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Research Article

Techno-economic and environmental analysis of microgrid: A case study of Karabuk University

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ABSTRACT

The interest for microgrids has increased in the last decades, bringing important conditions such as energy efficiency, reduction of production pollution, reliability of the system. Microgrid as a key of Smart Grid plays a vital role in power losses reduction, voltage profile improvement, mitigating the pollutant emission, enhance the reliability and quality of power system. In this paper the techno-economic and environmental analysis of Karabuk university Microgrid are considered. The Microgrid of Karabuk university campus is simulated and analyzed by HOMER (Hybrid Optimization Models for Energy Resources) software for optimization, sensitivity, demand response and pollutant emissions. The results of the techno-economic and environmental analysis suggest the integration of new distributed generation for 25-years of service time. In the proposed scenario, legalized cost of energy is \$0.284 with renewable fraction of 14.8%, net present cost and operating cost decrease to 11.28% and 21.21%, respectively. It has showed that the proposed hybrid microgrid system contributes to the clean university campus concept and provides the lowest cost of electricity with the best payback time.

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INTRODUCTION

The energy demand is growing exponentially in the world. Hydrocarbon resources are depletable and limited in supply. Therefore, natural resources should be used sparingly. The development trends of power systems in the world require not only to increase electricity production in large power plants, but also to raise the share of distributed generation (DG) based on renewable energy sources. Distributed energy resources (DER) have advantages over centralized power generation. These advantages such as system stability improvement, reducing transmission and distribution overload, power losses reduction, voltage profile improvement, pollutant emission reduction and others enhance the reliability and quality of power system [1-3].

In recent years, impetuous penetration of DER to power system, the development of power electronic system and implementation of new information and communication technology in the power systems led to the concept of Smart Grid. Microgrid (MG) as a key component of the Smart Grid can be functioned in small-scale version of electric

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power system in stand-alone mode or in grid-connected mode, i.e. with main grid [4].

The following features differ MG from conventional power systems [5-7]:

- Steady-state and dynamic characteristics of DERs differ from turbine-generator units that are used for generation in conventional power systems.
- There is a significant degree of imbalance by the reason of MG has single-phase loads and/or DER units.
- Power supply in MG can be provided by "non-controllable" sources, for example from wind energy conversion systems units.
- It is easier to connect and disconnect DERs and loads within MG for maintenance.
- Energy storage units can provide a stability operation and a power of a microgrid.

It should be noted that MG is formed as a new concept in power systems in the last decades. Various areas of MG such as architecture, operation, protection, control strategy, standards, communication, and optimization in detail have been studied and explored in the works [8-15].

Techno-economic analysis of MGs is discussed in several research. For example, the optimal design, planning, sizing and operation of a hybrid microgrid with the propose of minimizing the net present cost are discussed in [16]. In [17], a hybrid system that consists of PV panels, battery system and diesel generator is designed, and techno-economic analysis is conducted for Malaysian village household. In most articles [18-20] the effect of uncertain parameters on net present cost (NPC), operation results of resources, production of emissions and other parameters of best plans are evaluated using HOMER software.

Techno-economic analysis of the MG can be carried out using advanced modeling tools that should ensure the reliability of obtained results instead of complex and time-consuming algorithms and costly physical experiments. The survey related to software application for optimization and economic analysis showed that HOMER software has been widely applied and more popular tool than another applied tools [21, 22].

There are the issues such as increasing utility bills and indirect carbon emissions, maintaining a complex distribution network infrastructure in a large university community to provide uninterrupted power supply. The management of Karabuk university has installed PV panels at five of eight educational buildings of Karabuk University (KBU) campus to reduce the electricity consumption from utility grid, power managing costs and enhance green environment.

In this work, MG simulation, optimization, sensitivity, and demand response are performed on the example of KBU Engineering faculty. The purpose of the paper is to determine techno-economic and environmental performance of MG. Unlike works related to MG, in this article is analyzed the effectiveness application of microgrid system in KBU campus on the example of Engineering faculty building. Also, a new function of HOMER Grid software – the demand response application is considered to enhance efficient electricity price for KBU using MG system.

MATERIALS AND METHODS

In paper, the results for simulation, technical-economic analysis (optimization, sensitivity analysis, demand response) of KBU Microgrid is utilized by HOMER Grid software tool. This software developed by the National Renewable Energy Laboratory (NREL) and implements the following analysis: simulation, optimization, sensitivity and demand response. The following input data are required to process these analyses in HOMER: load profile, equipment characteristics, meteorological data, economic and technical data, search space.

The flow chart of the methodology steps is presented in Figure 1. The steps for analysis consist of pre-HOMER and post-HOMER analysis. In the post-HOMER analysis, we firstly have determined the largest electricity building of KBU consuming electricity. The analysis of electricity consumption among KBU buildings is demonstrated that Engineering faculty building is the largest consumer at the campus. Therefore, KBU MG system is designed on the example of Engineering faculty. Generally, in pre-HOMER input data are collected to perform techno-economic analysis in post-HOMER phase. The detailed load profile of Engineering faculty, equipment characteristics, technical data and meteorological data are carried out in pre-HOMER phase. Research investigations show that potential of wind energy in Karabuk region is low with 2.4 m/s annual

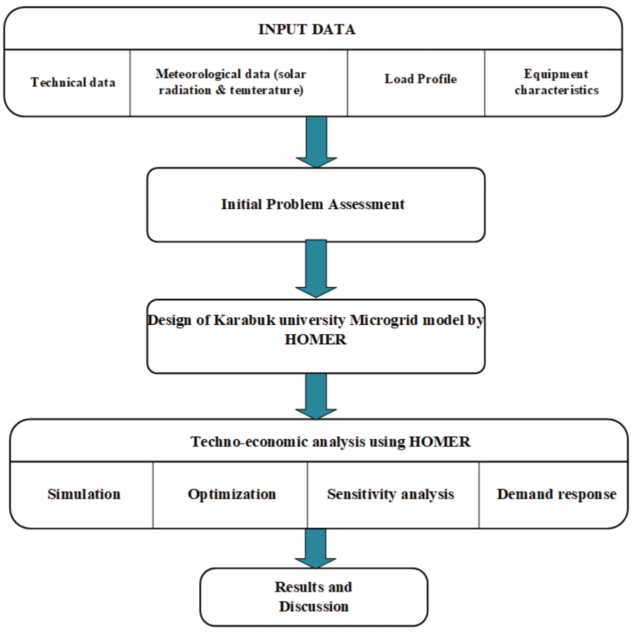

Figure 1. Steps for KBU MG analysis.

average wind speed and 21.3 W/m^2 annual average wind density [23-26]. Therefore, modelling of the MG with a wind turbine for Karabuk is not rational and we did not join wind conversion system to KBU MG. Meteorological data (solar radiation and temperature), load profile, technical data and equipment characteristics of Engineering faculty building have collected as input data for techno-economic processing in HOMER. Temperature and solar radiation data for Karabuk province is obtained from database of Turkish State Meteorological Service (TSMS) [27].

Techno-economic analysis is conducted for both islanded and grid-connected modes of MG system operation. The optimization of studied system is executed using HOMER software, and total NPC as objective function is minimized taking into account the constraints. The constraints are conditions that should satisfy configurations of system, for example the fraction of the total electrical demand, share of energy generated by renewable sources, power balance constraints.

System Characteristics

Demir Celik campus is the central campus of Karabuk university. The latitude and longitude location of KBU campus are 41º12'22"N and 32°39'35"E, respectively. KBU Demir Celik campus is shown in Figure 2.

The electric power of KBU campus is supplied by substation of Enerjisa Başkent A.Ş. company. Engineering faculty building of KBU is chosen as case study for microgrid. The proposed KBU MG is a 50 Hz with 0.4 kV LV network, which consists of diesel generator, PV panels, battery storage system, critical (controllable) and non-critical loads (non-controllable) is illustrated in Figure 3. Distributed generation units are located near area of electrical consumption to prevent electrical losses. Critical loads power supply provided by diesel generator and solar PV system. The components of KBU MG system are given in Table 1.

Figure 2. Demir Celik campus of KBU.

Design of Karabuk university Microgrid

KBU MG system architecture which is configurated in HOMER Grid simulation tool is shown in Figure 4.

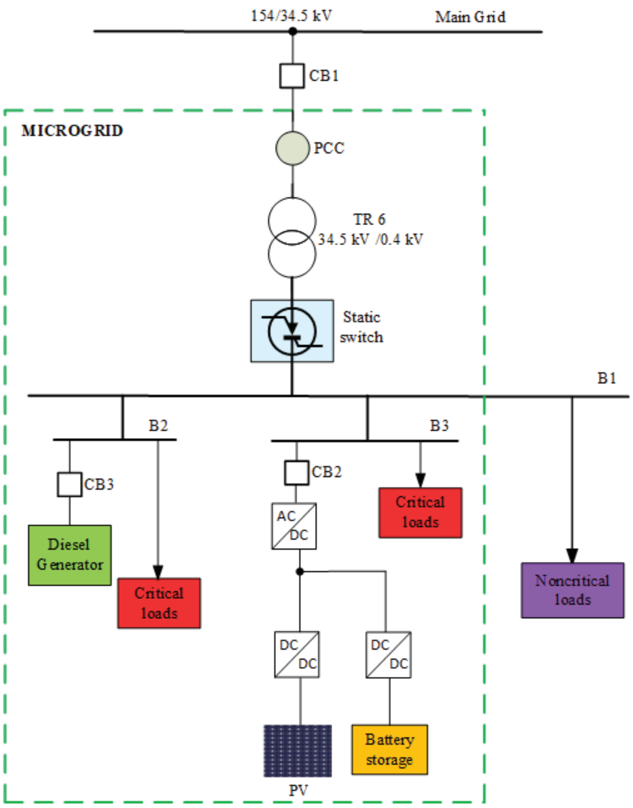

Figure 3. KBU MG single line diagram.

Table 1. KBU Microgrid components

Component	Name	Size	Unit
Diesel Generator	Kohler 410 Standby	430	kW
PV	ABB Trio-50.0 with Generic PV	279	kW
PV dedicated converter	ABB50 inverter	50.0	kW
Battery Storage	Hitachi LL1500-W	1	strings
Dispatch strategy	HOMER Peak Shaving		
Utility grid	Enerjisa Başkent A.Ş.		

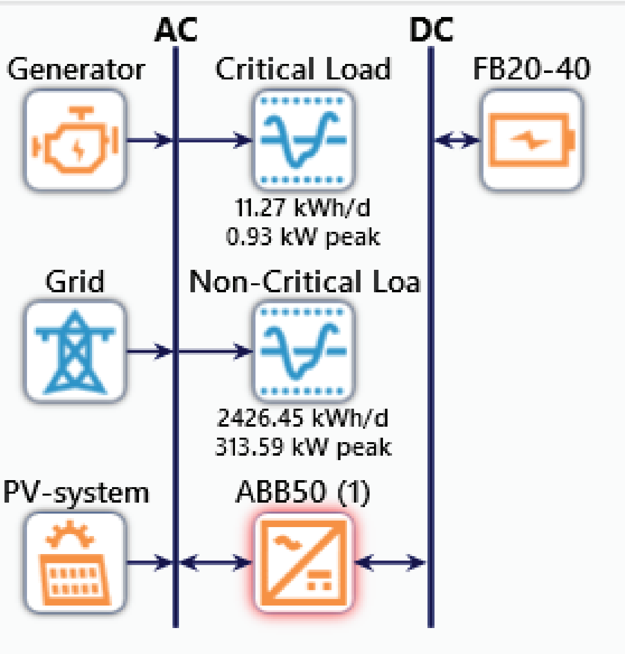

Figure 4. System architecture of KBU MG in HOMER.

Load Profile

The loads of studied faculty building are divided into critical and non-critical loads. MG can be operated in grid-connected mode (MG connected to distribution network) or in islanded mode (MG operates autonomously). By the reason of shortage of distributed energy resources within MG critical loads should be first served. Therefore, loads of Engineering faculty classified into critical and non-critical load. Daily and seasonal profile of critical loads are illustrated in Figure 5 and Figure 6, respectively. In the same way, daily and seasonal profile of non-critical loads calculated by HOMER are illustrated in Figure 7 and Figure 8, respectively. If there are some outages, failures in utility grid, MG disconnects from grid and the power for critical loads provides by diesel generator and PV-battery system.

Solar Resource

Solar resource indicates the amount of global solar radiation that strikes earth's surface. As mentioned above, the temperature and solar radiation data for Karabuk province are obtained from Turkish State Meteorological Service (TSMS). According to TSMS data an average solar

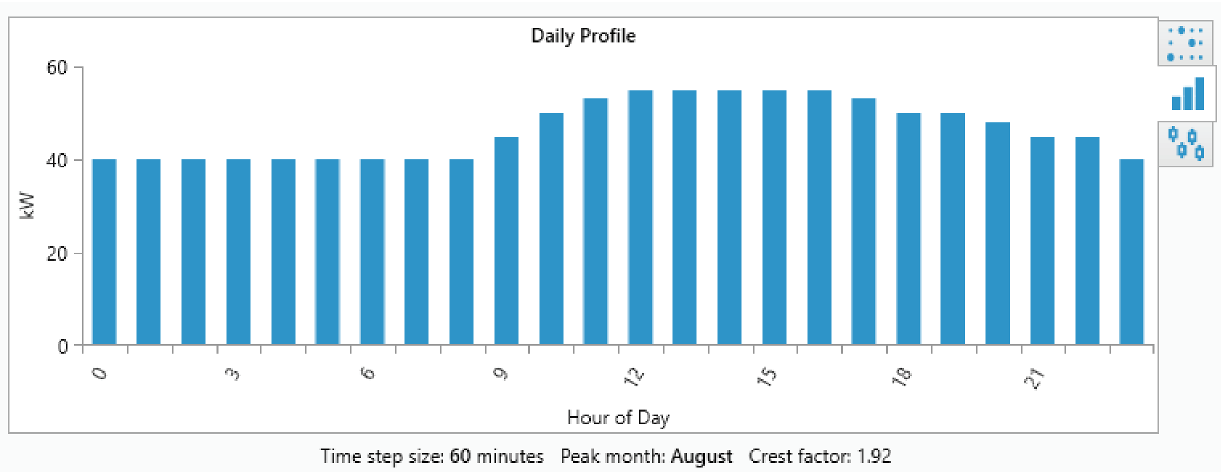

Figure 5. Daily profile of critical loads.

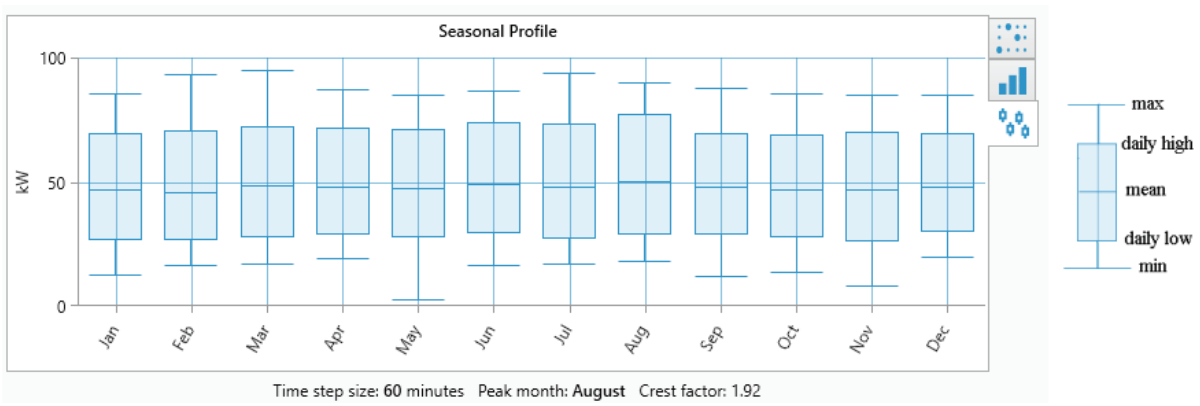

Figure 6. Seasonal profile of critical loads.

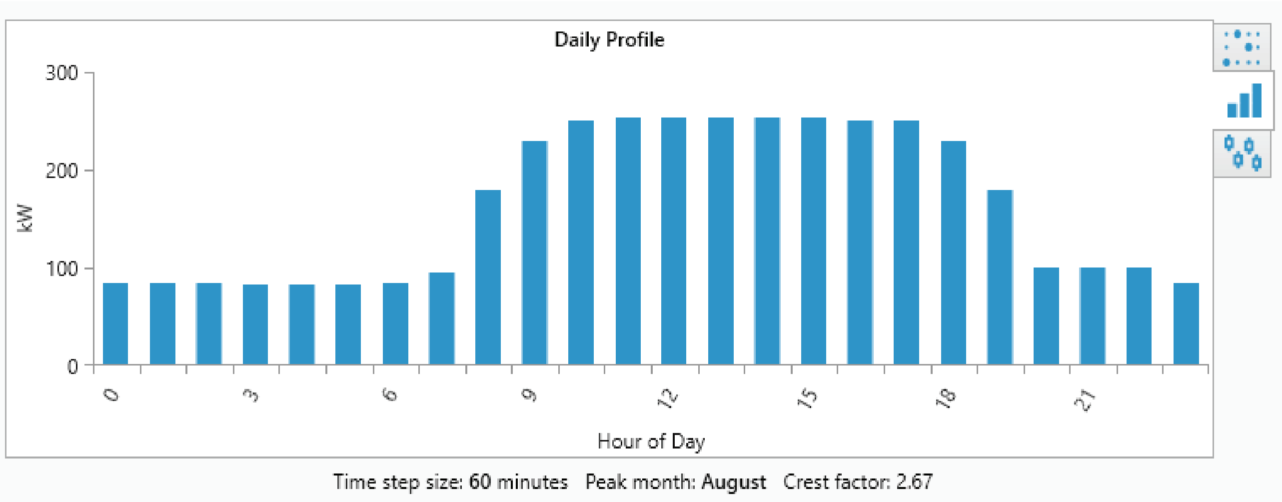

Figure 7. Daily profile of non-critical loads.

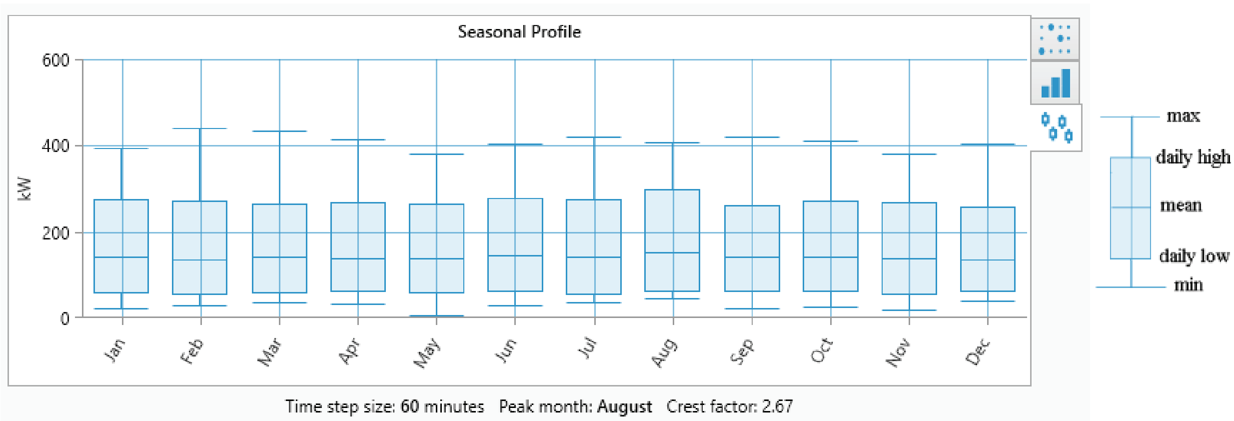

Figure 8. Seasonal profile of non-critical loads.

Figure 9. Solar Global Horizontal Irradiation.

radiation in Karabuk is 4.1 kWh/m²/day and a clearness index is 0.520. The clearness index is a measure of the clearness of the atmosphere, and which is expressed by the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. The solar irradiation and global horizontal radiations for Karabuk are shown in Figure 9. In order to account the degrading factors caused by temperature, soiling, tilt, shading etc. a derating factor of 80% is applied to each panel.

TECHNO-ECONOMIC ANALYSIS OF KBU MICRO-GRID

Optimization Analysis

Techno-economic analysis of the system consists of optimization, sensitivity and demand response analysis. HOMER using input data processes and simulates multiple system configurations results, and finally determine the best configuration that satisfies the technical restrictions at the lowest life-cycle cost.

NPC and levelized cost of energy (COE) are main indicators to determine economic metrics of energy systems by software tool. The life-cycle cost of the system that is represented in HOMER as NPC summarizes installing, operating, maintenance, replacement and fuel costs of all components during the project lifetime, also cost of purchasing electricity from the grid. The total NPC reduces if there are any incomes from sale of electricity to the grid. In HOMER the total NPC is calculated using the following equation [28].

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{1}$$

where: $C_{ann,tot}$ – total annualized cost of the system [\$/yr]; i – the annual real discount rate [%]; R_{proj} – the project lifetime [yr]; CRF (·) is a function returning the capital recovery factor, which is given by the formula:

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

where: N – number of years.

Levelized COE is calculated with the following equation:

$$COE = \frac{C_{ann,tot} - c_{boiler} H_{served}}{E_{served}} \tag{3}$$

where: c_{boiler} – boiler marginal cost [\$/kWh]; H_{served} – total thermal load served [kWh/yr]; E_{served} – total electrical load served [kWh/yr].

In our case study: $c_{boiler} = 0$, $H_{served} = 0$. Therefore, COE is described by the equation:

$$COE = \frac{C_{ann,tot}}{E_{served}} \tag{4}$$

Another economic metrics of considered system are the internal rate of return (IRR) and return on investment (ROI). IRR is a discount rate at which net present value (NPV) of all cash flows is equal to zero. IRR is defined from the following equation [29]:

$$0 = NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+IRR)^t} \tag{5}$$

where: CF_t – cash flow during the period t (years)

T – the life (years) of the system

NPV – the net present value of all cash flows from a particular project equal to zero.

ROI introduces yearly cost savings relative to the initial investment. ROI calculation is given by HOMER as follows [30]:

$$ROI = \frac{\sum_{i=0}^{R_{proj}} C_{i,ref} - C_i}{R_{proj}(C_{cap} - C_{cap,ref})} \tag{6}$$

where: $C_{i,ref}$ – nominal annual cash flow for base (reference) system; C_i – current system nominal annual cash flow; R_{proj} – project lifetime in years; $C_{cap,ref}$ – base system capital cost; C_{cap} – current system capital cost.

A financial metric for cash flow analysis is defined as payback period (PB) [30]. The PB can be calculated as:

$$PB = \left(\frac{Initial\ Investment}{Cash\ flow\ per\ period}\right) \tag{7}$$

Renewable fraction (RF) is the fraction of energy that generated from renewable sources and supplied to loads. In can be calculated as follows [30]:

$$RF = 1 - \frac{E_{nonren} + H_{nonren}}{E_{served} + H_{served}} \tag{8}$$

E_{nonren} – non-renewable electrical production [kWh/yr]

H_{nonren} – non-renewable thermal production [kWh/yr]

E_{served} – total electrical load served [kWh/yr]

H_{served} – total thermal load served [kWh/yr].

Sensitivity Analysis

In the sensitivity process HOMER analyze optimization of the system for uncertainty variables such as global solar, wind speed and diesel fuel price which entered by modeler.

HOMER executes sensitivity analysis of multiple values for each input variable. These multiple values specified for input assumptions is called sensitivity variable. User can designate one, two or more sensitivity variables for each input variable and sensitivity analysis can be one, two-dimensional and so on depending on the quantity of sensitivity variables.

In this process, the program evaluates the influences of uncontrolled parameters or changes. Finally, a list of various hybrid system configurations will be presented in the table, considering total NPC, COE and operating cost of each configuration from lowest to highest value and HOMER will show the optimal configuration system with lowest total NPC, COE and operating cost. In HOMER, random number generator is also used to select the times of outages and demand response events. The "seed" is some number used by the random number generator. Random seed affects random outages and random demand response events.

Demand Response

As fined in the literature demand response (DR) is the process to reduce or shift of intentional energy usage by costumers while peak time in response in market prices [31, 32]. DR is also an effective way to shave of peak demand, to manage of risk and reliability, to reduce of energy cost and carbon emission [33].

DR programs are significant and valued resource of power systems. Over the last few decades, with integration of large fraction of renewable generation into power systems, demand response programs become more functionable tool enabling to provide not only peak load reductions, and also enhance efficient price formation in electricity market, improve reliable operation of power systems [34].

DR resources have connection with energy markets in the following ways: either as dispatchable system operator, or non-dispatchable system operator. Dispatchable system operators interface directly with wholesale market to bid and get reduced payment for DR. Non-dispatchable system operator takes part in price-based demand response programs that provide customers with updated price information by promoting them lower energy consumption while peak load time. These resources are not "steady", because they are not dispatchable, and system operators do not sure about feedback users' responses. Non-dispatchable price-based programs can be used by residential and small customers with smart meters.

DR can be employed in MGs for loads managing and to distribute the consumption among hours. If in grid-connected mode DR is used to get economic benefit, while in islanded mode DR can be utilized to provide the security of power supply [35].

HOMER Grid using the electricity production data of all generation units simulates the demand response model. The program calculates the amount of baseline load reduction based on the measures and records of customer baseline load. HOMER demand response program also supplies how much customers should bid to reduce and what battery/generator capacity they should invest in to reduce grid purchases during DR event.

RESULTS AND DISCUSSION

The simulation results are performed with specified data through HOMER to obtain the optimal result for grid-connected KBU microgrid. After simulation HOMER proposes the best option of NPC, legalized cost of energy (LCOE), operation cost, reduced electricity bill, and other economic parameters for different cases. There are four cases: Case 1 – Utility and generator (base case); Case 2 – Utility, PV-system and generator; Case 3 – Utility, PV-system, battery storage and generator; Case 4 – Utility, battery storage and generator. The comparison results of yearly electricity production and consumption data for all cases of system configuration are presented in Table 2. These analyses show that the systems with solar PV configuration (Case 2 and Case 3) have more electricity production than other systems (Case 1 and Case 4). The share of electricity production by solar PV for Case 2 and Case 3 is 20.7% and 20.6%, respectively. Because there are only AC loads in LV bus, the electricity consumption is the same for all cases. The surplus yearly electricity sold to grid by systems with solar PV configurations are 2,409 kWh and 2,382 kWh for Case 2 and Case 3, respectively.

Table 2. Yearly electricity production summary

Component	Case 1	Case 2	Case 3	Case 4
Production (kWh/year)				
PV-system	–	186,453 (20.7%)	185,573 (20.6%)	
Generator	39,452 (4.43%)	39,452 (4.37%)	39,452 (4.37%)	39,452 (4.43%)
Grid Purchases	851,755 (95.6%)	676,492 (75.0%)	677,308 (75.1%)	851,751 (95.6%)
Total	**891,208**	**902,397**	**902,333**	**891,204**
Consumption (kWh/year)				
AC Primary Load	851,923 (100%)	851,923 (99.7%)	851,923 (99.7%)	851,923 (100%)
Grid sales	–	2,409 (0.282%)	2,382 (0.279%)	–
Total	**851,923**	**854,332**	**854,305**	**851,923**
Excess electricity (kWh/year)	**39,284**	**303,284**	**324,189**	**39,284**

The HOMER processes optimization and sensitivity analysis, and then represents results for various configuration of hybrid system in table form. In Table 3 are given optimization results for various cases of system configuration. In this Table, we see that the most effective cost and economic metric results are obtained for Case 2 (Utility, PV-system and generator) with the smallest electricity price of $0.280 per kWh and 1.5 years payback period.

The winning system configuration consists of utility grid, diesel generator and PV-system. Base case configuration consists of utility grid and diesel generator. In Figure 10 is demonstrated the comparison of NPC between base case and lowest cost system configuration. Simple payback 1.5 years occurs when two lines intersect with each other. In the graphic of cumulative cash flow versus project lifetime we can see how the system saves money over the project by comparing winning system (blue line) and base case system (gray line).

The compare optimization results of base case with winning (low cost) system case are presented in Table 4.

Table 3. Case-wise comparison of optimization results

	Case 1 **Base case (Utility, generator)**	**Case 2** **Proposed system (Utility, PV-system and generator)**	**Case 3** **(Utility, PV-system, battery storage and generator)**	**Case 4** **(Utility, battery storage and generator)**
Initial capital ($)	645,000	700,871	758,318	700,000
Net Present Cost (M$)	1.95	1.73	1.79	2.01
LCOE ($/kWh)	0.316	0.284	0.289	0.326
Operating cost ($/year)	180,486	142,194	142,591	181,193
IRR (%)	N/A	68.0	31.0	N/A
Return of investment (%)	0	59.0	46.2	-11.3
Renewable fraction (%)	N/A	14.8	15.0	N/A
Simple Payback (year)	N/A	1.5	3.0	N/A
Annualized utility bill savings ($)	0	40,901	40,710	14.56
Demand charge savings ($/yr)	0	13.51	13.51	13.51
Annualized energy charge savings ($)	0	38,166	37,697	1.05

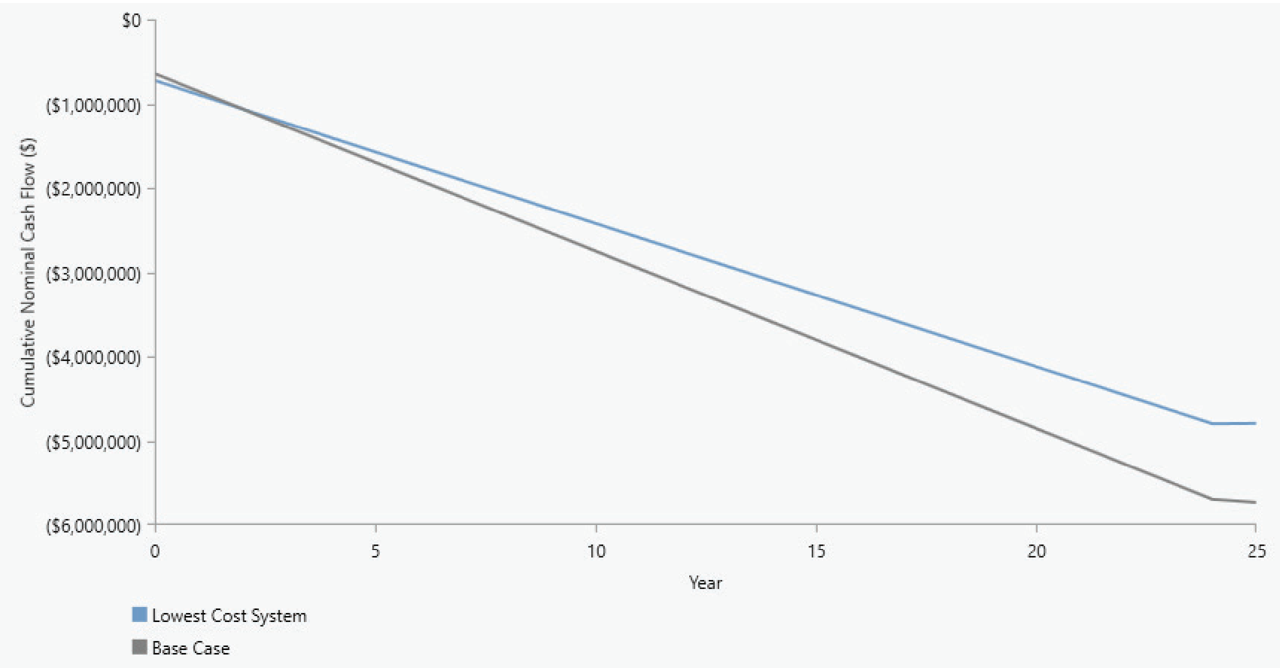

Figure 10. Comparison of NPC between base case and winning. (lowest cost) system configuration.

Table 4. Annual utility bill comparison between base case and winning system

	Base Case	Winning System
Initial capital ($)	645,000	700,871
Net Present Cost (M$)	1.95	1.73
LCOE ($/kWh)	0.316	0.284
Operating cost ($/year)	180,486	142,194
Annualized Energy Charge Savings ($/year)	0	38,166
CO2 Emitted (kg/yr)	561,667	458,074

The case-wise comparison of yearly emissions is given in Table 5. As can be observed from Table 5, the value of carbon monoxide and particulate matter emissions have not changed for all simulation cases. There are differences of carbon dioxide, sulfur dioxide and nitrogen oxides emissions between the systems with solar PV (Case 2 and Case 3) and without solar PV (Case 1 and Case 4) configurations. In difference from optimization results the best emissions reduction belongs to Case 3. This is due to the fact, that solar energy generated by Case 3 was greater than in the Case 2, and battery storage system was used in addition. It should be noted that by installing solar PV systems 18.44% of CO2 can be prevented to compared with the systems without solar PV.

In Figure 11 is summarized down estimated annual savings by the categories for proposed system.

The annual utility bill of Engineering faculty is reduced to $150,758 by adding PV-system to LV distribution network. The investment has a payback of 1.5 years and an IRR of 68%.

The share of monthly average electricity production of the Case 2 (utility grid – PV-system – diesel generator) is illustrated in Figure 12. Form this figure, we can see that

Table 5. Case-wise comparison of yearly emissions

Quantity	Case 1	Case 2	Case 3	Case 4
Emissions (kg/year)				
Carbon Dioxide	561,667	458,074	450,900	561,664
Carbon Monoxide	77.7	77.7	77.7	77.7
Unburned Hydrocarbons	0	0	0	0
Particulate Matter	2.19	2.19	2.19	2.19
Sulfur Dioxide	2,334	1,885	1,854	2,334
Nitrogen Oxides	1,304	1,085	1,069	1,304

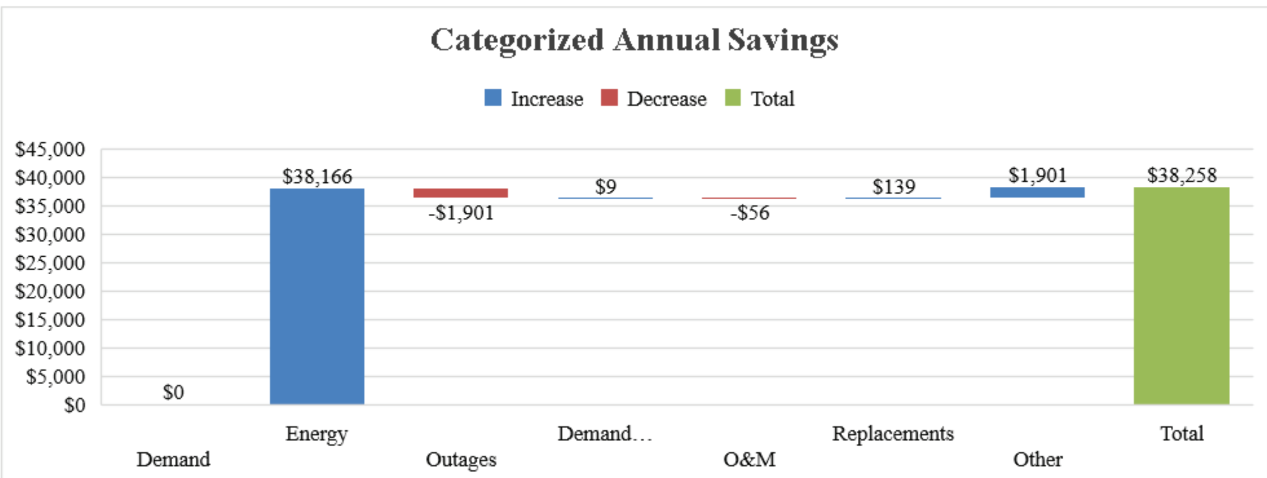

Figure 11. Annual savings of the proposed (winning) system by categories.

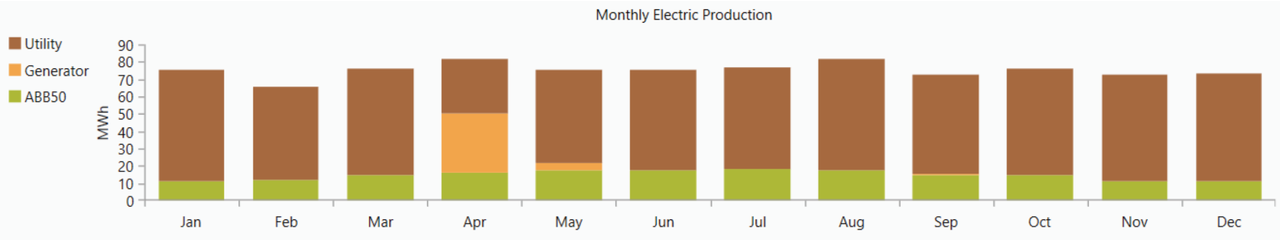

Figure 12. Monthly average electricity production for proposed system.

diesel generator mostly is operated during outages in grid (April and May), while PV-system generation cannot fully provide the system electricity demand.

In demand response program power distribution and retail company Enerjisa Başkent A.Ş. offers an incentive of $3.00 for every kW reduced. During the notification by the utility KBU should reduce the electric consumption for one hour. Signing up for this program KBU gets a total revenue of $4,239. In the demand response events that occur in a year, and the revenue incurred by reducing Engineering facility's peak during each one of them are given in Table 6. One of these events that occurred on January 30 is illustrated

Table 6. Demand response and revenue

Event Date	Reduction (kW)	Revenue ($)
30 Jan 17:00	280	$841.00
01 Apr 18:00	71.7	$215.00
08 May 13:00	195	$585.22
03 Jul 16:00	148	$445.22
24 Jul 11:00	232	$696.15
12 Sep 10:00	230	$691.27
12 Nov 12:00	255	$765.43
Total	**1411.7 kW**	**$4239.29**

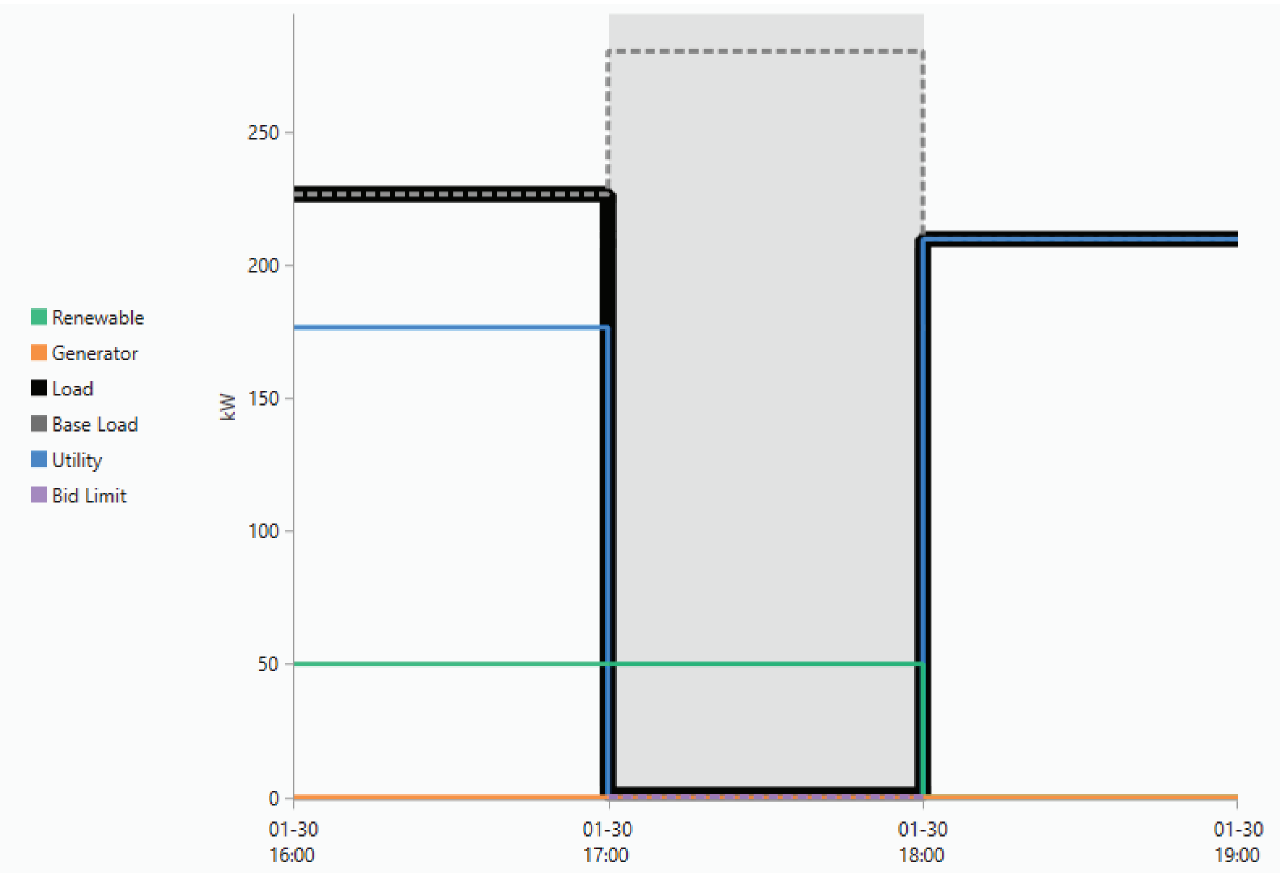

Figure 13. Demand reduction during DR program.

in Figure 13. According to the demand response program the revenue was $841 for optimized demand reduction bid of 280 kW.

CONCLUSION

Techno-economic and environmental analyzing of KBU microgrid have accomplished. Microgrid system has planned and designed for one substation of KBU distribution network. Islanded and grid-connected modes of MG system operation are considered for techno-economic analysis. The optimization result includes the overall performance and the economic feasibility of the KBU MG system over its lifetime. According to the simulation results on HOMER the optimized case solution has been determined with sensitivity parameters from four cases. On example of KBU Engineering faculty the results of current system and proposed system have been compared and determined that hybrid Microgrid enhances the reliability of system operation, decreases the net present cost, localized cost of energy per kWh and pollution. The comparison results show that the best case for KBU MG comprises utility, PV-system and diesel generator. Annual LCOE for proposed case is $0.284 per kWh.

It has been observed that MG applying is significantly decreases net present cost and cost of energy, also CO2 emissions. In MG system NPC, COE and CO2 emission reduced in 11.28%, 10.12% and 18.44%, respectively by compare with base case system. The annual utility bill of Engineering faculty is reduced to $150,758 by adding PV-system of 406 kW to LV distribution network. The investment has a payback of 1.5 years and an IRR of 68%.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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