DESIGN OF A GRID-CONNECTED CAMPUS MICROGRID CONSIDERING ENERGY EFFICIENCY AND FINANCIAL FEASIBILITY

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ABSTRACT

Microgrids have been recognized as one of the most efficient energy solutions to power critical assets such as universities, hospitals, and industrial sectors. This paper presents the design of a grid-connected campus microgrid based on financial analysis. The design takes into account economic effects of energy efficiency control and evaluates microgrid financial feasibility based on economic measures including lifecycle cost, net present value, and simple payback period. In this research, financial analysis for the microgrid is conducted in Microgrid Decision Support Tool.

INTRODUCTION

A microgrid can be defined as a cluster of distributed generation and storage units to serve specific interconnected loads. Such a power system can operate independently as a standalone entity or connected to a utility grid. Microgrids bring a series of technical and economic benefits to both the utilities and customers such as high penetration of renewable energy, improved power quality and system reliability, significant reduction of greenhouse gas emission, and so on [1,2].

In 2015, an IoT (Internet of Thing)-based microgrid project launched in the campus of Seoul National University (SNU), South Korea and is expected to be completed by the middle of 2019. The IoT-based architecture of the microgrid offers important demand-side flexibilities such as load control, energy efficiency control, and ability to participate in demand response programs provided by the utilities that will benefit both them and their customers [3]. After this project, a series of modular IoT-based microgrids will be implemented in SNU and other campuses. This paper presents the design procedure of microgrid for the SNU campus in terms of economic analysis and financial feasibility. The design is based on economic and financial analysis and it evaluates the project financial feasibility based on key metrics including lifecycle cost (LCC), net present value (NPV), and simple payback period (SPB). In addition, because this microgrid will also be IoT-enabled, the analysis takes into account the potential benefit of energy efficiency control by IoT smart sensors and considers its influence on the project financial performance. The analysis results show that the energy efficiency control substantially enhances the project profitability since it contributes to the overall load reduction.

All the simulations in this research are conducted in Microgrid Decision Support Tool (MDSTool) which is our own software mainly designed for techno-economic and financial analysis of microgrids. MDSTool has the open architecture which offers several important advantages when compared with other commercial tools like HOMER, iHOGA, HYBRID2, and SAM [3]. Because of its open architecture, new dispatch algorithms can be defined and developed by users. Assumptions and constraints can be modified and added. Technology model can be changed. A detailed financial structure specific to a region or a country can be applied.

MDSTOOL

The architecture of MDSTool is described in Fig. 1. The software has two simulation models which are performance model and economic model. The MDSTool includes various distributed energy resource (DER) technologies such as photovoltaic (PV), wind turbine, small hydro, geothermal, biomass, internal-combustion-engine generator, fuel cell, energy storage system (ESS), and so on.

The performance model simulates a one-year operation

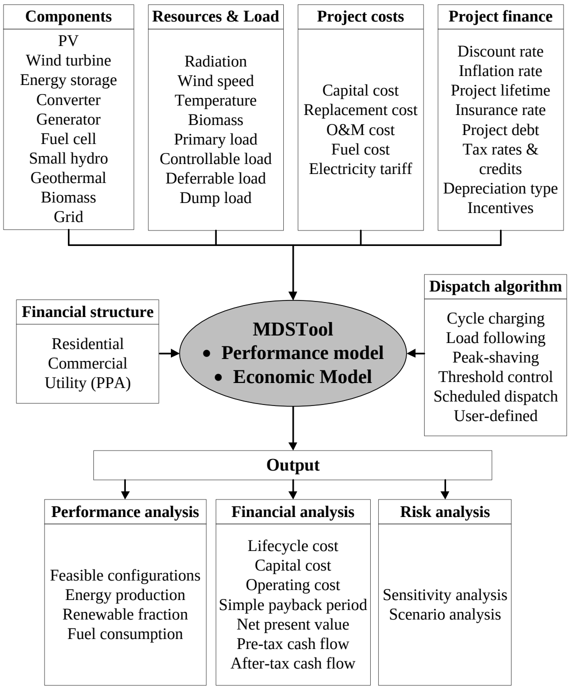

Fig. 1. Architecture of MDSTool

of various microgrid configurations which are different combinations of DERs. The inputs of this model contain 8760-hour time-series data of the electricity load demand and weather resources, technical and cost parameters of microgrid components, project financial parameters, and an economic dispatch algorithm. The output of performance model is a set of time-series data of system energy output which details the hourly energy consumption and generation. The dispatch algorithm defines the optimal operation of the system by minimizing the cost of supplying the load demand. At each time step, the energy generated by renewable energy resources (RESs) is always the first priority to power the load. In the case if the renewable energy is insufficient to supply the load, the dispatch algorithm will decide which component will operate and at what power level at that time step to provide the remaining demand at minimum operating cost as described in Equation (1).

$$\min C_{total,t} = C_{gen,t} + C_{dch,t} + C_{gbuy,t} - \sum C_{rev} \qquad (1)$$

subject to the following constraints:

$$P_{load,t} = P_{G,t} + P_{S,t} + P_{gbuy,t} - P_{gsell,t} \qquad (2)$$

$$\begin{aligned} &P_g^{\min} \le P_{g,t} \le P_g^{\max} \\ &P_{dch,t} \le P_{dch,t}^{\max} \\ &P_{gbuy,t} \le P_{gbuy,t}^{\max} \\ &P_{gsell,t} \le P_{gsell,t}^{\max} \end{aligned} \qquad (3)$$

$$SoC_{\min} \le SoC_t \le SoC_{\max} \qquad (4)$$

where, the subscript t is time step, C_{total} ($) is the total cost of supplying the dispatch load calculated by subtracting the renewable power from the total load demand, C_{gen} ($) is the cost of operating generators, C_{dch} ($) is the cost of discharging ESS, C_{gbuy} ($) is the cost of buying electricity from the utility, C_{rev} ($) is the revenue from net metering, demand response and ancillary services, P_{load} (kW) is the total load demand, P_G (kW) is the power generated by DERs including RESs, P_s (kW) is the storage net output power, P_{dch} (kW) is the storage discharge power, P_{gbuy} (kW) and P_{gsell} (kW) are the utility purchase and the electricity sold to grid respectively, P_g (kW) is the output power of generators, SoC (%) is the state-of-charge of ESSs.

At the end of the performance simulation, the tool will evaluate the technical feasibility of each configuration. This evaluation is based on the following reliability metrics: loss-of-load-probability (LOLP) and loss-of-power-supply-probability (LPSP) [4]. Only feasible configurations are selected to be the input of the economic model.

The economic model of MDSTool uses the output data of the performance model to calculate the total installation and operation costs over the project lifetime, and economic metrics including LCC, NPV, and SPB used to evaluate the microgrid financial feasibility. LCC is the cost incurred through the ownership of an asset over the asset's lifetime or the analysis period [5]. This measure is used to rank alternative projects that produce the same benefits and returns. NPV and SPB are widely used for economic evaluation since they directly address benefits and returns of an investment.

Table 1. Load parameters

Building	Max. load (kW)	Average load (kW)	Min. load (kW)	Load factor
Building 5	472	110	18	0.23
Building 6	290	88	18	0.30
Building 7	272	87	24	0.32
Total load	914	285	61	0.31

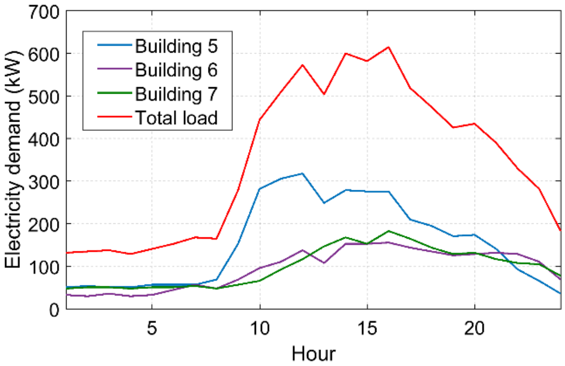

Fig. 2. Load patterns of a typical spring day

$$LCC = \sum_{n=0}^{N} \frac{F_{ATC,n}}{(1+d_{nom})^n} \qquad (5)$$

$$NPV = \sum_{n=0}^{N} \frac{F_{ATCF,n}}{(1+d_{nom})^n} \qquad (6)$$

where, F_{ATC} ($) is the after-tax cost, F_{ATCF} ($) is the after-tax cash flow, N (years) is the project lifetime, d_{nom} (%/year) is the nominal discount rate.

SPB can be expressed as the first point in the project lifetime at which the cumulative forecasted cash flow equals or exceeds the initial investment ($C_{install}$) [5].

$$\sum_n F_{ATCF} \ge C_{install} \qquad (7)$$

MICROGRID DESIGN

Three buildings of College of Humanities such as buildings #5, #6, and #7 were selected as the microgrid demonstration site at SNU campus. In addition, PV and ESS were chosen as DERs in the microgrid.

Analysis of load demand

Table 1 presents the load data of three buildings. Figure 1 shows the load profile of a typical day in spring. The maximum value of the total load is 914 kW, and the average load is 285 kW. This results in a low load factor which is 0.31. A low load factor indicates that the difference between the average load and the peak load is significant. This means that a considerable amount of savings by the microgrid will come from monthly demand charge reduction.

Electricity tariff

The tariff applied is the Korea Electric Power Corporation (KEPCO) educational tariff. It is a time-of-use (TOU) rate with three billing periods including off-

Table 2. KEPCO educational tariff

Time period	Energy charge ($/kWh)			Demand charge ($/kW)
	Summer	**Spring/fall**	**Winter**	**(All seasons)**
Off-peak	0.0453	0.045.3	0.0493	6.9800
Mid-peak	0.0900	0.0597	0.0885	
On-peak	0.1559	0.0802	0.1272	

Table 3. KEPCO tariff's time period classification

Classification	Summer, Spring, Fall	Winter
Off-peak	23:00~09:00	23:00~09:00
Mid-Peak	09:00~10:00 12:00~13:00 17:00~23:00	09:00~17:00 12:00~17:00 20:00~22:00
On-peak	10:00~12:00 13:00~17:00	10:00~12:00 17:00~20:00 22:00~23:00

peak, mid-peak, and on-peak. Tables 2 and 3 describe the tariff structure in detail [6].

Energy efficiency control

The economics of energy efficiency control is evaluated in this present study. The energy efficiency control is implemented by integrating IoT technology with various sensors, lighting control system (LCS), electric heat pump (EHP), and building energy management system (BEMS). The total capital cost of energy efficiency control is 220,000 $. From the estimation results of the SNU campus IoT microgrid, the investment in energy efficiency control results in 10 % energy saving.

Design of microgrid

Tables 4 and 5 show component costs and financial parameters of the project, respectively. In this present study, the design of a campus microgrid is based on financial analysis considering financial feasibility and economics of energy efficiency control, which are verified by LCC, NPV, and SPB.

Three cases are simulated:

- Case 1 is the base case which is the existing system assuming that the whole load is met by the utility (KEPCO).
- Case 2 is the grid-connected microgrid case containing a PV and an ESS to supply the entire load.
- Case 3 is the same as case 2 but with the addition of energy efficiency implementation.

In this study, the ESS is operated by peak shaving control strategy which discharges the ESS during peak-load periods and charges the ESS at periods having low electricity rates that often coincide with low load periods as shown in Fig. 3. This strategy guarantees a reduction in the demand charge.

To determine the microgrid optimal sizing, various configurations are simulated with different rated capacities of ESS and PV. Because the design in this study considers the microgrid financial feasibility, the optimal configuration is defined as the one that produces the highest NPV. The results are shown in Fig. 4. It is apparent that an increase in the PV rated power results in higher NPV, and the optimal size of ESS is different when the PV size varies. The size of PV is normally constrained by the available installation space and the capital cost. Based on on-site evaluation, the PV of 200 kW is selected. According to Fig. 4 with respect to the PV of 200 kW, the ESS optimal size is 900 kWh as at which the project NPV reaches a peak.

Table 4. Component costs and parameters

Technology	Cost	Value	Unit
PV	Capital cost	2000	$/kW
	O & M cost	10	$/kW/y
	Life time	25	y
ESS	Capital cost	400	$/kWh
	Replacement cost	200	$/kWh
	O & M cost	5	$/kWh/y
	Throughput	3000	kWh/unit
Converter	Capital cost	300	$/kW
	Replacement cost	200	$/kW
	O & M cost	0	$/kW
	Life time	15	y
Energy efficiency	Capital cost	220,000	$

Table 5. Project financial parameters

Categories	Parameter	Value	Unit
Financial parameters	Nominal discount rate	8	%
	Expected inflation rate	2.38	%
	Project lifetime	25	y
Taxes & insurance	Federal income tax rate	20	%
	Local income tax rate	2	%
	Property tax rate	0.3	%
	Annual insurance	0.5	%
Project debt	Debt size	100	%
	Loan term	25	y
	Loan rate	7.0	%

The financial analysis results of three cases are presented in Table 6. The capital cost of case 1 is zero because it is the present power system. In this base case, the annual energy charge is 228,403.19 $/y while the annual demand charge is 53,806.64 $/y. These result in the LCC of 3,789,500.00 $. Compared to the base case, both the annual demand charge and the annual energy charge in cases 2 and 3 are noticeably reduced. This is owing to the PV generation and the ESS operation by the peak-shaving control strategy. Consequently, the LCC of cases 2 and 3 is lower than that of the base case.

Table 6. Financial analysis results

Case	Rated capacity			LCOE ($/kWh)	Capital cost ($)	LCC ($)	NPV ($)	SPB (y)	Annual demand charge ($/y)	Annual energy charge ($/y)
	PV (kW)	ESS (kWh)	Converter (kW)							
Case 1: Base case	-	-	-	0.1063	-	3,789,500.00	-	-	53,806.64	228,403.19
Case 2: Microgrid without energy efficiency control	200	900	200	0.0999	620,000.00	3,561,200.00	244,840.00	8.05	11,538.37	190,162.69
Case 3: Microgrid with energy efficiency control	200	900	200	0.0957	840,000.00	3,411,800.00	386,690.00	8.02	7,520.16	167,475.95

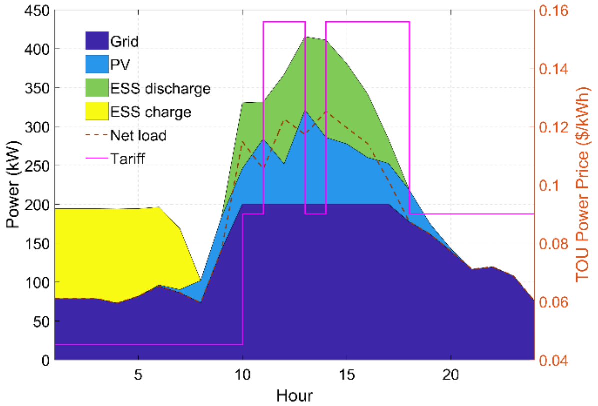

Fig. 3. Energy output of a typical day

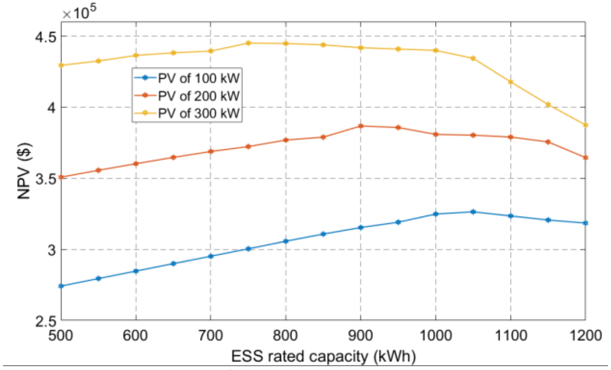

Fig. 4. Impact of variations in ESS and PV size

In case 3, when the energy efficiency control is implemented, its extra investment is added to the microgrid capital cost. The demand charge and energy charge in case 3 are further reduced when compared with case 2. This makes the LCC of case 3 lower than the LCC of case 2. As a result, the LCOE of case 3 is the lowest among the three cases considered. These results demonstrate that the energy efficiency is economically feasible.

With regard to financial performance, both case 2 and case 3 have the SPB of 8 years. When the energy efficiency control is integrated into the microgrid, case 3 produces higher NPV of 386,690.00 $ compared to that of case 2 which is 244,840.00 $. This again proves the financial feasibility of the designed microgrid as well as of the energy efficiency control.

CONCLUSION

This paper presents the design of a campus microgrid based on financial analysis. The financial feasibility of the microgrid is evaluated using LCC, NPV, and SPB. The optimal sizing of the microgrid is decided so that the project NPV is the highest. The analysis results show that the microgrid is economically viable with lower LCC in comparison with that of the base case. In addition, when the energy efficiency control is implemented, the microgrid becomes more financially attractive with higher NPV and shorter SPB.

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