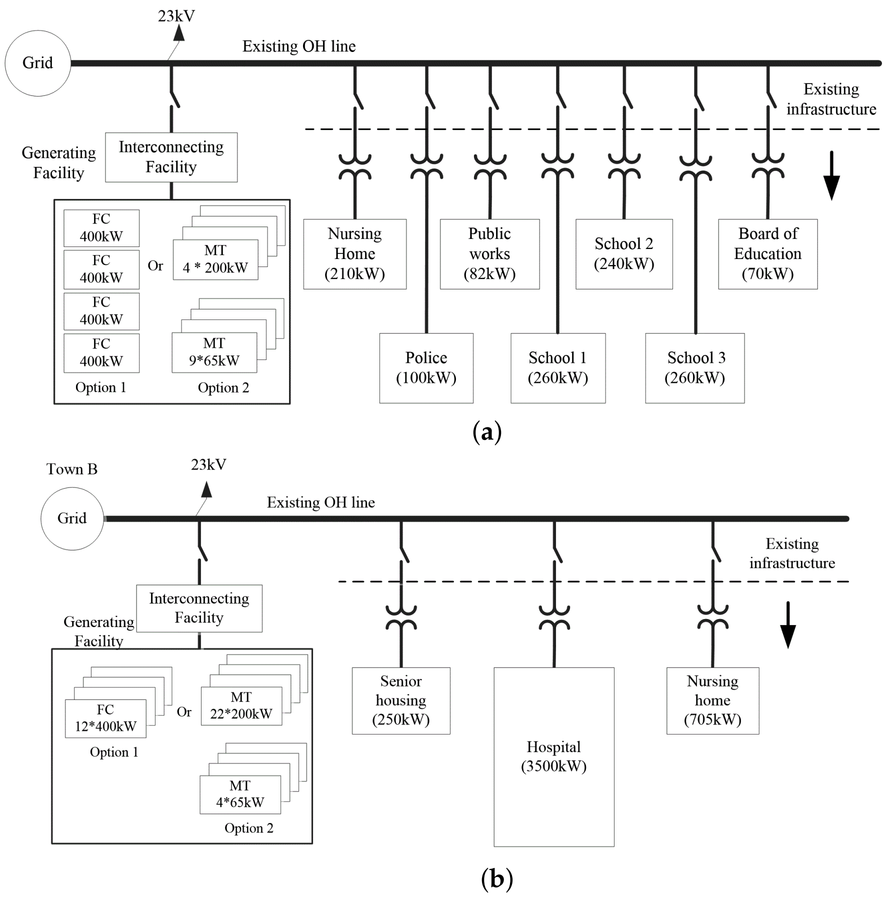


Figure 4. Microgrid configuration for critical load of a selected town: (**a**) Town A; and (**b**) Town B.

4.1. General Input Data

Table 1 shows the general input data used for estimating LCC of hardening options in this paper [17–22]. The initial capital costs of UG were quoted by the utility company.

Table 1. General input data. FC: fuel cell and MT: micro-turbine.

Data	Option	Value	Remarks
Project Time	-	**40 years**	-
Capital cost; Town A [17–19]	UG	$34,001,800	Circuit miles: 8.8
	EG	$1200/kW	Rated power: 1222 kW
	MT	$2400/kW	Included tax credit, rated power: 1385 kW
	FC	$4200/kW	Included tax credit, rated power: 1600 kW
Capital cost; Town B [17–19]	UG	$14,848,540	Circuit miles: 4.4
	EG	$1200/kW	Rated power: 4455 kW
	MT	$2400/kW	Included tax credit, rated power: 4660 kW
	FC	$4200/kW	Included tax credit, rated power: 4800 kW

Table 1. *Cont.*

Data	Option	Value	Remarks
Replacement cost ratio	EG MT FC	1.0 1.0 0.8 and 1.0	System replacment: 1.0 System replacment: 1.0 Stack: 0.8, System: 1.0
Efficiency [17,20]	EG MT FC	N/A 34% 43.5%–48%	Fuel consumption curve includes efficiency data - Stack aging degradation: 0.5%/year for 10 years
Fuel consumption curve	EG MT FC	0.277 L/kWh [21] 0.0941 m^3/kWh 0.0941 m^3/kWh	Including EG efficiency - -
Operating ratio (annual)	MT FC	0.96 0.95	- -
O&M cost [17,22]	UG EG MT FC	$4052/mile $0.015/kWh $0.0185/kWh $0.035/kWh	Over-head QandM: $917/mile - - -
Life time	UG EG,MT,FC	40 years 20 years	- FC Stack: 10 years [20]

The total costs of interconnecting facilities to connect the FCs or MTs with high-voltage lines (23 kV) in Town A and Town B are $5,701,584 and $3,957,640, respectively, and will be added with the initial capital cost of the generator unit.

4.2. Probabilistic Input Data

4.2.1. Reliability Data of Hardening Options

The reliability indices of hardening options under category-3 weather conditions shown in Tables 2 and 3 are used for interruption hours by failures of hardening options.

Table 2. Reliability data of hardening options (Town A). SAIDI: system average interruption duration index. Pro: probability.

Do-Nothing (T_{fg})		UG		EG		MT		FC	
SAIDI (h/year)	Pro.	SAIDI (h/year)	Pro.	SAIDI (h/year)	Pro.	SAIDI (h/year)	Pro.	SAIDI (h/year)	Pro.
47.02	0.975029	10.20	0.999924	1.90	0.997043	4.17	0.999802	6.43	0.999869
141.06	0.000517	30.61	0.000010	5.71	0.001194	12.51	0.000031	19.28	0.000021
235.10	0.000769	51.02	0.000007	9.51	0.000717	20.86	0.000028	32.14	0.000015
329.14	0.001704	71.42	0.000008	13.32	0.000425	29.20	0.000023	44.99	0.000011
423.18	0.003484	91.83	0.000006	17.13	0.000264	37.54	0.000026	57.85	0.000010
517.23	0.005039	112.24	0.000004	20.93	0.000175	45.89	0.000020	70.70	0.000010
611.27	0.004941	132.64	0.000008	24.74	0.000103	54.23	0.000011	83.56	0.000010
705.31	0.003881	153.05	0.000003	28.54	0.000046	62.57	0.000015	96.42	0.000012
799.35	0.002390	173.46	0.000001	32.35	0.000015	70.92	0.000006	109.27	0.000007
893.39	0.001235	193.86	0.000005	36.16	0.000009	79.26	0.000011	122.13	0.000004
987.43	0.000509	214.27	0.000007	39.96	0.000003	87.60	0.000005	134.98	0.000005
1081.47	0.000245	234.68	0.000003	43.77	0.000001	95.95	0.000005	147.84	0.000004
1175.51	0.000140	255.08	0.000004	47.57	0.000001	104.29	0.000004	160.69	0.000003
1269.55	0.000043	275.49	0.000003	51.38	0.000001	112.63	0.000004	173.55	0.000004
1363.60	0.000029	295.90	0.000001	55.18	0.000000	120.98	0.000002	186.40	0.000004
1457.64	0.000021	316.30	0.000002	58.99	0.000002	129.32	0.000002	199.26	0.000001
1551.68	0.000012	336.71	0.000000	62.80	0.000000	137.66	0.000001	212.11	0.000004
1645.72	0.000006	357.12	0.000001	66.60	0.000000	146.01	0.000001	224.97	0.000000
1739.76	0.000003	377.52	0.000001	70.41	0.000000	154.35	0.000002	237.83	0.000002
1833.80	0.000003	397.93	0.000002	74.21	0.000001	162.69	0.000001	250.68	0.000004

Table 3. Reliability data of hardening options (Town B).

Do-Nothing (T_{fg})		UG		EG		MT		FC	
SAIDI (h/year)	Pro.	SAIDI (h/year)	Pro.	SAIDI (h/year)	Pro.	SAIDI (h/year)	Pro.	SAIDI (h/year)	Pro.
44.14	0.975454	16.53	0.999935	2.22	0.999016	3.98	0.999876	4.69	0.999934
132.42	0.002403	49.58	0.000012	6.65	0.000233	11.94	0.000029	14.07	0.000017
220.69	0.004399	82.64	0.000006	11.08	0.000170	19.91	0.000018	23.46	0.000009
308.97	0.004749	115.69	0.000007	15.51	0.000160	27.87	0.000012	32.84	0.000007
397.25	0.003934	148.75	0.000005	19.94	0.000094	35.83	0.000011	42.22	0.000009
485.52	0.002934	181.80	0.000007	24.37	0.000087	43.79	0.000011	51.60	0.000003
573.80	0.002073	214.85	0.000009	28.80	0.000064	51.75	0.000010	60.99	0.000005
662.08	0.001523	247.91	0.000005	33.23	0.000051	59.72	0.000005	70.37	0.000003
750.35	0.001068	280.96	0.000004	37.66	0.000042	67.68	0.000008	79.75	0.000001
838.63	0.000691	314.02	0.000002	42.09	0.000028	75.64	0.000009	89.13	0.000002
926.91	0.000358	347.07	0.000004	46.52	0.000023	83.60	0.000002	98.52	0.000002
1015.18	0.000193	380.13	0.000000	50.95	0.000009	91.56	0.000001	107.90	0.000002
1103.46	0.000113	413.18	0.000000	55.38	0.000003	99.53	0.000001	117.28	0.000002
1191.74	0.000058	446.24	0.000000	59.81	0.000008	107.49	0.000003	126.66	0.000000
1280.02	0.000027	479.29	0.000001	64.24	0.000007	115.45	0.000001	136.05	0.000001
1368.29	0.000012	512.35	0.000001	68.67	0.000004	123.41	0.000002	145.43	0.000001
1456.57	0.000004	545.40	0.000000	73.10	0.000000	131.38	0.000000	154.81	0.000000
1544.85	0.000004	578.45	0.000000	77.53	0.000000	139.34	0.000000	164.19	0.000001
1633.12	0.000002	611.51	0.000001	81.96	0.000000	147.30	0.000000	173.58	0.000000
1721.40	0.000001	644.56	0.000001	86.39	0.000001	155.26	0.000001	182.96	0.000001

These reliability indices were obtained by applying a distribution evaluation method, which combines Sequential Monte Carlo simulation with the wind storm classification based on the National Oceanic and Atmospheric Administration's Atlantic basin hurricane database (HURDAT) [23].

4.2.2. Discount Rate and Growth Rate

One estimate of the discount rate, the regulated cost of capital, is 7.68% [24]. Another estimate is the social discount rate. A component, the real social discount rate, is 7% [25]. The long-term inflation rate estimate ranges between 1.6% and 2%, with an average of 1.8%, yielding a range between 8.6% and 9% for the social discount rate. Thus, we assume a lognormal discount rate with a mean of 8.6% and a typical range of 9% − 7.68% = 1.32%. We conservatively assume that the typical range approximates $2 \times \sigma$ [26], resulting in a standard deviation of 0.66%. The growth rate is assumed to be equal to the long-term inflation rate. Its lognormal distribution has a mean of 1.8% and a standard deviation of 0.2%.

4.2.3. Grid Rate

For the years 2010, 2015, 2020, 2025, 2030, and 2035, the price forecasts are (in cents) 5.9, 6.0, 6.7, 7.7, 8.7, and 10.2 [19]. Between the years, a growth rate of 2.2% is applied. Each price is used as the mean to a lognormal distribution for that year. The standard deviation estimate is 2.15 cents. We assume that selling and buying prices are the same.

4.2.4. Natural Gas Price

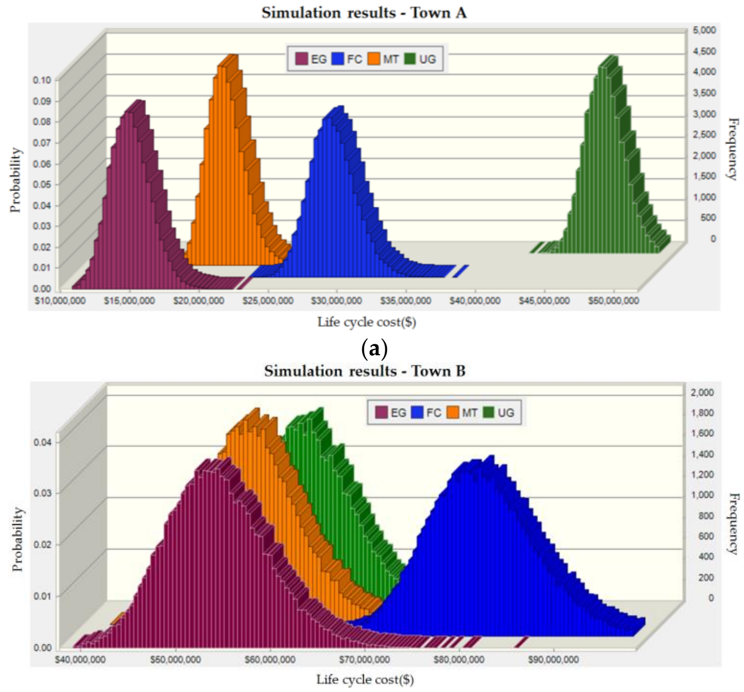
The natural gas prices (in $\$/m^3$) are 0.121, 0.141, 0.152, 0.158, 0.165, 0.171, 0.179, and 0.188 for the years 2013–2020 [27]. It is assumed to be log-normally distributed with a mean of 0.188 every year afterward and a standard deviation of 0.034.

4.2.5. Diesel Price

The diesel prices are (in $/L) are 0.7754, 0.7542, 0.7542, 0.7542, and 0.7542 for 2013–2017 [28]. It is assumed to be log-normally distributed with a mean of 0.7542 every year afterward and a standard deviation of 0.0106.

4.3. Monte Carlo Simulation Results

Oracle crystal ball (Oralcle Corporation/Crystal Ball, Redwood, CA, USA) was used for Monte Carlo simulations. Figure 5 shows the overlaid graph of LCC of hardening options with probability density. Tables 4 and 5 summarize simulation results of LCCs and the rankings of hardening options for the two selected towns.



(**a**)

(**b**)

Figure 5. Graphical comparisons of Monte Carlo simulation results: (**a**) Town A; and (**b**) Town B.

Table 4. Monte Carlo simulation results for Town A. Std.: standard and Err.: error.

Statistics	UG	EG	MT	FC
Trials	50,000	50,000	50,000	50,000
Mean	$46,730,412	$14,994,018	$20,227,892	$28,809,085
Median	$46,672,406	$14,927,494	$20,113,017	$28,718,110
Std. deviation	$1,412,934	$1,485,678	$1,361,704	$1,686,376
Skewness	0.2710	0.3027	0.5086	0.3464
Kurtosis	3.09	3.16	3.45	3.19
Coeff. of variability	0.0302	0.0991	0.0673	0.0585
Minimum	$41,870,648	$9,946,469	$16,072,968	$23,131,038
Maximum	$53,920,997	$22,383,557	$27,517,404	$37,236,825
Range Width	$12,050,349	$12,437,088	$11,444,436	$14,105,787
Mean Std. Err.	$6319	$6644	$6090	$7542
Rank	4	1	2	3

Table 5. Monte Carlo simulation results for Town B.

Statistics	UG	EG	MT	FC
Trials	50,000	50,000	50,000	50,000
Mean	$60,019,352	$54,215,510	$55,939,691	$80,937,534
Median	$59,775,351	$53,953,165	$55,576,689	$80,641,979
Std. deviation	$5,072,177	$5,367,375	$4,833,765	$5,761,886
Skewness	0.2875	0.3036	0.5017	0.3363
Kurtosis	3.12	3.17	3.52	3.24
Coeff. of variability	0.0845	0.099	0.0864	0.0712
Minimum	$42,170,109	$35,419,683	$40,923,654	$60,732,901
Maximum	$85,528,913	$85,952,364	$85,813,275	$111,246,747
Range Width	$43,358,804	$50,532,681	$44,889,621	$50,513,846
Mean Std. Err.	$22,683	$24,004	$21,617	$25,768
Rank	3	1	2	4

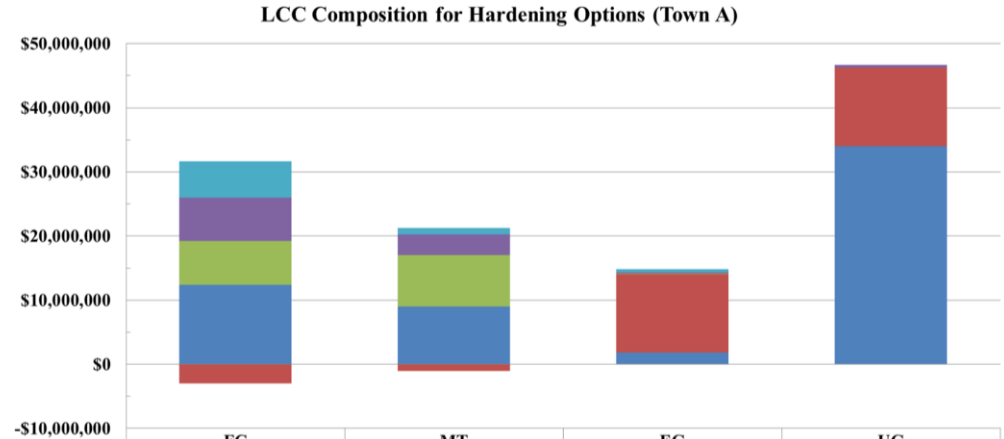
For Town A in Figure 5, EG has the lowest LCC to harden the critical power loads due to its low initial capital cost. However, the LCC of EG may significantly increase as the duration of the power outage increases because the operating cost by diesel fuel is higher than that of other hardening options. The UG has low O&M and electricity generation costs, but was less attractive due to its high initial capital cost. The MT can be a favorable alternative solution among other microgrid-distributed generation options because its capital and operating costs are competitive when compared to photovoltaic, wind turbine, and FC systems. The FC has a high initial and replacement cost, in spite of its high efficiency and being an environmentally friendly system. However, the benefits of the FC will be increased if its social or environmental benefits are considered.

For Town B in Figure 5, the EG has the lowest LCC due to lower capital and annual operating costs like Town A, but its LCC is not significantly lower than that of other options. The MT is also an attractive hardening option owing to low generation cost of electricity for higher critical load power. The initial capital cost of UG is relatively lower than that of Town A due to a shorter circuit mile and lower construction cost, which will be highly dependent on geographic location of the town. As a result, the order of the low cost of hardening options is changed slightly and the distribution of the cost in Town B is much more overlapped than that of Town A.

Figure 6 shows LCC compositions for hardening options. For Town A, the FC and MT options acquire revenue by selling power back to the grid due to their high power capacity, but the FC has high initial, operating, and replacement costs, whereas the MT has a high fuel cost due to its low efficiency. The UG has the highest initial capital cost, which increases its LCC. The initial capital cost of the EG is much less than that of the other options, resulting in the lowest LCC.

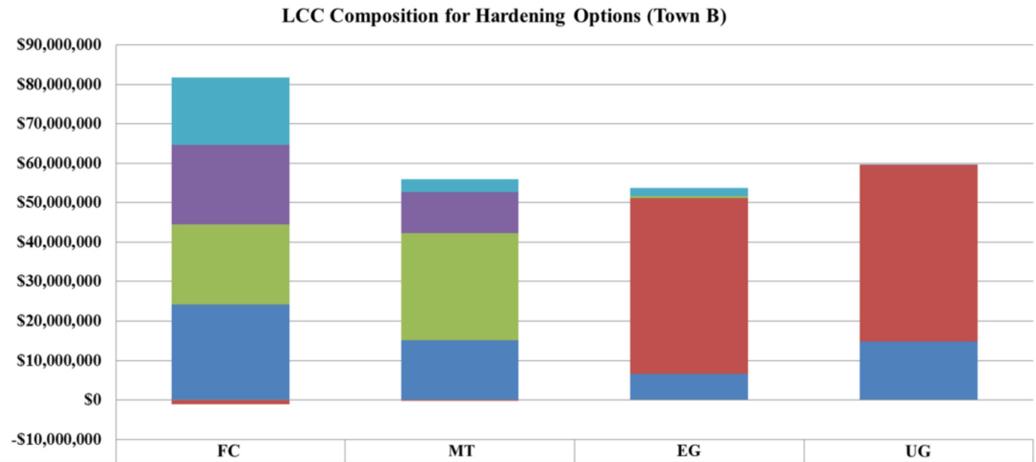
For Town B in Figure 6, the revenue of microgrid options is low because the power capacity is close to the total load. The FC suffers from high initial, operating, and replacement costs due to higher power capacities of critical facilities, resulting in a high LCC. It is noticeable that the MT, EG, and UG have a similar LCC. The initial capital cost of the UG is lower than that of the microgrid options, resulting in a better rank than that of Town A.

It is worthwhile to mention that the results of the analysis may be different depending on whether the facilities of hardening options are utility-, publicly-, or privately-owned and whether they are self-financed. For the case of microgrid projects in Connecticut, USA, the ownership of FC, EG, and MT to critical loads typically comes from the towns or university while the state grants the interconnection and engineering costs. Considering the economic aspects only, the utility company would prefer EG to UG, but many towns may not want to possess a diesel generating facility located in their town center.



	FC	MT	EG	UG
Replacement	$5,670,259.9	$961,232.5	$530,065.9	$0.0
O&M	$6,779,850.5	$3,198,888.8	$126,171.5	$378,004.8
Fuel	$6,810,389.4	$8,042,887.4	$148,295.3	$0.0
Electricity	-$2,972,325.8	-$1,072,018.4	$12,210,780.1	$12,261,819.5
Capital	$12,421,583.6	$9,025,583.6	$1,833,000.0	$34,001,800.0

(**a**)



	FC	MT	EG	UG
Replacement	$17,010,780	$3,234,183	$1,932,442	$0
O&M	$20,069,101	$10,436,104	$87,916	$189,002
Fuel	$20,449,980	$27,071,818	$420,613	$0
Electricity	-$1,037,876	-$176,522	$44,560,235	$44,693,567
Capital	$24,117,640	$15,141,640	$6,682,500	$14,848,540

(**b**)

Figure 6. LCC compositions for hardening options: (**a**) Town A; and (**b**) Town B.

In this case study, the dispatch controller, which decides the optimal moment to purchase or sell energy to the grid in order to run the system at the lowest possible cost, is not considered for a simple cost model structure. However, the levelized cost of energy (LCOE, dollar/kWh), which is a measure of a power source to compare different methods of electricity generation, is calculated from the total annualized cost and the generated power both from microgrid and power grid. As a result, the LCOE of FC and MT at Town A are 0.151 and 0.121, respectively. For Town B, the LCOE of FC and MT are 0.141 and 0.099, respectively. These values can be employed for the economic dispatch by comparing the LCOE with variable grid rates.

5. Conclusions

This paper has presented the framework for the evaluation of a life-cycle cost of hardening options. The stochastic input data are considered to minimize the risks associated with estimated cost errors resultant from uncertainties inherent to input data. Using a Monte Carlo simulation, the range of possible LCC outcomes can be forecasted for selected hardening options, resulting in leading to better decisions for power systems for storm preparedness and response. The proposed LCC approach applied case studies of two towns and can be summarized as follows:

- EG have a lower LCC for power system hardening compared to other hardening options due to low initial capital cost. Additionally, the installation and maintenance are simple and easy. However, if the power outage happens more frequently due to extreme weather events, the operating cost of EGs, like the fuel and O&M costs, tend to significantly increase and, thus, EG as an option will be less attractive in hardening a power system.
- UG can be an alternative solution since UG tends to have low operating costs, such as low O&M and electricity generation costs. Additionally, it has a longer lifetime compared to other options. However, UG tends to have a high initial capital cost and longer construction time, which makes UG less attractive. If the circuit miles of UG are short and the initial capital costs are relatively low, UG can be a better candidate as a hardening option.
- FC systems generally have high initial and replacement costs in spite of high efficiency and environmentally friendly operation. Additionally, its operating cost depends highly on the fuel and O&M costs. FC systems can become a better option as a sustainable energy source if their technology is enhanced and their capital, replacement, and O&M costs are reduced in the future.
- MT systems can be an alternative solution among many existing distributed generation systems. Their capital and operating costs reach an acceptable level compared to other distributed sources, such as PV, wind turbine, and FC.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

x	Subscripts to represent: g: grid; u: undergrounding; e: emergency generator; d: microgrid; l: critical loads; oh: overhead-line system
Y_{p}	Project time (year)
T_{y}	Total hours for one year (hour)
$T_{\mathrm{f}x}$	Interruption hours by failures of "x" (hour/year)
$T_{\mathrm{r}x}$	Running-time of "x" (years)
T_x	Life-time of "x"(years)
E_x	Annual power from "x" (kWh/year)
E_{gb}	Annual power back to grid (kWh/year)
P_x	Rated power of "x" (years)
R_{d}	Averaged annual operation ratio of microgrids
η_x	Efficiency of generator unit "x" (%)
r_{net}	Annual net discount rate (%)

r_d	Annual discount rate (%)
r_g	Annual grow rate (%)
F_{ds}	Diesel consumption coefficient (L/kWh)
F_{ng}	Natural gas consumption coefficient (m^3/kWh)
L_{ug}	Circuit miles of undergrounding line (mile)
L_{oh}	Circuit miles of overhead line (mile)
C_{NPC}	Total net present cost ($)
C_{ic}	total initial capital cost ($)
C_{svg}	Salvaged cost of power generator unit ($)
C_{oa}	Annual total operating cost ($/year)
C_{el}	Annual net electricity cost ($/year)
C_{rv}	Annual revenue ($/year)
C_f	Annual fuel cost ($/year)
C_{re}	Annual replacement cost ($/year)
C_{OM}	Annual O&M cost ($/year)
C_{bg}	Buying rate from grid ($/kWh)
C_{sg}	Selling rate to grid ($/kWh)
C_{ng}	Natural gas price ($/$m^3$)
C_{ds}	Diesel price ($/L)
C_{xOM}	O&M cost of "x" generator unit ($/kWh, $/mile)
C_{xREP}	Replacement cost of "x"generator unit ($)

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