Renewable Energy Management: Technical and Economic Evaluation of an Optimized Photovoltaic System

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Abstract

This work explores how a photovoltaic (PV) system, can further contribute to worldwide efforts to reduce energy cost and environmental concerns by providing an overview of energy management analysis. Additionally, it illustrates the economic impact of installing the proposed PV system for a selected data center in Dubai, UAE. A Mixed Integer Linear Programming optimization model has been proposed that uses the output of the PV panels. The proposed model minimizes cost by optimizing the PV system size, so that the required electrical load is satisfied while minimizing the cost of purchased electrical energy from the utility grid. In this model, the system efficiency, the government incentives, the potential rebates, the inflation in electricity prices, the interest rates, the system salvage value and the electricity tariffs have been considered. A cases study is conducted in which the optimal solution does not recommend using the PV system with the current electricity prices. Sensitivity analyses have shown that changing the system cost to zero, i.e. offering it for free to the users by the governements, or the government may increase the energy costs from 0.57 [AED/KWh] to 1.1 [AED/KWh] through the imposition of taxes, this result in recommending installing the PV system.

Keywords
Optimization; economic and technical analysis; PV panels; energy management; solar energy.

1. Introduction

It is becoming extremely critical to manage energy consumption at all premises for the purpose of reducing costs and environmental impacts (Al-Salaymeh et al. 2010). It is well-known that using fossil fuels, such as oil and gas in power generation plants creates many environmental issues, mainly due to their emission of polluting greenhouse gases (GHG) into the atmosphere.

Energy production and consumption due to the increased economic progress of developing countries has increased dramatically in the last few decades. It is expected to increase by 65% in 2040, reflecting the growing prosperity and the expanding economies of such areas, while global energy demand will grow about 35% due to the world population expansion (Bortolini et al. 2014). This increase has a huge impact on both the economy and global warming caused by CO_2 and other GHG emissions.

Solar panel electricity systems, also known as solar photovoltaic (PV) systems, are one of the best available options to generate electricity from a sustainable source. However, the PV systems are conceptually categorized into two distinct types, namely the off-grid PV system and the on-grid PV connected system. The off-grid PV system consists of a PV system that supplies all the energy

required by the user through a storage system. In contrast, an on-grid PV system is a system that only supplies user requirements for electricity during daylight hours while the grid electricity supplies the user requirements at night. It is important to note that the on-grid PV system has no energy storage components.

In this paper, we consider a grid-connected PV system and we propose an optimization model to size the system so that it satisfied a pre-specified load. We suppose that the surplus energy produced by the system can be sold to the utility while the difference between the system capacity and the load can be covered by the grid electricity. We consider in the objective function the system cost, including the maintenance cost, the salvage value of the system after the end of its lifecycle, the rent of the land that is required to install the system, the price of the electricity that can be purchased from the utility and the price of the surplus PV produced electricity that can be sold to the utility.

2. Literature Review

The optimum PV system size is considered when deciding the required load to be covered while simultaneously minimizing the electricity purchased from the utility supplier (Cucchiella et al. 2015). The optimal size for a grid connected PV system from the consumer's angle at a residential site is discussed in (Hemandez et al. 1998). A linear programming model was developed, where the objective was to minimize the annual energy cost, investment cost, operation/maintenance cost, and consumption from utility cost, taking into account the salvage value as a benefit. The system capital cost was assumed to be equal to a constant value to be paid every year considering the time value of money. The capacity constraints were based on PV generated capacity, utility purchased capacity and customer demand capacity along with constraints related to the installed available area to accommodate the system. Following this model, the paper linked a percentage reduction of CO_2 emissions that can be achieved by saving 1 kilowatt unit of electricity generated from the PV system. A second approach used by (Ren et al. 2009) was the sensitivity analysis. This type of analysis of optimal system size considers many factors such as capital cost, system efficiency, interest rate and sale price of generated electricity from a PV system. In order to analyze the relationship between numerous influential factors and optimal PV capacity, multiple regression methods were employed. The optimal PV capacity has been obtained for the proposed system and another sensitivity analysis has been developed to calculate the simple payback period while considering the sale price value of the excess electricity to the utility and then by reducing the capital cost through governmental incentives and improving the PV system efficiency. The review of all researches from the year (2006-2016) was discussed in (Youssef and Zekry 2017), that used artificial intelligence (AI) in all aspects of PV systems design such as control, and monitoring. To the best of our knowledge, the proposed model is different from the existing literature in the sense that it is the only comprehensive model that optimizes the PV system size while taking into account all the parameters that we mentioned earlier.

3. Integer Linear Programming Model

In this section, we develop the proposed optimization model, where we list part of the model parameters, the model decision variables and the model objective function. For the complete model, including the other decision variables, parameters and especially constraints, the reader is referred to (Allaham 2016).

3.1 Model Parameters

The parameters of the optimization model are (Allaham 2016):

- $\mathbf{C^t}$: The net present value (NPV) of the PV system cost per panel in month t, including all electrical devices, price of panels, operations, and maintenance cost [AED/panel/month].
- $\boldsymbol{Pr_{UTL}^{-t}}$: Average price per KWh of the energy purchased from the utility considering the NPV over 25 years [AED/KWh].
- $\boldsymbol{Pr_{UTL}^{+t}}$: Average price per KWh of the energy sold to the utility from the power generated by the photovoltaic system considering the NPV over 25 years [AED/KWh].
- **SV**: Average yearly photovoltaic systems salvage value per photovoltaic panel at the end of the systems life cycle considering the NPV over 25 years [AED] (Cucchiella et al., 2015).
- $\boldsymbol{Rent^P}$: Cost of rent of the space for one photovoltaic panel per year [AED/m2].

3.2 Decision Variables

The Decision variables of the model are:

- **N**: Number of photovoltaic panels to use in the photovoltaic system [Panels].
- $\boldsymbol{KWH^{t}_{UTL}}$: Amount of energy to be purchased from utility in month t [KWh].
- $\boldsymbol{KWH^{t}_{S}}$: Amount of surplus energy from the photovoltaic system in period to be completely sold to utility [KWh].

3.3 Objective Function and Constraints

This section describes the optimization model that minimizes the total cost over the system life span considered in months (T). The optimization model is defined as follows:

$$\text{Min } Z = \sum_{t=1}^{T} (C^{t} \times N + Pr^{-t}_{UTL} \times KWH^{t}_{UTL} - Pr^{+t}_{UTL} \times KWH^{t}_{S}) - SV \times N + Rent^{P} \times N \quad (1)$$

Equation (1) describes the objective function that minimizes the total cost of the photovoltaic system over T months, including the system installation and maintenance cost, the purchased electricity cost from the utility and the land rent cost that is used to accommodate the full system. The objective function also includes the revenue generated from selling the surplus kilowatt hours generated from the photovoltaic system to the utility and the salvage value cost of the photovoltaic panels at the end of the system life span. In the complete paper, this objective function is to be minimized subject to a set of constraints that includes, for instance, constraints to make sure that the load requirements are covered either from the PV panel produced electricity or from the electricity purchased from the utility. Other constraints ensure that the area that is available to install the system is not exceeded.

Subject to the following constraints:

$$KWH^{t}_{PVL} + KWH^{t}_{UTL} = KWH^{t}_{PL}; \quad \forall t = 1,2 \dots T \quad (2)$$
$$KWH^{t}_{PV} = KWH^{t}_{PVL} + KWH^{t}_{S}; \quad \forall t = 1,2 \dots T \quad (3)$$
$$KWH^{t}_{PV} = N \times EPP^{t}; \quad \forall t = 1,2 \dots T \quad (4)$$
$$KWH^{t}_{S} \le M \times Y^{t}_{S}; \quad \forall t = 1,2 \dots T \quad (5)$$
$$KWH^{t}_{UTL} \le M \times Y^{t}_{UTL}; \quad \forall t = 1,2 \dots T \quad (6)$$
$$Y^{t}_{S} + Y^{t}_{UTL} \le 1; \quad \forall t = 1,2 \dots T \quad (7)$$
$$A_{P} \times N \le A_{AV} \quad (8)$$
$$Y^{t}_{S}, Y^{t}_{UTL} \in \{0,1\} \quad (9)$$
$$KWH^{t}_{PVL}, KWH^{t}_{UTL}, KWH^{t}_{PL}, KWH^{t}_{PV}, KWH^{t}_{S}, EPP^{t} \ge 0; \quad \forall t = 1,2 \dots T \quad (10)$$

Equation (2) ensures that the total energy required to feed the load in any month *t*.

Equation (3) explains the total energy generated from the photovoltaic system in period (t).

Equation (4) describes total energy produced by the photovoltaic system in any month *t* as a function of the energy generated.

Equation (5) forces the decision variable KWH^{t}_{S} at any period (t) to be equal to zero if its decision variable Y^{t}_{S} is equal to zero.

Equation (6) forces the decision variable KWH^{t}_{UTL} at any month *t* to be equal to zero if its decision variable Y^{t}_{UTL} is equal to zero.

Equation (7) ensures that the amount of purchased energy and sold to the utility cannot both be positive.

Equation (8) ensures that the area required to install photovoltaic panels to be not exceeding the available rented land area.

Equation (9) ensures that in any month *t* the decision variables Y^{t}_{S} and Y^{t}_{UTL} are binary.

Equation (10) ensures that all the decision variables at period (t) are positive

4. Optimization Results and Sensitivity Analysis

The optimization model defined in section (III-C) using has been implemented in the optimization software Lingo using the basic data presented in the Table 1 (Allaham 2016):

Table 1. Model Input Data

Parameters	***SV* [AED]**	**A_{AV} [m2]**	**CrentP [AED/ m2]**	**Ct [AED/Panel]**	**Pr^{+t}_{UTL} [AED/KWh]**	**Pr^{-t}_{UTL} [AED/KWh]**
Values	6.6	33,817	107.6	12.96	0.57	0.57

4.1 Results of the Basic Numerical Example

We solved the optimization model described in Equation (1) with the calculated parameters values in Table 1 in Lingo 15.0, on a Platform with Microsoft Windows Vista 2007, 3GB RAM, Processor Intel Core 2 Duo @ 2GHz, to get the optimum system cost and size. From the solution results of the software, if the objective value is negative then this indicates an annual profit, and if positive, then it indicates an annual loss (cost). Upon the obtained value of the decision variable N, the decision could be taken whether or not to opt for the PV system installation. The solution reveals that the optimum number of photovoltaic panels (N) of the system to be installed is 0, where all of the required electrical energy to supply the load is to be purchased from the utility ($\mathrm{KWH}^{t}_{\mathrm{UTL}}$) and the objective value cost is positive and equals 445,000 AED per year.

In order to investigate the impact of each parameter or multiple parameters on the decision to install the PV system, the problem has been solved while varying the values of some of the model parameters. Although the basic numerical example does not appear to recommend investing in the installation of the PV system, it is a factor that would prove worthwhile for decision-makers to take a proactive approach toward encouraging the community to switch over to renewable energy sources for long-term benefits.

4.2 Impact of the Land Rent Cost and the Surplus Electricity Price on the Optimal Solution

To study the impact of the land rent cost on the solution, we varied the land rent between 0 and 295.9 [AED/m2/year] while maintaining the other parameters equal to their values shown in the basic example in section 4.3. The model is solved and noted its optimum solutions.

Figure 1 identifies the effect of changing the land area rent cost on the objective value and the optimum system size. From Figure 1 it is apparent that installing the PV system compared to the basic numerical example will be recommended and profitable when the land rent drops from its actual cost of 295.9 [AED/m2/year] to 85 [AED/m2/year] or below, i.e. to almost 30% of its actual cost. The objective function value indicates a negative value (profit) of 87,893 [AED/year] and the optimal number of panels to install is $N = 12{,}297$ panels. For the case when the land rent costs 90 [AED/m2/year] and above, the objective function value still indicates a negative value (profit) of 26,408 [AED/year], and the optimal system size to install is also $N = 12{,}297$ panels. Where the land rent increases to 129 [AED/m2/year], it will still not be recommended to install the PV system as the optimal objective function value equals 455,000 [AED/year].

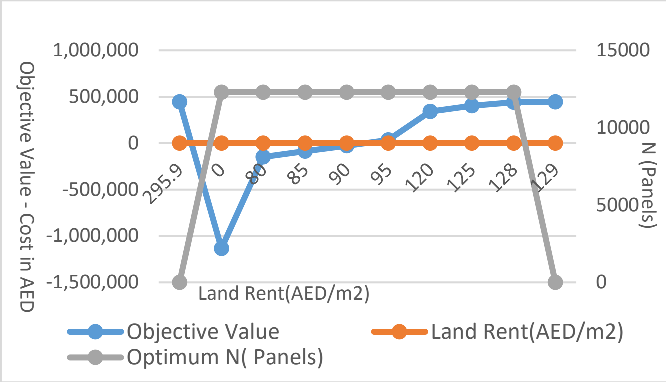

Figure1. Effect of the land rent cost on objective valueand on optimum N panels with electricity selling and purchase price equal to 0.57 [AED/KWh].

4.3 Impact of the System Cost on the Optimal Solution

As stated in previous sections, PV system installations would not be recommended even if provided free of cost or fully subsidized by the government, owing to the high land rent rates and current prices for purchasing and selling energy. Figure 2 shows that the PV system will be recommended ($N \geq 0$) if the system cost remains at 12.96 [AED/panel/month] and prices for selling and purchasing energy remain at 0.7 [AED/KWh]. Figure 2 also reveals that given the parameter of the system for the basic numerical example, installing the PV system that costs 12.96 [AED/panel/month] will only be profitable if the electricity selling and purchasing prices are 1.1 [AED/KWh] and above. To encourage the use of renewable energy sources, the government may increase the energy costs from 0.57 [AED/KWh] to 1.1 [AED/KWh] through the imposition of taxes.

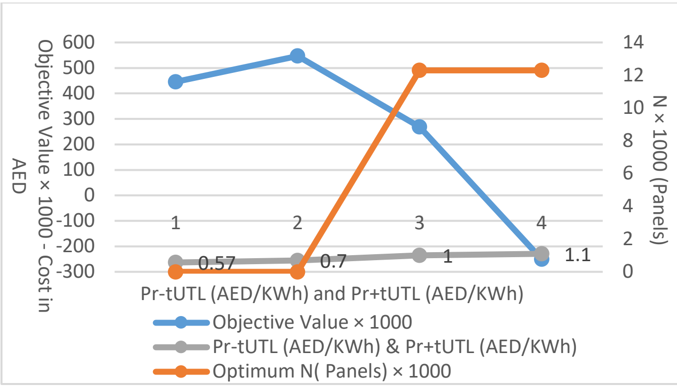

Figure 2. Effect of changing $\boldsymbol{Pr^{+t}_{UTL}}$/ $\boldsymbol{Pr^{-t}_{UTL}}$ with equal values and the basic system cost 12.96 (AED/panel/month) on the objective value and the optimum number of Panels.

Figure 3 shows the effect of having free system cost on the objective value and an optimum number of PV panels, where the other parameters remain the same as for the basic model. Increasing the surplus electricity selling price to 0.69 [AED/KWh] and keeping all the other parameters unchanged, except the system cost C^t [AED/panel/month], as in the basic numerical example will make installing the system profitable. The corresponding optimal profit would be 31,000 [AED/year] for an optimal number of panels equal to N = 12,297.

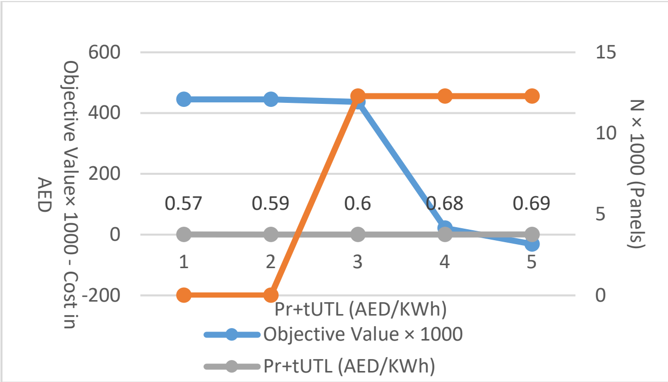

Figure 3. Effect of changing $\boldsymbol{Pr_{UTL}^{+t}}$ with a free System Cost and $\boldsymbol{Pr_{UTL}^{-t}}$ = 0.57 (AED/KWh) on the objective value and the optimum number of panels.

5. Conclusion

An optimization approach has been proposed to equip decision makers with the available and feasible options for switching over to energy efficient photovoltaic system installations that can satisfy the ever-growing demand for electricity. Lingo 15.0 optimization software was utilized in this work to solve the optimization model.

An optimization model has been presented considering monthly average values of the load to be supplied, average output energy from the PV panels based on average peak sun hours for the UAE. Based on actual values of the parameters of this model from the case study, the PV system installation is not recommended unless the land rent cost drops to 30% of its actual cost or the purchased/sold energy prices increases to 1.1 [AED/KWh] from their actual values of 0.57 [AED/KWh]. The impact of this work will target the consumers toward renewable energy source for generating electricity rather than conventional use of burning fossil fuel and its impact on commercial and environmental impact. This work can be used for future study related to case by case implementation in residential properties i.e. implementation of optimized PV system for Villas in UAE.

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