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Operation and Maintenance Cost Effect on Optimal Sizing of PV Array and Battery for a Grid-Connected House

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Abstract. In this paper, operation and maintenance cost effect of PV array and battery on optimal sizing of PV and energy storage capacity in a grid-connected house is analyzed. The mentioned cost is applied in objective function of studied system. The objective function also is made of other different costs including annual cost for purchasing electrical energy from grid and annual investment cost for system components and others. To exchange of energy between house and grid four modes are considered and finally, optimal sizing of PV capacity and energy storage will be obtained. A numerical method named direct search is used to optimize objective function.

Key words

Photovoltaic systems, optimal sizing, energy storage, operation and maintenance cost, direct search method

1. Introduction

Nowadays due to increase of fuel cost and pollution, using renewable energy resources like photovoltaic systems, wind turbines and fuel cells is common in all over the world. Among all these resources, PV systems applications are increasing rapidly. Maybe the most important reason is the simplicity of these resources in installation and operation. But the cost of PV panels is high, thus the attainment of optimal capacity is essential. Although in grid-connected PV systems which are more reliable and also more complex than stand-alone ones, the output power of panels affects LV[1] network power quality but utilization of energy storage can solve this problem [1] and also when produced energy is more than need, it can be saved and used later.

Optimal sizing of PV and energy storage in a grid-connected residential building has been analyzed in [2],[3]. It has been shown that optimal sizing of PV and battery capacity depends on two parameters. The first is power exchange mode between the building and grid and the second is the load profile. For example, if consumer can change load profile by shifting deferrable load to low load period, the optimal sizing will decrease [4], [5]. As it was noted earlier to define optimal sizing, objective function should be formed including different costs of system and then it must be minimized. O&M[2] cost that has not been considered for system before, is entered to objective function in this paper. Although the value of this cost for PV panels may be low, for batteries it is considerable.
This paper is organized as follows. Section 2 describes the topology of system and optimization algorithm. In section 3 the method is analyzed on a sample system as a case study and results are presented. Finally conclusions are given in section 4.

2. Description of Optimization Algorithm

The system topology studied in this paper is shown in figure 1.

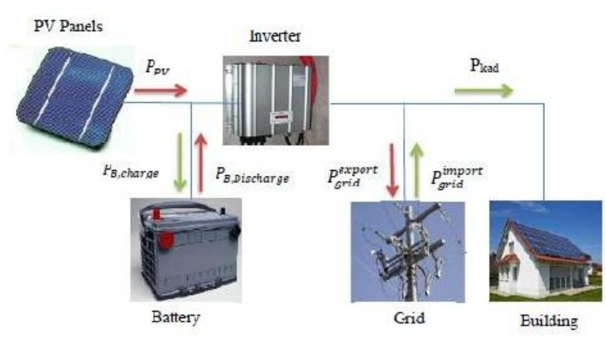

Fig. 1. Topology of the system

Considering allowable exported power from grid and imported power to it ($P^{export}_{grid,h}$,$P^{import}_{grid,h}$), Four modes for exchanging power between house and grid will be discussed [2].

Storage capacity for each PV size can be obtained using annual load profile of building, annual PV generation profile and power exchange mode. Also objective function

[1] Low Voltage

[2] Operation and Maintenance

including different costs is formed and optimal sizing of PV array and storage with minimizing objective function is obtained. In this study optimization is done using direct search method. Objective functions and the assumptions used in this paper are explained in following subsections.

A. Objective Function

In this paper, O&M cost is defined as follow:

$$CP_{om} = CP_{om}^{PV} + CP_{om}^{ES} + CP_{om}^{inverter} \tag{1}$$

Where:

$$CP_{om}^{PV} = C_{om}^{PV} \times P_{PV} \times 8760 \tag{2}$$

$$CP_{om}^{ES} = \sum_{\substack{P(h)\neq 0 \\ h=1,\dots,8760}} C_O \times P_M + \sum_{\substack{P(h)=0 \\ h=1,\dots,8760}} C_M \times W_{hourly} \tag{3}$$

$$CP_{om}^{inverter} = C_{om}^{inverter} \times R_{inverter} \times 8760$$
(4)

CP_{om}^{PV} , CP_{om}^{ES} and $CP_{om}^{inverter}$ are respectively, O&M cost related to PV array, battery and inverter. C_{om}^{PV} and $C_{om}^{inverter}$ are the rate of O&M cost for PV array and inverter, respectively. Also P_{PV} and $R_{inverter}$ are their nominal capacities. W_{hourly} is hourly discharged energy of the battery when it is in idle mode and P_M is the maximum usable power of battery both in charging and discharging mode. It should be noted that $P(h)$ is the power of battery in each hour of year. C_O and C_M , respectively, are O&M specific costs [6],[7]. O&M cost will be added to objective functions which are defined for each power exchange mode as follow:

1) Zero power export (self-consumption):

$$C_{total} = CP_{inv} + CP_{om} + CP_{ele} - CR_{self-consumption} \tag{5}$$

2) Maximum power export:

$$C_{total} = CP_{inv} + CP_{om} + CP_{ele} - CR_{feed-in-tariff} \tag{6}$$

3) Maximum power import:

$$C_{total} = CP_{inv} + CP_{om} + CP_{ele} + CP_{ccl} - CR_{feed-in-tariff} \tag{7}$$

4) Maximum power import and export:

$$C_{total} = CP_{inv} + CP_{om} + CP_{ele} + CP_{ccl} - CR_{feed-in-tariff} \tag{8}$$

In these equations, C_{total} is system total annual cost. CP_{ele} , $CR_{self-consumption}$ and $CR_{feed-in-tariffe}$ are respectively, annual cost for purchasing electrical energy from grid, income from self-consumption and proceeds of selling electricity to grid. They are represented by following formulas [2]:

$$CP_{ele} = \sum_{h=1}^{8760} price_h \times P_{grid,h}^{import} \tag{9}$$

$$CR_{self-consumption} = \sum_{h=1}^{8760} rate_{self-consumption} \times P_{self-consumption,h} \tag{10}$$

$$CR_{feed-in-tariff} = \sum_{h=1}^{8760} rate_{feed-in-tariff} \times P_{grid,h}^{export} \tag{11}$$

Where, $price_h$ is electricity price at hour h , $rate_{self-consumption}$ is consumer incentive rate and $rate_{feed-in-tariff}$ is rate of selling electricity to the grid.

When imported power from grid violates the maximum level, consumer must pay a tax named CP_{ccl}. This cost is defined as follow [3]:

$$CP_{ccl} = \sum_{h=1}^{8760} rate_{CCL} \times \left(P_{grid,h}^{import} - P_{max}^{import} \right) \tag{12}$$

CP_{inv} is annual investment cost for PV system, battery and inverter:

$$CP_{inv} = CP_{inv}^{PV} + CP_{inv}^{storage} + CP_{inv}^{inverter} \tag{13}$$

Where:

$$CP_{inv}^{PV} = C_{PV} \times C_C\left(r, n_{PV}\right) \times \left(1 - Incrate_{PV}\right) \times P_{PV} \tag{14}$$

$$CP_{inv}^{storage} = C_C\left(r, n_{storage}\right) \times \left(C_P \times P_M + C_W \times E_{Bmax}\right) \times \left(1 - Incrate_{storage}\right) \tag{15}$$

$$CP_{inv}^{inverter} = C_{inverter} \times C_C\left(r, n_{inverter}\right) \times \left(1 - Incrate_{inverter}\right) \times R_{inverter} \tag{16}$$

In above equations P_{PV} is the nominal capacity of PV array and C_{PV} is its initial investment cost. r is interest rate, n_{PV}, $n_{storage}$ and $n_{inverter}$ are lifetime of PV array, battery and inverter [6],[8]. Also, *Incrate* is an incentive rate from government to encourage consumer to use renewable energy resources.

P_M and E_{Bmax} are respectively, the maximum usable capacity of battery (both in charging and discharging mode) and the maximum permissible energy of battery. C_P and C_W are their specific costs. $C_{inverter}$ is the initial investment cost of inverter and $R_{inverter}$ is its capacity. Also $C_C\ (r, n)$ is defined as capital recovery factor:

$$C_C\left(r, n\right) = \frac{r \times \left(1 + r\right)^n}{\left(1 + r\right)^n - 1} \tag{17}$$

B. Assumptions and Other Constraints

The first assumption considered in this paper is that CP_{ccl} will be counted only in night hours (7pm-12pm) during peak load condition. Also to keep the quality of grid power, energy can be injected to grid just between 6am-6pm.

In this system the balance between production and consumption per hour should be achieved [2]:

$$P_{PV,h} + P_{B,h} + P_{grid,h}^{import} = P_{load,h} \tag{18}$$

Where, $P_{PV,h}$ is the produced power of PV array and $P_{load,h}$ is equal to the required power for supplying the load. Also $P_{B,h}$ is the Battery power per hour and obtained from the following equations:

In charging mode:

$$E_{B,h+1} = E_{B,h} - \eta_c \times P_{B,h} \times \Delta t \tag{19}$$

In discharging mode:

$$E_{B,h+1} = E_{B,h} - P_{B,h} \times \Delta t \,/\, \eta_d \tag{20}$$

When the battery is in idle mode:

$$E_{B,h+1} = E_{B,h} - W_{hourly} \quad (21)$$

In these equations $E_{B,h}$ and $E_{B,h+1}$ are defined as energy of battery at the hour of h and h+1. η_c and η_d are respectively, battery efficiency in charging and discharging mode. It should be mentioned that Δt is considered equal to 1 hour in this study.

To improve battery operation and to increase the life time, following constraints are considered:

1) Constraints related to the energy of battery per hour [10], [11]:

$$E_{Bmin} \le E_{B,h} \le E_{Bmax} \quad (22)$$

Where E_{Bmin}, is the minimum battery electrical energy and E_{Bmax} is the maximum of this value. In this study E_{Bmin} and E_{Bmax} are considered as a percentage of battery nominal electrical energy (E_{Bnom}).

2) Constraints related to the power of battery per hour [12], [13]:

$$P_{Bmin} \le P_{B,h} \le P_{Bmax} \quad (23)$$

Where, P_{Bmin}<0 is maximum discharging rate and P_{Bmax} >0 is maximum charging rate for battery.
Also it is assumed that:

$$P_{Bmax} = -P_{Bmin} = (E_{Bmax} - E_{Bmin}) / T_c \quad (24)$$

Where, T_c is the minimum time necessary to charge (or discharge) battery from E_{Bmin} (or E_{Bmax}) to E_{Bmax} (or E_{Bmin}).

3. Optimization Problem Solutions

In this section a house with annual hourly load profile of figure 2 is used to find optimal sizing of PV and storage capacity. To analayze the effect of O&M cost on optimization problem, system parameters values have been choosed equal to them in [2]. The type and details of PV panel used in this study are shown in table I. Also the hourly generation profile of this panel is shown in figure 3 . It is assumed that only PV array capacity up to 4.8kw is allowed to be installed . Table II shows system economic data. In addition, details about inverter and battery are presented in tables III and IV.
Now for each exchange mode, optimal plan is obtained.

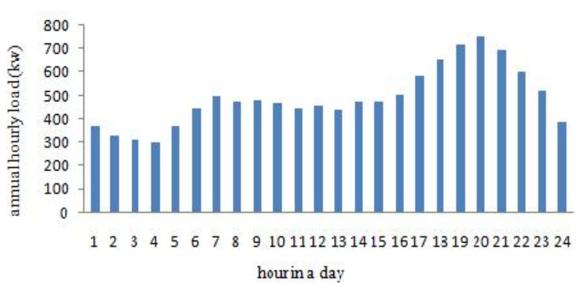

Fig. 2. Annual Hourly load Profile

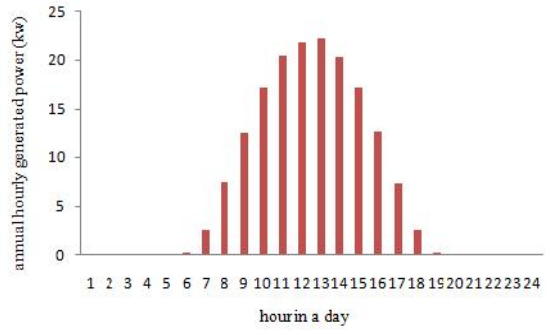

Fig. 3. Hourly Generation profile of PV Panel

Table I. PV Panel Parameters

maximum power (W)	100
Efficiency (%)	12
capital cost ($)	400
C_{om}^{PV} ($/Kw)	0.005
Life time	20 years

Table II. System Economical Data

Electricity price (1am-6am)($/kwh)	0.2
Electricity price (7am-5pm)($/kwh)	0.3
Electricity price(6pm-12pm) ($/kwh)	0.5
feed-in-tariff rate ($/kwh)	0.4
self-consumption rate ($/kwh)	0.23
CCL rate ($/kwh)	0.4
Installation incentive rate for PV, Battery and Inverter	0.4
Interest rate	0.06

Table III. Inverter Parameters

$C_{inverter}$ ($/kw)	500
Life time	10 years
$C_{om}^{inverter}$	0.015

Table IV. Battery Parameters

E_{Bmax}/E_{Bnom} (%)	100
E_{Bmin}/E_{Bnom} (%)	20
T_C (hour)	2
C_P ($/kw)	0
C_W($/kwh)	400
C_O($/kw)	0.02
C_M ($/kwh)	0.005
W_{hourly}	0
Life time (years)	3
Charge efficiency (%)	100
Discharge efficiency (%)	80
Initial state of charge (%)	20

A. Zero Power Export (Self- Consumption)

As it was said before, in this mode the house is not allowed to send any power to grid. Optimal plan for this mode is shown in table V in two ways, considering CP_{om} and without CP_{om}.

It can be concluded that O&M cost has decreased the optimal size of PV and battery. As a result, CP_{inv} and $CR_{feed\text{-}in\text{-}tariff}$ are decreased but CP_{elec} and total annual cost are increased.

Figure 4 shows different costs of the system. According to this figure, increasing the PV array capacity makes O&M cost increased.

As it was mentioned earlier, there is an incentive rate from government to diminish the investment cost for consumer. In this study it is equal to 0.4. If this rate is increased, annual cost will decrease rapidly so that for incentive rate equal to 0.5 this decline is significant [2]. But in figure 5 it is obvious that for incentive rates equal to 0.4 or 0.5 due to increasing annual cost, there is no tendency to use high capacity of PV array or battery and this is the result of adding O&M cost.

Table V. Optimal plan for self-consumption mode

Optimal plan	considering CPom	Without considering CPom
P_{PV} (kw)	1.5	2.5
E_{Bnom} (kwh)	2.1	5.5
CP_{inv} ($)	566	1054
CP_{elec} ($)	3423	3104
$CR_{feed\text{-}in\text{-}tariff}$ ($)	0	0
$CR_{self\text{-}consumption}$ ($)	565	793
CP_{CCL} ($)	0	0
CP_{om} ($)	296	0
C_{total} ($)	3720	3365

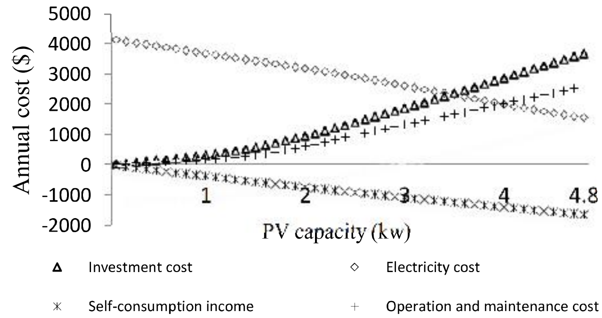

Fig. 4. Different costs of the System

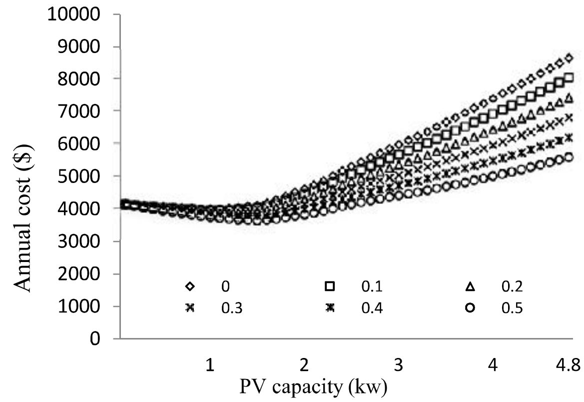

Fig. 5. Total Annual cost for different installation Incentive Rates

In previous section, self-consumption rate was introduced. It is clear that increasing this rate makes annual cost decreased. Without considering O&M cost, for rates 0.23 to 0.5, increasing PV capacity results in decreasing annual cost [2] but if O&M cost is added to objective function, this change would not be made (Fig. 6).

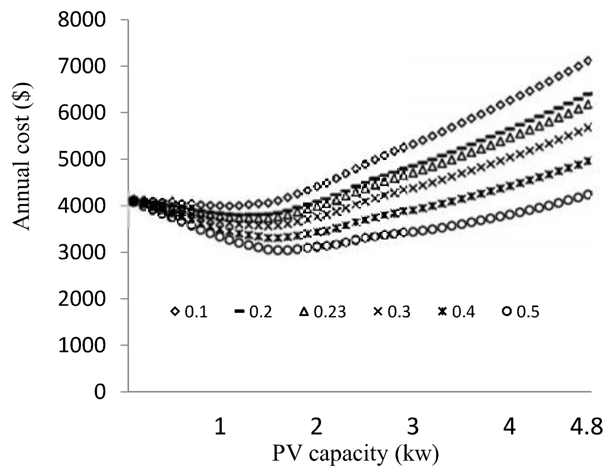

Fig. 6. Total annual Cost for different self-consumption Incentive Rates

B. Maximum Power Export

In this mode it is considered that consumer can only send 1.5kw per hour to grid. The results related to optimal plan are shown in table VI. Like previous case with considering CP_{om}, optimal capacity of PV array and battery are decreased.

If consumer can send more than 1.5 Kw per hour into grid, due to increase in income from selling energy to grid, annual cost will be decreased so that for the rates 1.5 Kw to 3kw, increase in usage PV capacity results in decreasing annual cost [2].But if O&M cost is considered the decline of annual cost is not significant (Fig.7).

Table VI. Optimal plan for Maximum Power Export Mode

Optimal plan	With considering CPom	Without considering CPom
P_{PV} (kw)	3	2.5
E_{Bnom} (kwh)	0.7	1.9
CP_{inv} (\$)	810	1017
CP_{elec} (\$)	3045	2968
$CR_{feed\text{-}in\text{-}tariff}$ (\$)	500	652
$CR_{self\text{-}consumption}$ (\$)	0	0
CP_{CCL} (\$)	0	0
CP_{om} (\$)	527	0
C_{total} (\$)	3882	3333

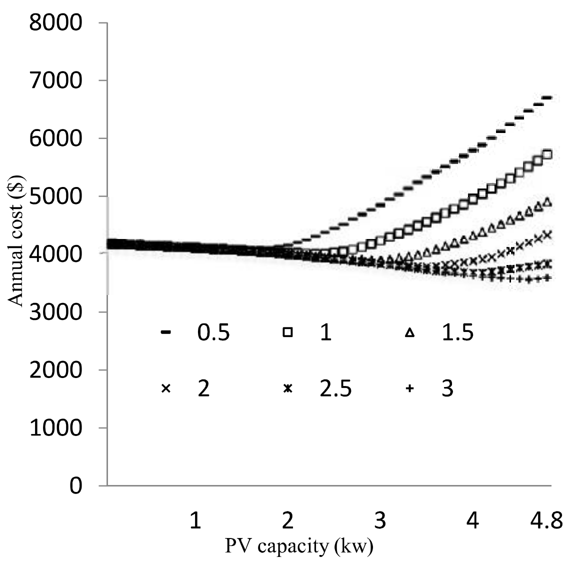

Fig. 7. Sensitivity of total annual cost to Maximum Power Export Limit

C. Maximum Power Import

The optimal plan for this case is presented in table VII. It is assumed that consumer can only receive power with maximum level 2kw per hour (between 7pm-12pm). When the maximum imported power is determined, battery capacity is obtained according to load profile. In other words, it is not dependent on generation profile.

As a result, the battery capacity has a fix value for each PV array size (Fig. 8) and as in this mode there is no limitation for selling energy to grid, it is obvious that the optimal plan is usage of all allowable capacity for PV array and thus, optimal plan is not affected by adding O&M cost.

Table VII. Optimal plan for maximum power import mode

Optimal plan	With considering CPom	Without considering CPom
P_{PV} (kw)	4.8	4.8
E_{Bnom} (kwh)	3.2	3.2
CP_{inv} (\$)	1500	1500
CP_{elec} (\$)	2697	2697
$CR_{feed\text{-}in\text{-}tariff}$ (\$)	1187	1187
$CR_{self\text{-}consumption}$ (\$)	0	0
CP_{CCL} (\$)	24	24
CP_{om} (\$)	916	0
C_{total} (\$)	3950	3034

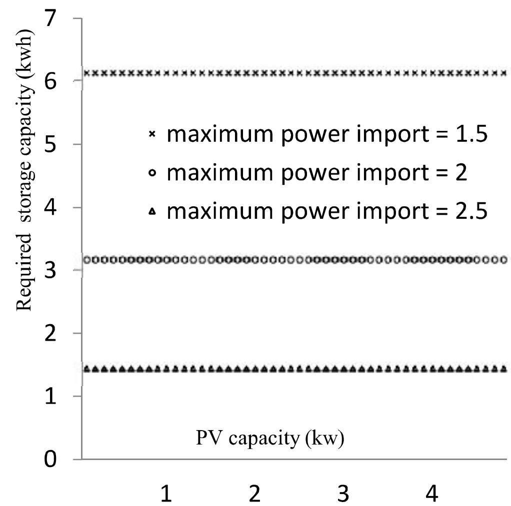

Fig. 8. Sensitivity of Required storage Capacity to Maximum Power Import Limit for Different PV Capacities

D. Maximum Power Import and Export

This mode is combination of two previous modes. Maximum power that can be sent into grid or received from is respectively, 1.5kw and 2kw per hour. Optimal plan is shown in table VIII. It can be seen that CP_{om} has not changed the optimal capacity for PV array and battery but total annual cost has been increased.

According to figure 9, the difference between annual cost values for PV capacities up to 4kw is low and the minimum cost is related to 3.6kw for PV array.

Table VIII. Optimal Plan for Maximum Power Import and Export Mode

Optimal plan	With considering CPom	Without considering CPom
P_{PV} (kw)	3.6	3.6
E_{Bnom} (kwh)	3.2	3.2
CP_{inv} ($)	1220	1220
CP_{elec} ($)	2776	2776
$CR_{feed\text{-}in\text{-}tariff}$ ($)	473	473
$CR_{self\text{-}consumption}$ ($)	0	0
CP_{CCL} ($)	18	18
CP_{om} ($)	726	0
C_{total} ($)	4267	3541

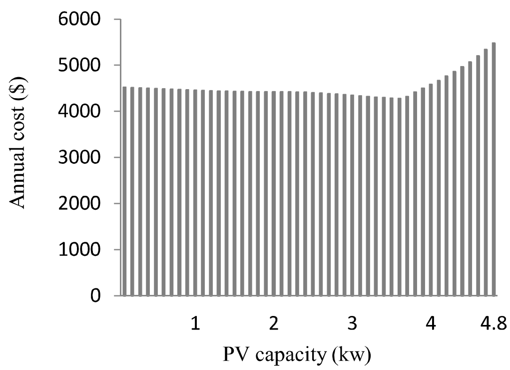

Fig. 9. Annual Cost Values for different PV Capacities

4. Conclusion

In this paper O&M cost effect on optimal sizing of PV and battery for a grid-connected house was analyzed. It was shown that adding O&M cost for PV array and battery into system objective function, makes it more accurate. In other words, taking this cost into account leads to a more realistic PV system. To do this, four different working modes in order to exchange electrical energy between house and grid were introduced and optimal sizing of PV and battery with and without considering O&M cost were calculated. It was seen that in all modes general tendency to use photovoltaic system would be decreased in case of including O&M cost in system so that particularly in two modes (self-consumption and maximum power export) optimal size of PV array and battery was decreased. Furthermore, as an important economic factor for PV system owner, in all modes total annual cost was exactly determined. As a result, to encourage electrical energy consumers to install PV systems, this cost must be reduced especially for batteries as much as possible.

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