System design optimization for stand-alone photovoltaic systems sizing by using superstructure model

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Abstract Although the photovoltaic (PV) systems have been increasingly installed as an alternative and renewable green power generation, the initial set up cost, maintenance cost and equipment mismatch are some of the key issues that slows down the installation in small household. This paper presents the design optimization of stand-alone photovoltaic systems using superstructure model where all possible types of technology of the equipment are captured and life cycle cost analysis is formulated as a mixed integer programming (MIP). A model for investment planning of power generation and long-term decision model are developed in order to help the system engineer to build a cost effective system.

1. Introduction There are considerable efforts and studies have been made to find methods to optimize the design of the systems so that they are cost effective. Life cycle cost analyses are commonly adopted to size the investment costs of the system, to estimate the operation and maintenance (O&M) costs and to find the costs to replace the equipment over the system’s life span [1-3]. The mentioned costs for each equipment; PV modules, inverters, batteries, are usually quantified in kWh which do not depict the individual cost. Therefore there is no explicit relationship between the investment costs and the number of units purchased or the physical dimensions of the unit. This relationship is important in real designs, in which physical dimensions are part of the constraints.

This work aims to produce a cost effective system with an optimized design subjects to the energy demand and control system perspective so that maximum power generated can be harvested. At this stage, this work employs a static superstructure design optimization with life cycle cost analysis (LCCA) approach that captures not only individual investment costs of the available equipment but also the physical dimensions of the equipment such as weights, lengths and widths. These physical dimensions are not addressed in many previous works. The problem is formulated as a mixed integer linear problem (MILP) and developed in General Algebraic Modelling Software (GAMS) in order to find the most optimized combination of the equipment subject to energy demand determined by system designers [4-5]. The results from the superstructure design such as the technology of the PV module, converter and inverter topologies, battery technology and electrical connection are key information to describe the system behaviour and useful for the control system development.

In this paper, the methodology section discusses the superstructure design framework detailing the problem formulation and optimization using GAMS. The next section summarizes the results and discussion, in which some selected results are presented and explained. The concluding remarks and research work that can be extended from this work are briefly discussed in conclusion and future work section.
2. Methodology
This research is developed in stages. The first stage is to develop the profile database in which all the physical dimensions cost and total efficiency of the equipment are gathered and tabulated. The static superstructure model is then design enlisting all sets of the equipment. Next, the system specification is obtained and formulated in mixed integer programming in which a single objective function and constraints, both equality and inequality are expressed mathematically. The mathematical expression of the objective function is then linearized and GAMS is used to realize the mixed integer problem programming.

2.1. Superstructure Design
The primary objective of the model is to obtain an optimal expenditure a system. Previously, a designer has to invest in order to build up a PV system that meets the energy demand. In this model only one type of PV module, one type of battery technology and one type of inverter are allowed to be selected for the construction of a system. Figure 1 shows the interactions between the components. All the dimensions and costs of the equipment are tabulated and transformed to the GAMS programming language.

![Figure 1. The superstructure framework](image)

2.2. Mixed Integer Programming (MILP)
The general form of the Mixed-Integer-Linear programming is

\[
\begin{align*}
\text{min}_{x, y} & \quad f(x, y) \quad \text{(1a)} \\
\text{subject to} & \quad h(x, y) = 0 \quad \text{(1b)} \\
& \quad (x, y) \leq 0 \quad \text{(1c)} \\
& \quad x \in \mathbb{R}^n, y \in \{0, 1\}^m \quad \text{(1d)}
\end{align*}
\]

Where \( f(x, y) \) is the objective function, \( h(x, y) \) is the equality constraints, \( g(x, y) \) is the inequality constraints \( x \) is the continuous variables and \( y \) is the binary variables.

The objective function formulated is to minimise the life cycle cost (LCC) of an installed stand-alone PV system. The simple LCC consists of initial costs of purchasing the equipment, equipment replacement (ERP) and operation and maintenance (OM). However in this report the ERP focuses on the battery replacement cost (BRP) since the battery life span is relatively shorter than any other components, which requires frequent replacement and the cost to assemble a battery bank is the second expensive after the PV module. The objective function and its breakdowns are summarized in equations (2)-(4) [6-8],

\[
\min LCC = \text{InitialCost}_{\text{equip}} + \sum_{\text{equip}} \frac{\text{costGM}_{\text{equip}}(1+i)}{(1+i)^t} + \frac{\text{costREP}_{\text{equip}}(1+i)}{(1+i)^t} \quad \text{(2)}
\]

\[
LCC = \text{Equipment Cost} + \text{Operation and Maintenance} + \text{Replacement Cost} \quad \text{(3)}
\]

\[
\text{InitialCost}_{\text{equip}} = \text{costPV}_e + \text{costBat}_b + \text{costInv}_v + \text{BOS} \quad \text{(4)}
\]
The inequality equations (5) and (6) are describing the energy generation constraints that the PV array must produce and the maximum weight that the PV array can have in order to be mounted on the rooftop,

\[ \text{NumberOfPV} \times \eta \times P_{\text{max}} \geq \text{Energy Demand} \]  
\[ \text{NumberOfPV} \times \text{ModuleWeight} \leq W \]

The selection of the battery and inverter technology are described by inequality equations (7) and (8)

\[ \text{NumberOfBattery} \times (\text{AhCapacity} \times \text{RatedVoltage}) \geq \text{Energy Demand} \times \left( \frac{D_{0}\text{A}}{D_{0}\text{D}} \right) \]
\[ \text{NumberOfInverter} \times \text{RatedContPower} \geq \text{LoadACPower} \]

The inequality equations (9) and (10) are important so that the system will not having high voltage loss which will affect the energy supplied to the end user.

\[ V_{\text{drop}} \leq 0.03 \times V_{\text{bus}} \]  
\[ V_{\text{drop}} = \sum I_{\text{cell}} \times \left( \frac{E_{\text{cell}}}{A} \right) \]

3. Results and Discussions

The financial planning normally emphasizes on the initial costs or the investment costs. Many individuals prefer to have low start up costs and they are ready to compromise on long term maintenance and replacement costs. The model developed selects the best components according to constraints set in the problem minimizing the initial purchase of each component. This research only considers 20 types of PV modules, 20 types of battery, 5 types of inverter and 5 sizes of wire. Table 1 shows the total start up cost of a PV system that has the capacity to supply 12kWh energy. It is obvious that the cost to purchase the batteries is the most expensive, exceeding the total cost of the PV modules. It is expected because the system is developed in such that it can continuously supply the energy to the load for five no solar irradiance days. Since the system only allows 50% of the battery capacity to be discharged in order not to reduce the battery life span, a larger storage capacity is required, which means more units are needed to be purchased.

| Component | Component Selected | Total number of component to be purchased | Total Cost (USD) |
|-----------|--------------------|----------------------------------------|-----------------|
| PV module | PV13               | 14                                     | 23940.00        |
| Battery   | B16                | 78                                     | 28938.00        |
| Inverter  | V2                 | 3                                      | 7395.00         |
| Wire      | W4                 | 30                                     | 334.50          |
| **Total** |                    | **61676.5**                            |                 |

Interestingly, the operating life time of a battery is comparatively shorter than any other component in the PV system developed. In table 1, battery B16 was selected based on its initial cost. However, B16 is a flooded lead acid battery that has a maximum life cycle of 1000 at 50% DoD. From table 2 it can be seen that battery B19 is 20 thousands cheaper than B16. B19 comes from a sealed gel battery class with a higher life cycle at 50% DoD compared to typical flooded lead acid batteries. In addition to that, sealed gel batteries do not use water as charging-discharging medium, which significantly reduces the cost to maintain unlike flooded lead acid batteries whose water levels need to be checked regularly.
Table 2. Selection comparison of the battery based on initial cost and life-cycle criteria

| Type of battery | BRP (times) | Initial Purchase Cost (USD) | Purchase + Replacement Cost (USD) |
|-----------------|------------|-----------------------------|----------------------------------|
| B16             | 13         | 28938                       | 350398                           |
| B19             | 4          | 70900                       | 338748                           |

The system designer may prefer to mount the PV array on a rooftop to save the ground area. However the rooftop has some limitations one of which is how much of weight of the PV modules it can withstand. Let assume a rooftop of a building can only withstand 250kg of auxiliary weight with ample space to place the modules. If a constraint is introduced in the model formulation in such that the total weight of the PV array is not exceeding 250kg, then the model selects PV1 whose total weight is 215.6kg. Table 3 shows the comparison of the weight and total cost between PV1 and initially selected PV module, PV13.

Table 3. Selection comparison of the photovoltaic module based on initial cost and weight

| PV module | Total Weight (kg) | Total Cost    |
|-----------|-------------------|--------------|
| PV1       | 215.600           | 24318.000    |
| PV13      | 259.000           | 23940.00     |

4. Conclusion and Future Work

In this paper the superstructure design optimization with life cycle cost analysis for standalone photovoltaic systems has been presented. The static mathematical model of the system has been formulated which includes the PV modules, inverters, batteries and wires. Mixed integer linear programming, which has been developed using GAMS, is employed to find the optimum total costs for installing the PV system subject to the energy demand required by the user and other physical dimensions constraints. The developed static model considers a constant load profile assuming the peak sun hour and temperature do not vary throughout the operation.

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