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# A Multi-Period and Multi-Objective Optimization Model of a Microgrid System Investment Model

Jhoenson Siy, Lanz Uy, Patric Uy, Charlle Sy*

Industrial Engineering Department, De La Salle University, 2401 Taft Avenue, Manila, Philippines, 1004
charlle.sy@dlsu.edu.ph

Microgrids are small-scale, low voltage power supply networks designed to supply electrical loads for a small community. This study extends existing mixed-integer linear programming microgrid investment models by considering multi-period and multi-objective investment setups. The optimization of the microgrid model provides investors a mix of distribution energy sources that maximizes the net present value (NPV) with consideration of the allowable budget and emission constraint under multiple periods. Through the NPV, the return of investment of the investor would be determined for the period that the model was run. Upon the analysis of the model, it was seen that the model chooses to prioritize the use of diesel generators until the emission constraint is maxed out. After which, it moves to the utilization of wind power then photovoltaic power. The use of electricity from the grid only happens when the demand for electricity is greater than the generating capacity of the system. Through the computational experiments performed, it was validated that the model can generate the purchasing pattern given the different parameters. This provides investors the set of equipment that they need to invest on each period based on their limited resources.

## 1. Introduction

There are currently 7 billion people worldwide, and 1.3 billion people of which have limited or totally no access to electricity. The said crisis does not only concern energy shortages; but it is also compounded with environmental issues such as pollution and climate change. An emerging alternative solution to address the said concerns is through building a microgrid system. Microgrids (MG) are small-scale, low voltage power supply networks designed to supply electrical load for a small community such as a university campus, a commercial area, and others (Wang et al., 2014). MGs are also considered as effective means to deal with the issues on increasing demand and shortage of electricity by having its own generating sources which could make the MG system independent from the main grid (Gadonneix et al., 2013).

In terms of environmental concerns, Stadler et al. (2014) presented in their paper that MG systems are also able to have a significant impact on the fulfillment of 20/20/20. That is, by the year 2020, we should be able to reduce the greenhouse gas emissions by 20 %, increase energy efficiency by 20 %, and increase the share of renewables to 20 %. Aside from this, Basak et al. (2012) stated that on-site microgrid implementation can provide electric service reliability, better power quality, and lower electricity costs by 20 – 25 %. Microgrid implementation can also benefit local utilities by allowing system repairs without affecting customer loads, providing dispatchable load for use during peak power conditions, and lowering stress on the transmission and distribution system.

The MG system is a rising innovation for the energy generation, transmission and distribution industry that started around two decades ago. There are already a number of researches that have established and accepted the concept of MG; and in fact some examples of actual implementation are seen in Fort Carson, Mesa del Sol, Santa Rita Jail, New York University, and others (Berkley Lab, 2014). However, investment in the equipment and resources needed in a microgrid system requires a big amount of capital, and therefore, the feasibility of commercializing it is questioned.

Successful stories of microgrid implementation have not only shown its feasibility but also its benefits in reliability, quality, greater efficiency, and reduction of electricity cost (Ahmed, 2011). However, there are still

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technical and cost-related issues in MGs that need to be resolved. This study then extends existing mixed-integer linear programming MG investment models by considering multi-period and multi-objective investment setups. The optimization of the Microgrid model provides investors a mix of distribution energy sources that maximizes the net present value (NPV) with consideration of the allowable budget and emission constraint under multiple periods. Through the NPV, the return of investment of the investor would be determined for the period that the model was run.

## 2. Microgrid System

A microgrid is a small-scale centralized energy system that has generators, controllable loads and storage batteries which could generate, transmit, and store energy within a small geographic area (Berkley Lab, 2014). According to Soshinkaya et al. (2014), microgrids usually use renewable sources of energy such as photovoltaic panels, wind turbines, bio-diesel generators, and the like. Moreover, MGs as shown in Figure 1, could also be configured to be connected or disconnected from the main grid for it to operate in grid connected mode or islanded mode, respectively.

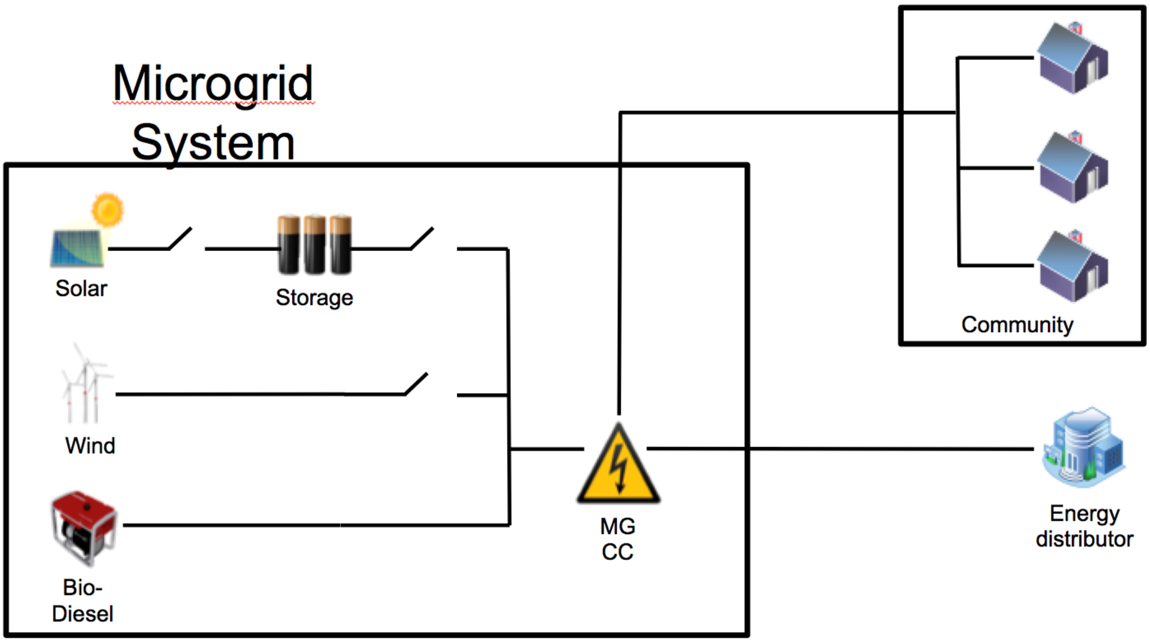


*Figure 1: Microgrid topology shows generation and transmission of energy*

There are three basic functions of a microgrid: first, it must be able to meet the customer's electricity demand. Second, it must have the capability to manage the supply and demand of the electricity and take into account the power balance, voltage quality, flexibility and electrical safety of the system Soshinkaya et al. (2014). Lastly, it must have the 'plug and play' function on two levels: (1) flexible system for smooth implementation of new devices, (2) disconnect from the main grid when enough power is produced and resynchronize a connection when needed (Ihamaki, 2012).
An investor's point of view will be considered for this study. The investor of the microgrid system is defined to be the one purchasing the facility as well as using the electricity generated. The investor and the consumer are considered as one entity in this study and it is the one directly interacting with the main grid. Although it is considered as one entity, it does not necessarily mean that it only supplies electricity to one household. For example, a townhouse could be considered as one entity; in this case, the owner of the townhouse could be the investor. The investor will be the one to distribute the generated electricity to the individual houses. Moreover, when it comes to the point that the microgrid's electricity generation exceeds the demand, the townhouse owner will also be the one to sell the excess electricity to the main grid. Similarly, this set up could be compared to a university set up with multiple buildings which consume different amounts of electricity.

## 3. Model Development

The following section shows the model development for the Microgrid System. The indices together with the major parameters are initially presented. This would then be followed by a thorough discussion on the different components of the system. Additional notations used in the model such as cost and profit parameters will be introduced as needed in the succeeding discussion.

*Table 1: Nomenclature*

| Indices | Definition |
|---|---|
| $i$ | Generation technologies, where *i* = {diesel 'dg', photovoltaic 'pv', wind 'w', battery 'ba'} |
| $t$ | Time period index with respect to the present year 0, where *t* = {0, 1, 2, 3, …, N} |
| Parameters | |
| $l_t$ | Customer load (electricity) in KW for month *t* |
| $mr$ | Market generation carbon emission conversion rate converting kWh to kg-carbon (kg-carbon/kWh) |
| $dr$ | Diesel generation carbon emission conversion rate converting kWh to kg-carbon (kg-carbon/kWh) |
| $ec$ | Fraction of charged electricity into battery that is not lost in energy transfer |
| $ed$ | Fraction of electricity discharged from battery that is not lost in energy transfer |
| $wi_t$ | Efficiency of the wind turbine in converting wind energy to electricity during month *t* |
| $p$ | Power rating of diesel generator (kW) |
| $d_t$ | Number of days the batteries can supply the community in case of emergency during month *t* |
| $si_t$ | Fraction of maximum solar insolation incident upon location during month *t* |
| $ct_t$ | Maximum amount of allowable carbon emission generated by the system during month *t* |
| $s_t$ | Number of days in month *t* |
| Decision Variables | |
| $c_{i,t}$ | Amount of KW or units of generation source *i* installed on month *t* (kW) |
| $g_t$ | Amount of electricity purchased by the microgrid during month *t* (kWh) |
| $u_t$ | Amount of electricity sold by the microgrid during month *t* (kWh) |
| $v_t$ | Binary variable on deciding whether the electricity from PV would go to the battery or to the customer |
| $j_t$ | Generated electricity of the diesel generator installed on month *t* sold to customer (kWh) |
| $y_t^1$ | Electricity from wind power that is supplied to the customer during month *t* (kWh) |
| $y_t^2$ | Electricity from wind power that is sold to the grid during month *t* (kWh) |
| $x_t^1$ | Electricity from photovoltaic power that is supplied to the customer during month *t* (kWh) |
| $x_t^2$ | Electricity from photovoltaic power that is sent to the battery during month *t* (kWh) |
| $x_t^3$ | Electricity from photovoltaic power that is sold to the grid during month *t* (kWh) |
| $f_t$ | Total electricity stored in batteries during month *t* (kW) |
| $z_t^1$ | Total net electricity supplied from batteries during month *t* (kW) |

### 3.1 Generation Technologies

The first component in the microgrid system is the generation technologies. In this study, three generation sources have been considered: Photovoltaic, Wind power and Diesel generator. The left hand side of Eq(1) shows that the total amount of electricity produced by the photovoltaic panels is equal to the product of the purchased capacity and solar insolation. Solar insolation converts the panels into usable energy and is defined as the total amount of *solar* radiation energy received on a given surface area during a given time. This is then equated to the possible outputs of electricity from the photovoltaic panels. Similarly, Eq(2) shows that the total amount of electricity that can be produced by wind power is equal to the product of its capacity and percentage efficiency. This energy source could be used by the consumer or be sold to the grid. Eq(3) shows that the total amount of electricity from diesel generators that can be generated in a month must be less than the capacity of the diesel generator purchased.

$$\sum_t c_{pv,t} \cdot si_t = x_t^1 + x_t^2 + x_t^3 \quad \forall t \tag{1}$$

$$\sum_t c_{w,t} \cdot wi_t = y_t^1 + y_t^2 \quad \forall t \tag{2}$$

$$j_t \le c_{dg,t} * p * s_t \quad \forall t \tag{3}$$

**3.2 Battery**

In this study, battery was considered to be part of the system to ensure that when all sources are down, the community would still have the ability to operate. Eq(4) shows that the capacity of the battery must always be greater than a certain limit relative to the load requirement per month. Eqs(5) and (6) show how the battery would work inside the system. A binary variable is attached to the right hand side of the equation to limit the model in such a way that if there are excess capacity inside the battery, electricity would flow into the battery. If the volume of electricity is greater than the remaining space, the amount that would flow inside the battery is simply equal to the difference between the capacity and the electricity previously stored. Eq(7) defines the total amount of electricity in the battery at any given time. There are certain losses from the electricity transferred and the electricity from the previous period because it is part of the battery's nature to have certain losses in both transmission and storage. Eq(8) shows that at any point in time, the amount of electricity inside the battery must always be on a certain limit. This is to ensure that when an emergency occurs, the system would always have spare electricity for the community. Lastly, Eq(9) shows that the amount of electricity stored for any time period must not exceed the overall capacity of the battery.

$$\sum_t c_{ba,t} \geq \frac{l_t}{s_t} * d_t \qquad \forall t \tag{4}$$

$$x_t^2 \geq (\sum_t c_{ba,t}) - (z_{t-1}^1 * ed) - (M * v_t) \qquad \forall t \tag{5}$$

$$x_t^2 \leq (\sum_t c_{ba,t}) - (z_{t-1}^1 * ed) + (M * (1 - v_t) \qquad \forall t \tag{6}$$

$$f_t = ( x_t^2 * ec) + (f_{t-1} * ed) + c_{ba,t} - z_t^1 \qquad \forall t \tag{7}$$

$$z_t^1 \leq (f_{t-1} * ed) - (\frac{l_t}{s_t} * d_t) \qquad \forall t \tag{8}$$

$$f_t \leq \sum_{t=1}^t c_{ba,t} \qquad \forall t \tag{9}$$

**3.3 Emission**

The diesel generators and the electricity purchased from the grid are considered to be sources of emissions in the model. The electricity obtained from each of the two sources is multiplied to a rate that converts the amount of electricity (KWh) to kilograms of carbon (kg-carbon). The sum of which should not exceed the allowable carbon emitted by the system in a given month.

$$(j_t \cdot dr) + (g_t \cdot mr) \leq ct_t \qquad \forall t \tag{10}$$

**3.4 Electricity Supply and Demand**

The following equations show the relationship between the supply and demand of electricity. Eq(11) shows that the electricity provided by the system must be greater than the demand of the consumer. Meanwhile, Eq(12) shows that the amount of electricity sold back to the grid is equal the excess amount generated. In short it is equal to the amount of electricity provided minus the demand for that particular period.

$$x_t^1 + z_t^1 + y_t^1 + g_t + j_t \geq l_t \qquad \forall t \tag{11}$$

$$u_t = x_t^1 + z_t^1 + y_t^1 + g_t + j_t + y_t^2 + x_t^3 - l_t \qquad \forall t \tag{12}$$

**3.5 Objective Function**

Part of the objective function shows the profit/loss from purchasing and selling to the grid. The second part of the objective function shows the cost of the entire system, which could be broken down into two categories: investment cost and operation cost. The total cost for wind and PV is equal to the total capacity purchased multiplied to its cost per unit *fc.* Furthermore, since the output of these two sources is equal to its capacity, the operation cost is also equal to the capacity multiplied to its variable cost *vc*. The overall objection function computes for the net present value of the entire system, with the use of the discount rate $\alpha$.

$$Max\ N = \sum_t \left( (sp_t \cdot u_t - bp_t \cdot g_t) - \sum_i (c_{it} \cdot fc_{it}) - \sum_i ((c_{it} + j_t) \cdot vc_{it}) \right) \cdot (1 + \alpha)^{-t} \tag{13}$$

## 4. Computational Study

Computational experiments were performed through the use of a CPLEX solver in Matlab (Matrix Laboratory). The solution time in Matlab was recorded to be 3 minutes, and 5.3 seconds on a 12 GB ram and Intel Core i7-4770 3.40 GHz processor. Theoretical values were used for the model parameters.

A 12-month planning horizon was considered under a customer load of 20,000 kWh. The carbon emission per kilowatt generated from grid purchases is greater than that of diesel. This shows that the market emits more carbon to the atmosphere per kWh of energy made as compared to that of diesel generators. In order for the model to capture this, the market generation carbon emission rate was set at 0.25 which was higher than the diesel carbon emission rate which was set at 0.2. It was also assumed that the market electricity buy price is greater than the electricity sell price from the grid. The latter is then greater than the market electricity sell price. The electricity buy price from the grid is the price which the ordinary customer pays the grid to buy a kWh of electricity (0.17 Php/kWh). On the other hand, the electricity sell price to the community is the investor's selling price of electricity, generated from the microgrid, to the community (0.13 Php/kWh). Lastly, the electricity sell price to the grid is the selling price of the excess electricity generated from the microgrid (0.10 Php/kWh). Based on the net-metering guide in the Philippines by Dietrich (2013), the relationships of the parameters set were logical. The selling price of the grid to its ordinary customers is the highest price while the energy sold to the grid would be cheaper as compared to the selling price of the grid. The fixed cost pertains to costs such as salaries, overheads, insurance, taxes paid per unit of distributed energy resource PV, wind, and battery. Also according to Dale (2013), the fixed cost for PV (0.0001 Php/kW), Wind (0.00016 Php/kW), and Batt (0.00002 Php/kW) is minimal however, the installation of wind would cost more than the installation of PV and battery. PV units are said to have cheaper fixed costs compared to wind as it only incurs minimal costs to maintain panels; the only maintenance required for PV panels are to be washed regularly with water. Furthermore, the fixed costs for installation of battery is even lower as there are no costs incurred when using the battery. The fixed costs of diesel generator (0.001 Php/unit) is the least expensive among the distributed energy resources.

Table 2 shows the set load requirements per period as well as the corresponding energy resource units required to be purchased per period. As can be seen in the results, the model prioritizes (from top priority to least priority): diesel generator, wind, PV, and then grid purchases. Generally, the cause of this prioritization are the different costs that will be incurred when a respective energy resource equipment is chosen.

*Table 2: Purchase Decisions*

| Time Period | PV (kW) | Wind (kW) | Battery (kW) | Diesel (Units) | Grid (kWh) | Load (kWh) |
|---|---|---|---|---|---|---|
| 1 | 34 | 629 | 2,006 | 1 | 384 | 20,000 |
| 2 | 0 | 48 | 2,055 | 1 | 0 | 20,000 |
| 3 | 0 | 833 | 0 | 0 | 0 | 20,000 |
| 4 | 0 | 833 | 0 | 0 | 0 | 20,000 |
| 5 | 0 | 833 | 0 | 0 | 0 | 20,000 |
| 6 | 0 | 832 | 3 | 0 | 0 | 20,000 |
| 7 | 0 | 398 | 2,772 | 0 | 0 | 20,000 |
| 8 | 0 | 822 | 30 | 0 | 0 | 20,000 |
| 9 | 0 | 818 | 4 | 1 | 0 | 20,000 |
| 10 | 0 | 819 | 0 | 1 | 0 | 20,000 |
| 11 | 0 | 833 | 0 | 0 | 0 | 20,000 |
| 12 | 0 | 0 | 0 | 0 | 0 | 20,000 |

The model would initially select the cheapest source of electricity, in the form of non-renewable sources such as the diesel generator and grid purchases. In the hypothetical values used, the diesel generator was set to be cheaper than purchasing from the grid. Furthermore, the diesel generator carbon emission rate was also lower than the carbon emission rate of purchasing from the grid. Because the model considers a target carbon emission parameter, the model limits the number of electricity acquired from non-renewable sources. However, it is important to take note that the carbon target is just a soft constraint. This would mean that the model can still buy more electricity from non-renewable sources subject to receiving a penalty cost. With that said, the model chooses to max out the carbon emission targets first by using the generator rather than purchasing from the grid. After which, the grid purchases became the least of the priority as the succeeding purchases would already be subjected to penalties.

Figure 2 shows the breakdown of electricity that supplies the load and the electricity sold to the grid. The PV needs to consistently fill the battery as the batteries are only assumed to be 60 % full when it is bought and the stored electricity diminishes from period to period. Since no additional units of PV were purchased aside from the 34 units in the first months only few kW are being stored for the next months; making the efficiency losses less visible. The generation technologies are subject to efficiency losses each time period. This is the reason why the model would tend to find new sources of electricity, whether purchasing new equipment or purchasing electricity from the grid, to satisfy the load. Renewable sources were used when the carbon target is already maxed out and there are still enough budget left. Since wind was set to be cheaper than PV in terms of investment and operational costs, the model tends to decide on buying wind instead of PV.

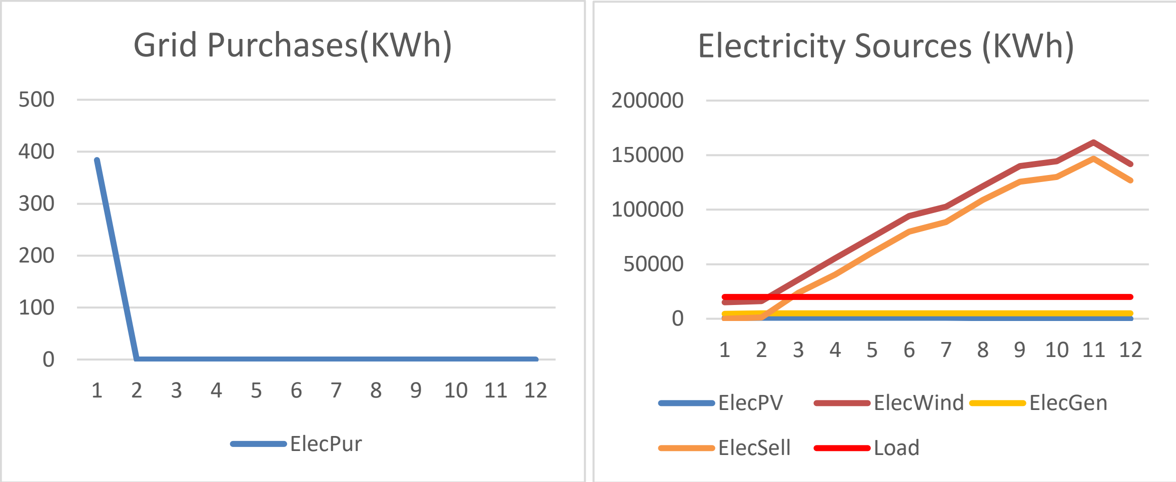


*Figure 2: Purchasing patterns for different energy sources*

## 5. Conclusions

A microgrid is an energy solution which views the generation and associated loads as a subsystem. It is a small-scale, low voltage power supply network designed to supply load for a small community. While the microgrid has several benefits, technical and cost-related issues must still be resolved. These issues are addressed in this study by developing an optimization model that considers multi-period and multi-objective investment setups for microgrids.

The computational studies performed showed that there are four factors that affect the model's decision: cost, budget, carbon emissions, and useful life. Since the objective of the model is to maximize the NPV of the system, the model would choose to prioritize the least cost among the different energy sources. However, when the emission and useful life enter the picture, the model would integrate the three factors and determine which energy source has the least cost for the more output. It was demonstrated that the model can generate the purchasing pattern given the different parameters. This provides investors the set of equipment that they need to invest on each period based on their limited resources.

### References

Ahmed M., 2011, Feasibility study of microgrid application in Langkawi and Socotra Islands. The 7th International Conference on Information Technology and Applications. Sydney, Australia, 21-21/11/2011, 1-5.

Basak P., Chowdhury S., HalderneeDey S., Chowdhury S., 2012, A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid, Renewable and Sustainable Energy Reviews 16, 5545-5556.

Berkley Lab, 2014 Microgrids at Berkley Lab by US Department of Energy <building-microgrid.lbl.gov/microgrid-definitions>, accessed 20.03.2016.

Dale M., 2013, A comparative analysis of energy costs of photovoltaic, solar thermal, and wind electricity generation technologies Applied Sciences, 3, 325-337.

Dietrich M., 2013, Net-Metering Reference Guide: How to avail solar roof tops and other renewables below 100 KW in the Philippines, Makati: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Gadonneix P., Sambo A., Tienan L., Choudhury A., Kim Y., Birnbaum L., Nadeau M., 2013, 2013 World Energy Issues Monitor. World Energy Council, London, United Kingdom.

Ihamaki J., 2012, Integration of microgrids into electricity distribution networks, MSc Dissertation, Lappeenranta University of Technology, Lappeenranta, Finland.

Soshinskaya M., Crijns-Graus W.H., Guererro J.M., Vasquez J.C., 2014, Microgrids: experiences, barriers and success factors, Renewable and Sustainable Energy Reviews, 40, 659-672.

Stadler M., Groissböck M., Cardoso G., Marnay C., 2014, Optimizing Distributed Energy Resources and Building Retrofits with the Strategic DER- CAModel, Berkeley: Ernest Orlando Lawrence Berkeley National Laboratory.

Wang R., Wang P., Xiao G., Gong S., 2014, Power demand and supply management in microgrids with uncertainties of renewable energies, Electrical Power and Energy Systems, 63, 260-269.