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Multiobjective Optimization of Photo Voltaic Battery System Sizing for Grid-Connected Residential Prosumers Under Time-of-Use Tariff Structures

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ABSTRACT The integration of photovoltaic and battery energy storage systems into utility grids is favorable for electricity customers, especially for high consumption load patterns due to the high electricity bill. To increase the annual bill savings and decrease the dependency on the utility grid, a procedure of optimally sizing the PV battery system is presented in this paper. A MATLAB-based code of the genetic algorithm is used to maximize the system self-sufficiency and minimize the discounted payback period while guaranteeing the system profitability. The optimization technique is introduced under the time-of-use tariff structure for residential prosumers in two scenarios. The first introduces a sellback energy price equal to the off-peak energy price, and the second introduces a sellback energy price equal to the on-peak energy price. The economic and technical effects of this optimization are described and analyzed. The effect of PV system capital cost, battery capital cost, and discount rate variations is evaluated by sensitivity analysis. The results indicate that for a sellback price equal to the off-peak price, a minimum discounted payback period can be achieved by installing the maximum PV system size without batteries, and it is reduced to half of its value for a sellback price equal to the on-peak price at the same PV system capacity. For a sellback price equal to the off-peak price, the minimum DPBP of 5.8 years can be achieved by installing a 20 kW_p PV system without batteries with 47% self-sufficiency and 2.4 years for a sellback price equal to the on-peak price by installing the same system capacity. The proposed approach highlights that increasing the battery size leads to high self-sufficiency without a considerable decrease in the annual bill savings that encourage customers to invest in the PV battery system.

INDEX TERMS Multiobjective optimization, residential load, rooftop PV battery system, time-of-use tariff structure.

ABBREVIATIONS

C_0	Total Initial Investment Cost
C_t	Net Cash Inflow During the Period t
d	Number of days
DPBP	Discounted Payback Period
E_{Nom}	Nominal battery energy
E(t)	Battery energy at time t
LCOE	Levelized Cost of Energy
N	Project Lifetime
NPV	Net Present Value
NPC	Net Present Cost
PV	Photovoltaic
r	Real Discount Rate
S-S	Self-Sufficiency
SOC	State of Charge
T	Project Total Period
t	Number of Time Periods

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I. INTRODUCTION

During the last decade, the importance of new technologies and changes in incentive policies and governmental regulations have led to the power grid being smarter, more reliable, and more distributed [1]. These changes help energy storage systems provide more utility grid services from the prosumers' perspective [2]. Energy storage systems can provide solutions to utility and prosumers at the same time, while their total economic benefits depend on their efficiency and capital cost [3]. Sizing the PV battery system represents an important part of the system design to satisfy a given load demand. Therefore, it is necessary to assess the technical benefits and economic feasibility of the system and determine the optimum sizing for a given load pattern [4].

This paper aims to introduce a novel optimization approach of the grid-connected PV battery system under a time-of-use (TOU) dynamic pricing scheme to a developing country to achieve the optimum system sizing for residential prosumers to achieve two converse objectives. The main objective of the optimization is to achieve maximum self-sufficiency, in addition to minimizing the discounted payback period to be less than or equal to 10 years, while maintaining the system profitability. The paper is subjected to two main scenarios: the first is to study the effect of implementing a sellback energy price equal to the off-peak energy purchasing price, and the second is to study the effect of implementing a sellback energy price equal to the on-peak energy purchasing price subjected to system technical and economic constraints. The Levelized Cost of Energy (LCOE), Net Present Value (NPV), and Annual Bill Savings are chosen as economic indicators, and self-Sufficiency (S-S) is chosen as a technical indicator to validate the profitability and efficiency of the proposed system. Some economic variations, such as the PV system capital cost, battery capital cost, and nominal discount rate, are studied as a system sensitivity analysis.

II. LITERATURE REVIEW

To achieve the optimum operation of the PV battery system while considering profits of different objectives, it is crucial to equip a suitable PV and battery capacity. Many models have been developed to determine optimal sizing for PV and battery storage systems. Aiming to minimize the annual comprehensive cost, the PV and battery storage capacity under different dynamic pricing schemes and subsidies were optimized [5]. The study showed that PVs need to be equipped with batteries to utilize peak valley electricity pricing under a TOU tariff structure. Additionally, it was concluded that higher electricity prices lead to more cost reductions, and more batteries could be installed. Utilizing the particle swarm optimization technique, Hejun Yang *et al.* proposed an optimized dispatch strategy to improve the operating efficiency of PV battery systems under TOU tariff structures [6]. The optimization method depended on two consequent stages: the first one was to optimize the status of battery charging, and the second one was to optimize the PV output during the different times even to feed the load, sell to the grid or charge the battery. This proposal aimed to achieve peak shaving to reduce the electricity cost.

On the other hand, ref [7] used a genetic algorithm technique to achieve the optimum location of PV battery systems considering the time value of money and the time of investment, and it was found that a good location of the system can provide and improve the economy of the distribution network. Scheduling the battery operation was used in a PV battery system to minimize the peak load and demand charges using a mixed linear programming technique [8]. The system calculated the NPV of the battery system only, and the results were compared with the basic tariff structure. It was shown that the proposed algorithm increased the NPV of the system and increased the battery lifetime, while Li-ion batteries are not financially viable on the demand side, and it is valid if the installation cost reaches \$450/kWh. Maximizing the self-consumption of PV battery system was targeted through Genetic Algorithm optimization technique by ref [9], and it was found that increasing the self-consumption can decrease the gross energy obtained from the utility to 80%. At the same time, the study didn't consider any economic factor. Yourim Yoon and Yong Kim used a real coded genetic algorithm to schedule the charging time of the energy storage system integrated with renewable power under a TOU tariff structure, and it was found that the electricity costs were reduced by 17% by scheduling charging of the energy storage systems compared to the system without it. Although both battery efficiency and battery capital cost can affect the overall cost, this study did not consider any of these factors [10].

To optimize the customer's choice of PV and battery component sizes between different retailers, Warren S. Vaz introduced a strategy taking into consideration two different objectives: the first was to minimize the total system cost, and the second was to minimize the carbon footprint (CO_2) under different operating scenarios [11]. On the other hand, a Pyomo optimization language was used in [12] to achieve the optimum operation of the battery system to minimize the monthly electricity cost by minimizing the demand charge for TOU customers or by minimizing the energy charge for NEM customers. In the Malaysian power sector, two consecutive studies were conducted to evaluate TOU tariff implementation [13] and [14]. The first study found that customers with low monthly energy consumption did not benefit from integrating PV with the grid, as their electricity bill is lower than the PV generation cost. Therefore, it was suggested in the second one that TOU electricity price optimization may give financial benefits for all customers, including low consumption customers. The results showed that introducing an optimized TOU with the current NEM incentive policy may reduce the annualized electricity cost for all customers. Without considering the battery system in the optimization problem, under a TOU and demand tariff structure, ref [15] introduced an optimization technique to achieve the optimum size of PV and the optimum battery charging schedule and discharging. It was clear that without introducing any constraints, the optimum solution was achieved without batteries, and a higher PV size leads to an increase in the NPV.

Under the TOU tariff structure, ref [16] used a GA to obtain the optimum PV battery sizing to achieve the minimum annual electricity cost. The optimization was based on scheduling the charging and discharging of batteries. It was found that the consumption profile, electricity, and battery price have a great effect on the optimum size of the installed PV. To minimize the annual cost of battery energy storage, including the energy cost and the battery cost. An optimization technique was proposed to size the battery capacity based on maximizing the self-consumption under the TOU tariff structure [17]. The proposed optimization technique revealed that the support required to residential electricity customers can be reduced. Achieving PV self-consumption and demand load shifting was aimed at by ref [18]. GA optimization was used to optimize the battery schedule of operation, including three different tariffs. The results indicated that adding batteries to grid-connected PV systems is not economically effective. Regardless of the economic reasons, a certain level of PV self-consumption can be reached by means of load shifting, while the study did not include the effect of electricity reduction during peak times, which may make an advantage for using battery storage systems. To increase the renewable energy cost higher than the fossil fuel energy cost, a teaching-learning optimization algorithm was introduced in [19] to find the minimum NPC and minimum COE. The study revealed that using a PV battery system under the proposed technique improves the NPC and COE by 15.6% and 16.8%, respectively. A linear programming optimization algorithm was implemented in Portugal by ref [20] to compare battery storage versus the demand response under the current electricity prices, and it was found that the demand response is more economically preferred than using battery storage. In contrast, a decrease in the battery capital cost could achieve a financial profit. Canada is one of the leading countries in applying TOU tariff structures for residential applications. Irtaza M. Syed and Kaamran Raahemifar introduced a predictive optimization technique to minimize the power purchased from the grid under a TOU tariff structure [21]. The program was repeated automatically every 15 minutes for prediction corrections. The proposed algorithm succeeded in reducing the electricity cost by reducing the grid purchased power and protected the customer from price hikes.

Based on the presented literature, PV and battery sizing has been optimized in several research works for specific outputs. However, this paper aims to optimize an output that is different from those addressed by other researchers. For instance, ref [11] aimed to develop a multiobjective optimization to minimize the total system cost and the carbon footprint CO_2. Alternatively, the current research aims to achieve maximum system self-sufficiency by increasing the number of installed batteries while achieving a minimum discounted payback period. These two objectives are contradicting by nature. To the best of our knowledge, this is the first study to adopt such objectives in this context.

The rest of the paper is organized as follows: an introduction to the genetic algorithm optimization technique in section 3, followed by an explanation of the used case study and the proposed method and technique to introduce the system constraints and objective functions in section 4. Then, it introduces the technical and economic effect of implementing the PV battery system followed by the optimization results for a small sellback energy price, followed by some economic variations as sensitivity analysis in the first part of section 5. The second part of section 4 is to study the effect of this implementation for a high sellback energy price followed by its sensitivity analysis. Finally, the paper is concluded in section 6.

III. IMPLEMENTATION OF MULTIOBJECTIVE OPTIMIZATION USING THE GENETIC ALGORITHM (GA) TECHNIQUE

GA is a commonly used technique to solve optimization problems even if these problems are constrained or unconstrained. At each iteration, it generates several points called the population. The best point in this population is the nearest one to the optimum solution. GA became a popular solver and attracted considerable attention for optimization problems because of its accuracy in finding the optimal solution. It is frequently used in power system applications such as optimal power flow, economic dispatch, optimal reactive power dispatch, power system planning and design and economic dispatch.

The implemented case study in this research is a villa in a residential compound in Egypt near Alexandria Governorate (31^0 03' N and 29^0 43' E). The energy generated by the PV system is directly related to the potential solar radiation at the case study location. With the help of HOMER software, solar radiation was obtained with a temporal resolution of one hour, which was used as an input parameter to the optimization code.

Fig. 1 shows the monthly average solar global horizontal irradiance (GHI) results at an annual average solar radiation of 5.2 kWh/m^2/d.

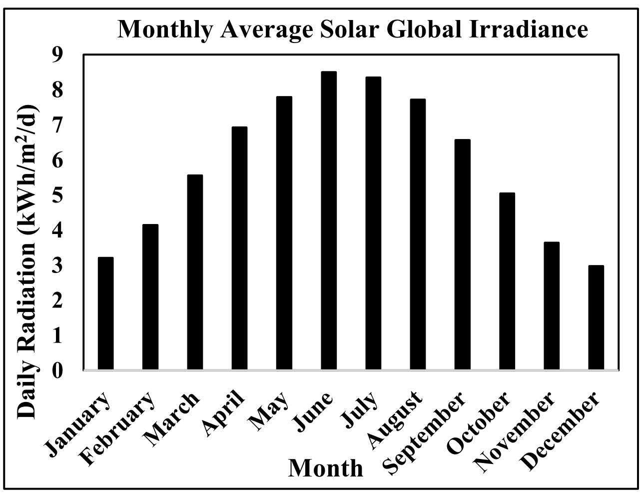

FIGURE 1. Monthly average solar global irradiance.

The load is assumed to be increased by 20% during peak times in the summer season, as indicated in Fig. 2.

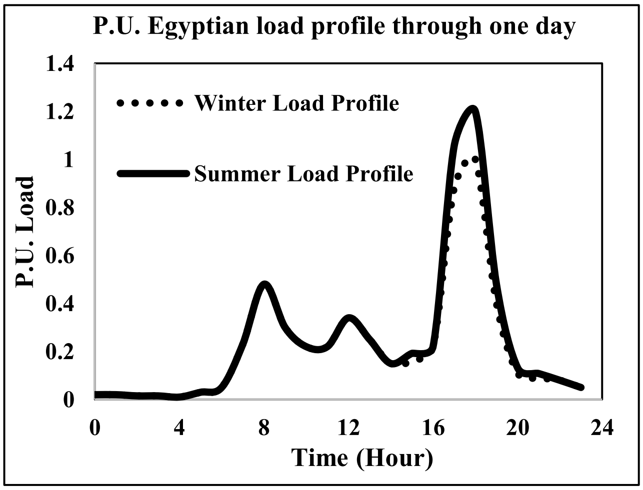

FIGURE 2. Annual average daily load profile [22].

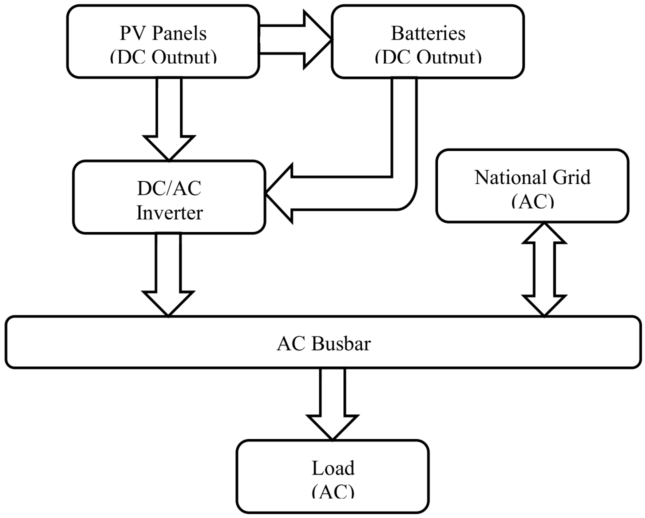

FIGURE 3. Basic topology of the grid connected PV battery system.

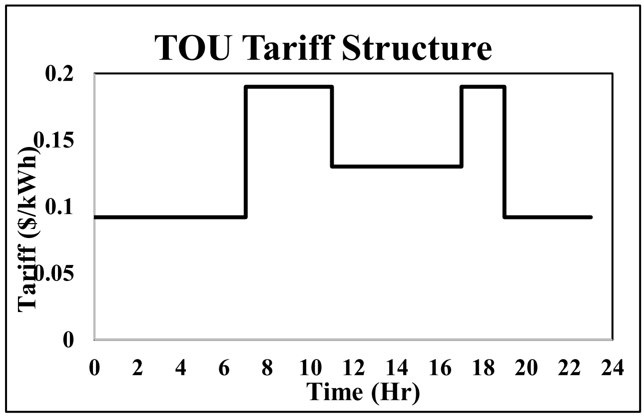

FIGURE 4. TOU peak periods tariff structure.

The cumulative load is 8,539 kWh in the winter season (from October to May) and 4,488 kWh in the summer season (from June to September), given a total annual load consumption of 13,027 kWh, with an average value of 35.69 kWh/d. These load data were considered in a MATLAB code as an input parameter in the developed multiobjective GA. The variation of such load data affects the amount of energy purchased from the grid and the energy sold to the grid and the output objective parameters.

Based on the Central Bank of Egypt, the Egyptian nominal discount rate is 8.75% [23]. The rooftop grid-connected PV battery system consists of PV panels, inverters, batteries, and the utility grid, as shown in Fig. 3. Based on a local market survey, the PV system capital cost is \$500/kW$_p$ and has a 25-year lifetime. The inverter has a 10-year lifetime, so it is replaced two times during the system's total lifetime. Both the PV system and the inverter have \$20 of annual maintenance and operational cost. The batteries used are Li-ion batteries (12 V and 200 Ah; 2.4 kWh); 10-year lifetime, with \$530 capital cost, \$200 replacement cost, and \$5 for the annual maintenance cost [24]. The overall project lifetime is 25 years. The system operation follows some constraints; batteries are not permitted to be charged or discharged from the utility grid, and they are charged if and only if there is a surplus power from the PV panels.

The system under study integrates PV and battery systems by implementing TOU tariff structures. The TOU tariff structure is proposed and is divided into three different periods (off-peak, mid-peak and on-peak), as shown in detailes in Fig. 4. The sellback price has a great effect on the system profitability and performance. Different countries applied different sellback prices, such as 8€cent/kWh in Germany [25] and 28.8 cent/kWh in Canada [26], and the prices ranged from 9.5 to 17 cent/kWh in Australia [27].

Grid-connected PV battery system sizing is optimized using the GA technique with the same TOU tariff for energy purchased and two different sellback energy price scenarios: the first by adjusting the sellback energy price equal to the off-peak energy purchasing price (\$0.092/kWh) and the second by adjusting the sellback energy price equal to the on-peak energy purchasing price (\$0.19/kWh). A sensitivity analysis follows each scenario to account for the variation in the PV system capital cost, battery system capital cost, and nominal discount rate to determine the system profitability by calculating the system NPV and the discounted payback period. The optimization is implemented using a purposely developed MATLAB code, and it is implemented as per the flow chart shown in Fig. 5.

The economic feasibility of using the batteries in this PV system is introduced using the net present value (NPV) and the annual bill savings, which are calculated using the following equation [28]:

NPV is the difference between the present value of cash inflows and the present value of cash outflows. It is used to analyze the profitability of a projected investment or project [29]–[31]. A positive net present value indicates that the projected earnings generated by a project exceed the anticipated costs. It is assumed that an investment with a positive NPV is profitable, and an investment with a negative

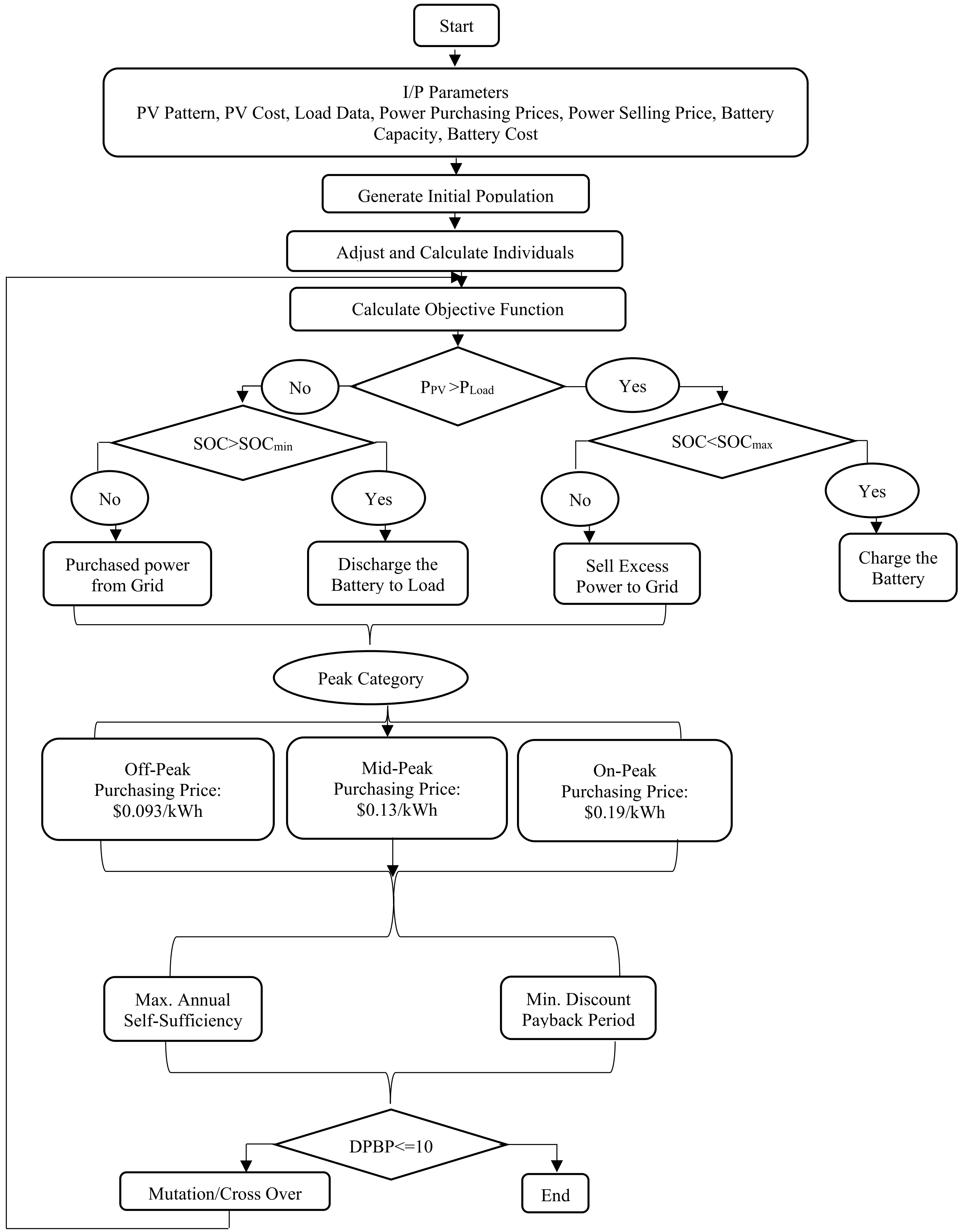

FIGURE 5. Genetic Algorithm optimization flow chart.

NPV results in a net loss.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{1}$$

where C_t is the net cash inflow during period t, C_o is the total initial investment costs, t is the number of time periods, and r is the discount rate.

Annual bill savings is an index that reflects how much money is saved annually by using the PV system compared to the total consumption from the power grid.

$$\begin{aligned} &\text{Annual Bill Savings} \\ &= \text{Electricity bill without PV system} \\ &\quad - [(\text{Energy Generated from PV system} \\ &\quad \times \text{Energy Purchasing Price}) + (\text{Energy Sold to Grid} \\ &\quad \times \text{Energy Selling Price})] \end{aligned} \tag{2}$$

The technical and operational feasibility is studied using the value of self-sufficiency introduced by the batteries.

Self-Sufficiency is the sum of (PV power which supplied the load and battery power which supplied the load) divided by the annual load [31]–[33]; it means the ability to supply one's own needs from power without external assistance from the grid.

$$\begin{aligned} \text{Self Sufficiency} = &[(\text{PV to load} + \text{Battery to Load}) \\ &/(\text{Grid to Load} + \text{PV to load} \\ &+ \text{Battery to Load})] \end{aligned} \tag{3}$$

A. OPTIMIZATION AND OBJECTIVE FUNCTIONS

The GA optimization technique is used to achieve two converse objectives: the first is to maximize the system self-sufficiency, and the second is to minimize the DPBP. The accumulated daily PV production pattern, load, and battery SOC are considered system inputs. The GA starts with a randomly generated population in each hour. The maximum number of iterations is set to 200. During the optimization procedure, GA is always requested to meet the system constraints.

The objective functions that represent self-consumption and DPBP are:

$$\mathbf{Y(1) = max \sum_{d=1}^{365} \frac{PV\ to\ Load + Battery\ to\ Load}{Total\ E_{Served}}} \tag{4}$$

$$\mathbf{Y(2) = min \sum_{N=1}^{25} \frac{Total\ System\ Investment}{Annual\ Savings}} \tag{5}$$

To achieve maximum system self-sufficiency, both PV and battery sizes have to be increased to feed the largest part of the load (equation 4). On the other hand, increasing the PV and battery sizes increases the capital investment cost, which leads to an increase in the payback period (equation 5). This, in turn, may lead to the system becoming financially unprofitable. Therefore, the optimization technique aims to maximize the system self-sufficiency with minimum investment cost while maintaining a payback period of less than or equal to 10 years.

B. SYSTEM CONSTRAINTS

The PV battery system operation follows specific operational constraints; namely, batteries are not permitted to be charged or discharged from the utility grid, and they are charged if and only if there is a surplus power from the PV panels. The system is considered a single point connected to the main utility grid. The load profile and PV production pattern for each time instant are considered input parameters.

The optimization system constraints are defined in equations (6) - (8).

$$\mathbf{20\% \leq SOC \leq 95\%} \tag{6}$$

$$\mathbf{NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o > 0} \tag{7}$$

$$\mathbf{DPBP \leq 10} \tag{8}$$

The system boundaries are subjected to a 20 kW_p PV system maximum size according to the limitation of the installation rooftop available area, and the batteries range from 0 kWh to 75 kWh as the maximum installation size. The system has to achieve maximum self-sufficiency while being profitable at the same time. Additionally, the system has to gain profits within a period of less than or equal to 10 years. Gaining a financial profit within ten years means that the system has a positive NPV, and it is profitable.

IV. GA OPTIMIZATION RESULTS AND SENSITIVITY ANALYSIS

A high energy consumption load pattern (35.28 kWh/d) is used for the optimization technique. The annual bill for such a load pattern is $1,202 without integrating neither PV nor battery systems under the block rate tariff structure. The optimization is carried out when the energy sellback price is equal to the off-peak energy purchasing price ($0.092/kWh), and then it is followed by increasing the energy sellback price to be equal to the on-peak energy purchasing price ($0.19/kWh).

A. SELLBACK ENERGY PRICE EQUALS TO OFF-PEAK ENERGY PURCHASING PRICE

Introducing TOU tariffs for this load pattern with three different periods (off-peak, mid-peak, and on-peak) achieves $1,731 of the annual electricity bill. Implementing PV to residential prosumers with a sellback energy price equal to the off-peak energy price ($0.092/kWh) affects the system profitability, as shown in Table 1 and the following figures.

TABLE 1. Discounted payback periods for different PV sizes for selling price equals the off-peak price.

System Capacity (kW_p)	DPBP (Year)	Annual Bill Savings ($/Yr)	Self-Sufficiency (%)
5	N/A	-431	40
10	15	428	44
15	7.3	1,291	46
20	5.8	2,138	47

1) OPTIMIZATION RESULTS (SCENARIO A)

The effect of adding different PV sizes on the economic indicators (NPV, LCOE, annual bill savings, and self-sufficiency) is studied, and the results are shown in Fig. 6 and Fig. 7.

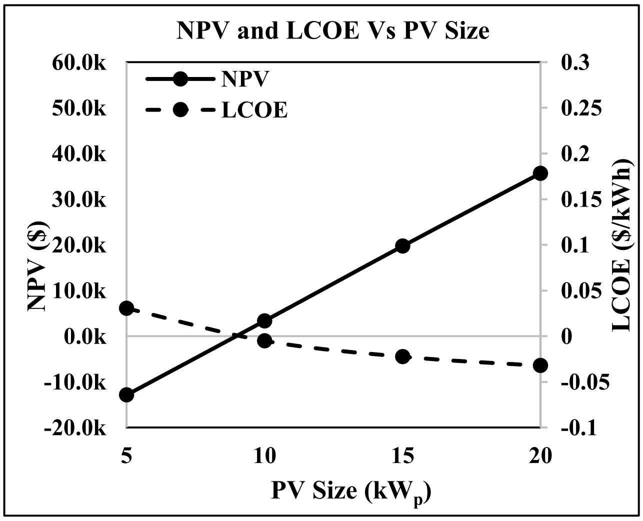

FIGURE 6. Effect of PV size on the NPV and LCOE for selling price equals the off-peak price.

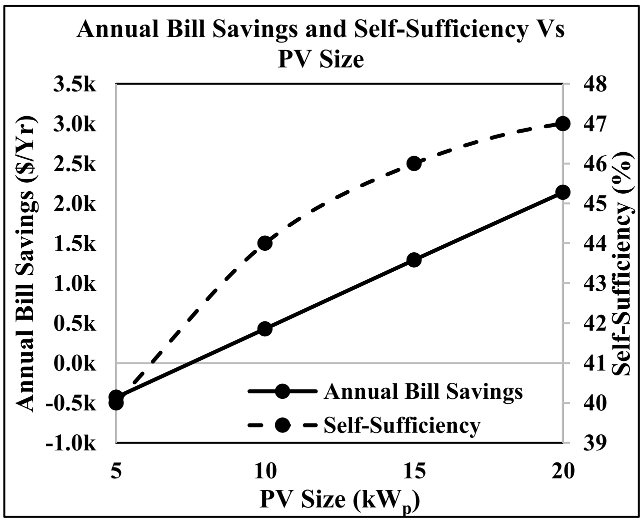

FIGURE 7. Effect of PV size on Annual bill savings and self-sufficiency.

As shown in Fig. 6, the system is not profitable until installing an 8.97 kW_p PV system; at this value, the NPV and the LCOE are equal to zero, as after this size, the NPV is positive, and the system begins to achieve profits. On the other hand, the energy cost is decreased rapidly by increasing the PV size because the system reduces the dependency on the utility grid, and it depends on the PV. Unlike the current Egyptian block rate tariff, the system is not profitable until installing a 12.87 kW_p PV system [34].

The results obtained from the previous figure indicate that increasing the PV system size increases the amount of energy sold to the utility, which leads to a decrease in the electricity bill and hence an increase in the annual bill savings. Additionally, increasing the PV size increases the amount of energy used from the system, which reduces the dependency on the utility grid and increases the system's self-sufficiency.

Based on the system evaluations, it is found that the minimum DPBP could be achieved by implementing a 20 kW_p PV system without batteries. The DPBP is 5.8 years, and 46.7% of self-sufficiency could be reached. On the other hand, the maximum self-sufficiency could be achieved by implementing a 20 kW_p PV system and 48 kWh battery system. DPBP increases to 18.4 years, and 98.8% self-sufficiency could be achieved. Both scenarios guaranteed system profitability with a positive NPV.

To achieve two converse objectives (maximum self-sufficiency and minimum discounted payback period) subjected to DPBP<= 10 years, the GA optimization technique is implemented, and it is found that the best system configuration consists of a 20 kW_p PV system and a 16.8 kWh battery system that obtains 9.9 years of DPBP and 77.4% self-sufficiency.

2) SENSITIVITY ANALYSIS (SCENARIO A)

The optimized system results (20 kW_p PV and 16.8 kWh battery system) may be subjected to parameter variations. The main varying parameters considered for sensitivity analysis are the PV system capital cost, battery system capital cost, and nominal discount rate.

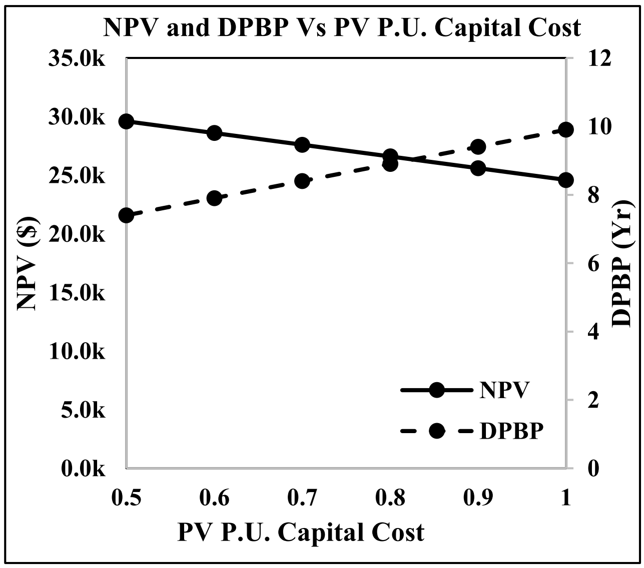

FIGURE 8. Effect of PV capital cost variations on NPV and DPBP when the selling price equals the off-peak price.

a: EFFECT OF PV CAPITAL COST REDUCTIONS

The PV system capital cost has fallen rapidly over the last ten years, and it is expected to continue to decrease. The PV system capital cost was reduced as follows (0.9, 0.8, 0.7, 0.6, and 0.5) P.U. from the original capital cost. These variations aim to study the effect on the NPV and DPBP, as shown in Fig. 8.

As a result of decreasing the system capital cost, the NPV is enhanced and increased, making the system more profitable. It decreases the DPBP due to a reduction in the system capital cost, e.g., decreasing the system capital cost to 0.5 P.U. from its original value ($500/kW$_p$) reduces the DPBP by approximately two years, while the NPV is increased by $5000. On the other hand, this reduction does not affect either the annual bill savings or the system self-sufficiency, as there is no change in the energy flow.

Decreasing the system capital cost may help to increase the system self-sufficiency, as it increases the maximum allowable batteries to be installed while maintaining the system constraints without changing, e.g., decreasing the system capital cost to 0.5 P.U. from its original value allows the installation of 26.4 kWh batteries instead of 16.8 kWh. The DPBP is 9.9 years with 93% annual self-sufficiency, but the annual bill saving is slightly decreased to $1,861/year instead of $1,955/year.

The rate of annual bill savings reduction is low, which encourages the customer to invest in the grid-connected PV battery system to reduce the dependency on utility in addition to gaining financial benefits.

b: EFFECT OF BATTERY CAPITAL COST REDUCTIONS

The battery capital cost has fallen rapidly, and it is expected to continue to decrease. The battery capital cost was reduced as follows (0.9, 0.8, 0.7, 0.6, and 0.5) P.U. from its original capital cost ($530/battery). These variations aim to study the effect on the NPV and the DPBP, as illustrated in Fig. 9.

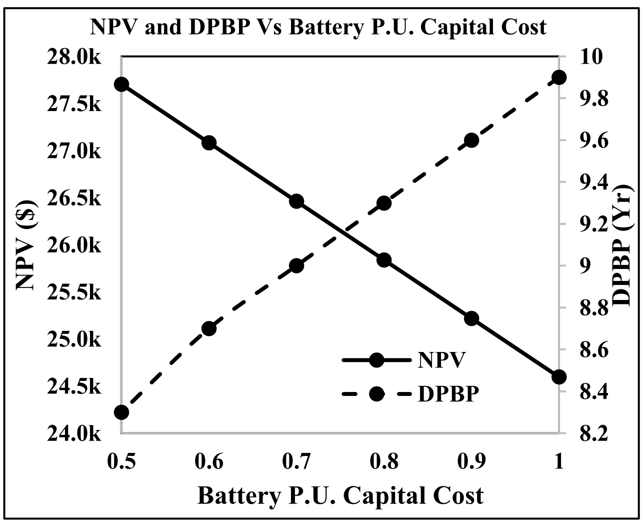

FIGURE 9. Effect of battery capital cost variations on NPV and DPBP for selling price equals the off-peak price.

Fig. 9 indicates that reducing the battery capital cost has a small effect on DPBP, but it enhances the system profitability and increases the system NPV. On the other hand, there is no effect on the annual bill savings, as reducing the battery capital cost does not affect the energy flow from or to the utility grid. The reduction in the battery capital cost may help install more batteries to increase the system self-sufficiency while maintaining the system constraints without changing, e.g., decreasing the battery capital cost to 0.5 P.U. from its original value allows the installation of 24 kWh batteries instead of 16.8 kWh, and the DPBP is 9.5 years with 89% annual self-sufficiency. However, the annual bill savings decrease to $1,905/year instead of $1,955/year.

c: EFFECT OF NOMINAL DISCOUNT RATE VARIATIONS

The discount rate may vary and change depending on the economic situation of the country, which affects the system profitability and the DPBP. The nominal discount rate was changed as follows (1.2, 1.1, 0.9 and 0.8) P.U. from its original value. These variations aim to study the effect on the NPV and DPBP, as shown in Fig. 10.

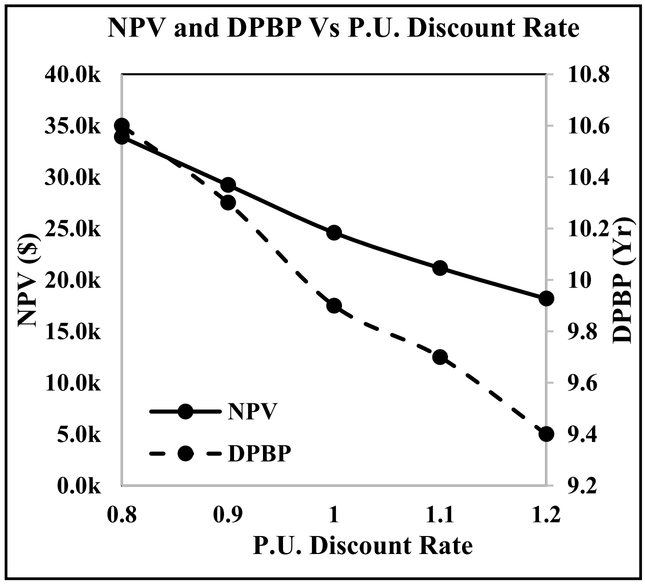

FIGURE 10. Effect of discount rate variations on NPV and DPBP for selling price equals the off-peak price.

As presented in Fig. 10, at the same inflation rate, decreasing the discount rate makes the system more profitable. With respect to the time value of money, the DPBP is increased, as it needs more time to achieve benefits. This increase in the DPBP led to a reduction in the number of installed batteries to achieve the system constraints that lead to a decrease in the system self-sufficiency, e.g., for 1.2 P.U. of the discount rate (10.5%), the DPBP is 9.4 years while decreasing it to 0.8 P.U. (7%) the DPBP is 10.6 years.

The previous sensitivity analysis proves that the lower PV capital cost and lower battery capital cost gain more profits for the system indicated in higher NPV and lower DPBP while increasing the discount rate is better from the DPBP point of view, but it decreases the system profitability.

The best system configuration is a 20 kW$_p$ PV system and 48 kWh battery system and achieves 98.8% self-sufficiency, 9.7 years of discounted payback period, $1,763/year of annual bill savings, and $15,289 of NPV.

B. SELLBACK ENERGY PRICE EQUALS TO ON-PEAK ENERGY PURCHASING PRICE

Implementing PV to residential prosumers with a sellback energy price equal to the off-peak energy price ($0.19/kWh) affects the system profitability, as shown in Table 2 and the following figures.

TABLE 2. Discounted payback periods for different PV sizes for selling price equals the ON-peak price.

System Capacity (kW_p)	DPBP (Year)	Annual Bill Savings ($/Yr)	Self-Sufficiency (%)
5	N/A	-24	40
10	3.8	1,697	44
15	2.7	3,440	46
20	2.4	5,169	47

1) OPTIMIZATION RESULTS (SCENARIO B)

The effect of adding different PV sizes on the economic indicators (NPV, LCOE, annual bill savings, and self-sufficiency) is studied, and the results are shown in Fig. 11 and Fig. 12, respectively.

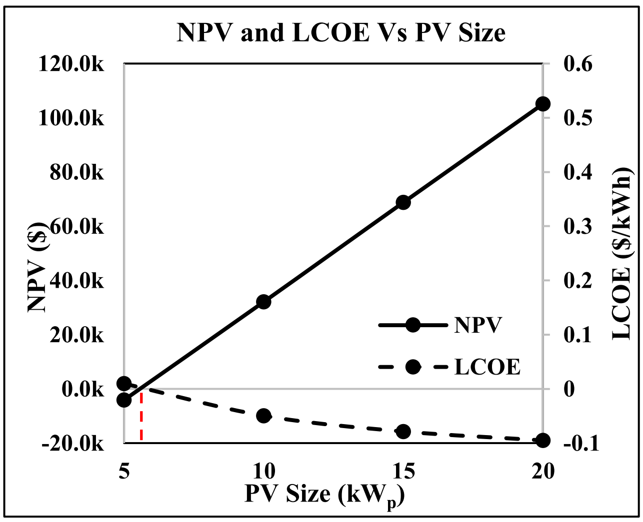

FIGURE 11. Effect of PV size on the NPV and LCOE for selling price equals the on-peak price.

The results obtained from the previous figure show that the system is not profitable until installing a 5.56 kW_p PV system. At this value, the NPV and the LCOE are equal to zero, as after this size, the NPV is in positive values, and the system begins to achieve profits. Unlike the results obtained from ref [35], the system is not profitable until installing a 21.4 kW_p PV system under the FiT incentive policy and an 11.67 kW_p PV system under the NEM incentive policy.

Increasing the PV system size increases the amount of sold energy to utility; hence, a decrease in the electricity bill could be achieved and increase the annual bill savings.

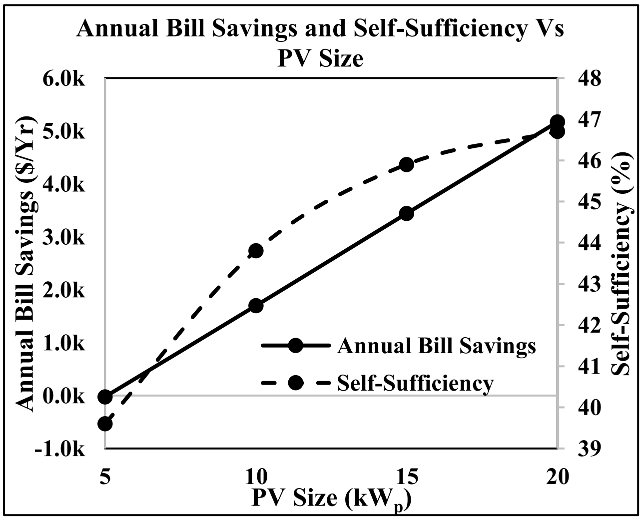

FIGURE 12. Effect of PV Size on Annual bill savings and self-sufficiency for selling price equals the on-peak price.

Based on the system evaluations, it is found that the minimum DPBP could be achieved by implementing a 20 kW_p PV system without batteries. The DPBP is 2.4 years, and 46.7% self-sufficiency could be achieved. On the other hand, maximum self-sufficiency could be achieved by implementing a 20 kW_p PV system and a 74.4 kWh battery system. The DPBP is 12 years, and 99.6% self-sufficiency could be reached. Both scenarios guaranteed system profitability with a positive NPV.

Implementing the GA optimization technique, it is found that the best system configuration consists of a 20 kW_p PV system and a 57.6 kWh battery system that obtains 10 years of DPBP and 99.3% self-sufficiency.

2) SENSITIVITY ANALYSIS (SCENARIO B)

The optimized system results (20 kW_p PV and 57.6 kWh battery system) may be subjected to parameter variations. The main varying parameters taken as a sensitivity analysis are the PV system capital cost, battery system capital cost, and nominal discount rate.

a: EFFECT OF PV CAPITAL COST REDUCTIONS

The PV system capital cost has fallen rapidly over the last ten years, and it is expected to continue to decrease. The PV system capital cost was reduced as follows (0.9, 0.8, 0.7, 0.6, and 0.5) P.U. from the original capital cost. The effect on the NPV and the DPBP is presented in Fig. 13.

As shown in Fig. 13, decreasing the system capital cost enhances and increases the NPV, which makes the system more profitable, and it decreases the DPBP due to a reduction in the system capital cost, e.g., decreasing the system capital cost to 0.5 P.U. from its original value reduces the DPBP by approximately 1.5 years.

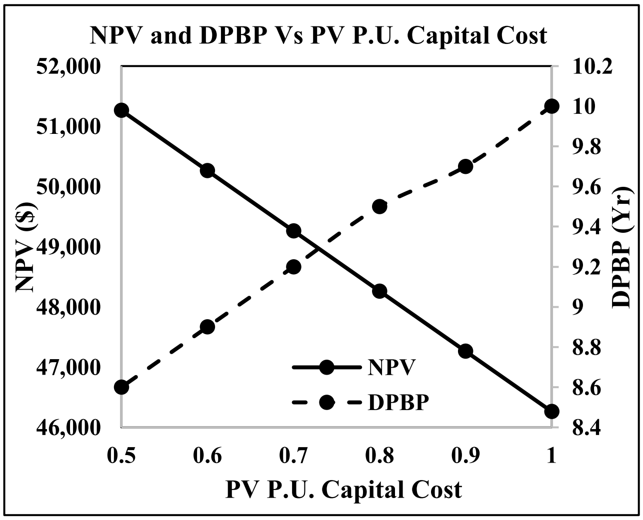

FIGURE 13. Effect of PV capital cost variations on NPV and DPBP for selling price equals the on-peak price.

b: EFFECT OF BATTERY CAPITAL COST REDUCTIONS

Due to the expected decrease in the battery capital cost, the battery capital cost is reduced as follows (0.9, 0.8, 0.7, 0.6, and 0.5) P.U. from the original capital cost. These variations aim to study the effect on the NPV and DPBP, as shown in Fig. 14.

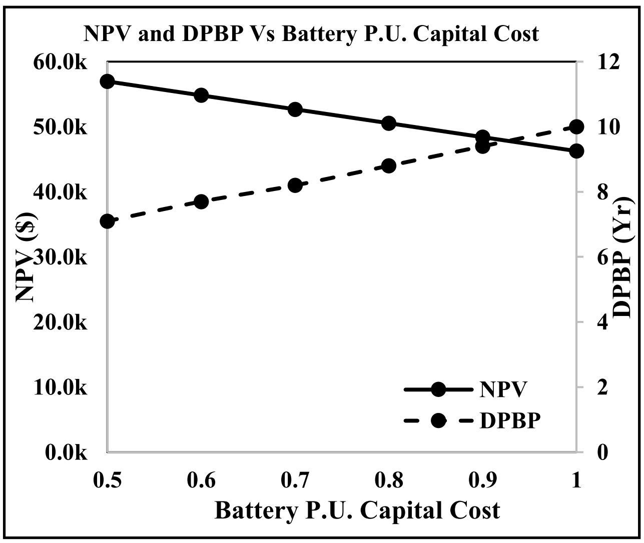

FIGURE 14. Effect of battery capital cost variations on NPV and DPBP for selling price equals the on-peak price.

For different system capital costs, reducing the battery capital cost enhances the system profitability by increasing the NPV, while it has a small effect on the DPBP.

c: EFFECT OF NOMINAL DISCOUNT RATE VARIATIONS

The nominal discount rate is now changed as follows (1.2, 1.1, 0.9, and 0.8) P.U. from its original value. These variations aim to study the effect on the NPV and DPBP, as shown in Fig. 15.

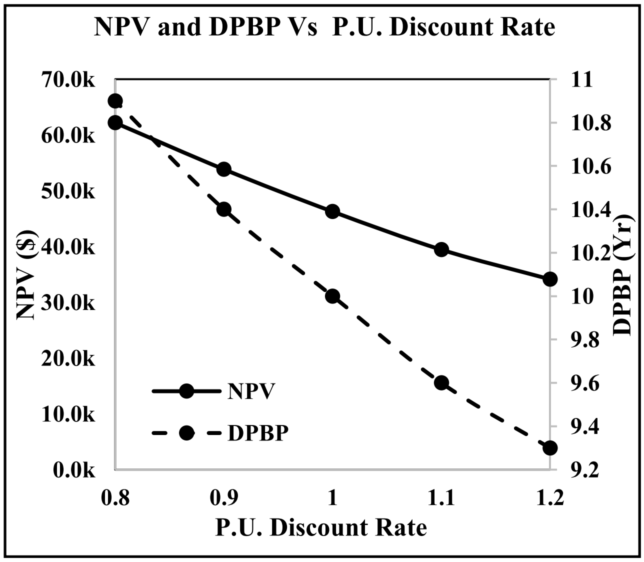

FIGURE 15. Effect of discount rate variations on NPV and DPBP for selling price equals the on-peak price.

As illustrated from the previous figure, decreasing the discount rate is preferred from the NPV point of view, which makes the system more profitable, but it is not recommended from the DPBP point of view, as it is increased., e.g., for 1.2 P.U. discount rate (10.5%), the DPBP is 9.3 years, while for 0.8P. U discount rate (7%) the DPBP is 10.9 years.

From the previous sensitivity analysis, it can be concluded that to achieve the best system configuration, lower PV and battery capital costs result in better financial profits and better DPBP. On the other hand, increasing the nominal discount rate is preferred from the DPBP perspective, while it decreases the system profitability.

The best system configuration is a 20 kW_p PV system and 74 kWh battery system and achieves 99.6% self-sufficiency, 6.2 years of discounted payback period, \$3.639/year of annual bill savings, and \$45,434 of NPV.

V. CONCLUSION

In this paper, a genetic algorithm optimization technique was proposed to obtain the optimum PV battery system sizing to achieve two converse objectives under the time-of-use dynamic pricing tariff structure. The first objective was to maximize the system's annual self-sufficiency, and the second was to minimize the discounted payback period of the system to be less than or equal to 10 years. The optimization was subjected to essential technical and economic constraints to guarantee the system's profitability. The optimization was proposed under two scenarios, the first for a low energy sellback price and the second for a high energy sellback price. The results indicated that increasing the battery energy system leads to increased system self-sufficiency, increasing the discounted payback period due to the high battery capital cost. Therefore, optimization was developed to achieve both targets together.

For a low energy sellback price equal to the off-peak energy purchasing price, the maximum system self-sufficiency is 98.8% and can be obtained by installing 20 kW_p PV in addition to a 48 kWh battery system with 18.4 years of discounted payback period, while the minimum discounted payback period is 5.8 years. It can be obtained by installing a 20 kWp PV system without implementing any batteries with 46.7% self-sufficiency. The optimum proposed solution was to install a 20 kW_p PV system in addition to a 16.8 kWh battery system that achieves 77.4% system self-sufficiency and 9.9 years of a discounted payback period.

For a high energy sellback price equal to the on-peak energy purchasing price, the maximum system self-sufficiency is 98.8% and can be obtained by installing 20 kW_p PV in addition to a 48 kWh battery system with an 8.8-year discounted payback period. In comparison, the minimum discounted payback period is 2.4 years and can be obtained by installing a 20 kW_p PV system without implementing any batteries with 46.7% self-sufficiency. The optimum proposed solution was to install a 20 kWp PV system in addition to a 57.6 kWh battery system that achieves 99.3% system self-sufficiency and 10 years of the discounted payback period.

For a sensitivity analysis, changes in PV and battery capital costs in addition to nominal discount rate variations were studied to study these effects on the optimum design, and it was found that decreasing either the PV system or battery system capital cost enables the installation of more batteries to obtain more self-sufficiency without disturbing the system constraints and guarantee the system profitability.

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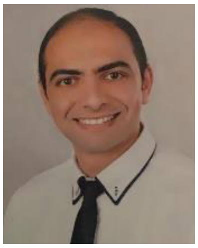

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