Rooftop Solar Installations for Demand Side Management - A Case Study

Vijaykumar Pundlik Sonawane¹, Manoj S. Soni¹, Aniket Ajay Lad¹
¹Centre for Renewable Energy & Environment Development (CREED), Department of Mechanical Engineering, Birla Institute of Technology & Science, Pilani

vpsonawane@yahoo.co.in

Abstract. Renewable energy options, especially solar energy show a strong potential to replace conventional fossil fuel based electricity generation. Demand Side Management is a method of influencing the electricity consumers’ demand for electricity and thus reducing the load on distribution and generation companies. With the help of Demand Side Management tools, consumers are able to modify their demand in such a way that installation of new power plants could be avoided. This paper studies the load pattern in the industrial sector of Jalgaon, Maharashtra and their potential for rooftop solar installations. The impact of rooftop solar on the consumption schedule is studied considering the ‘Time of Day’ (TOD) tariff in place. Further, the importance of storage system is studied by comparing the daily savings for cases with and without storage availability. For the case when battery storage is available, a linear programming based optimization model is used to estimate the maximum possible savings from the installation. To run the optimization, simulation software used is MATLAB.

1. Introduction
Ever since shortcomings of employing conventional fuels for energy production have been realized, many have started to move towards renewable energy resources for their energy requirements. Humans have been using renewable energy forever, but use of these resources for major use of electricity generation has gained much importance. People have recognized the benefits of using renewable such as low cost, less pollution, easy access and ability to replace fossil fuels. There have been major advancements in developments for technologies to convert renewable energies such as solar energy, wind energy, hydropower etc. [1]. Apart from developing new technologies to convert renewables, attempts have been made to improve the utilization of the existing technologies. One such method applied to improve the utilization of these energy resources is Demand Side Management (DSM) [2]. DSM focuses on managing the demands of the end customers of electricity, to reduce the load on power plant responsible for producing electricity, with the help from electricity produced from the renewables and ability to store energy in battery systems [3, 4], Demand side management influences the electricity requirement at the demand side [5]. DSM focuses on techniques such as peak load shedding, and relocating the demand in peak load period to off-peak periods [6]. In cases where reduction in peak electricity demand is not possible, DSM utilizes the batteries storage capacity to charge the battery during off peak period and then utilize this energy in peak demand periods. One-way in which utility operator uses DSM to reduce the possibility of excessive consumption during peak demand is Direct Load Control, by means of which utility operators remotely shut some of the customer equipment in such cases customers are needed to manage their loads accordingly [7].
In many places where customer is dependent on the grid electricity, grid operators have implemented policies of Time of Use (TOU) or Time of Day (TOD) tariff [8]. In TOU tariff, customer is charged differently for power consumption during peak and off-peak hours. In peak hours, price of electricity is considerably higher than that during off-peak period, and the price differential is high enough to motivate the customer to shift consumption from peak to off-peak period. One of the main objectives behind such systems is electricity cost optimization of the customer. Although policies such as TOD tariff are new to Indian electricity distribution market, but some of the government organizations such as MAHADISCOM have realized the importance of such policies and started implementing them [9]. Apart from this, DSM has an important role in energy management with renewable energy resources [6-8, 10, 11]. Most of the renewable sources of electricity are intermittent, their availability is different throughout the day, and it does not always match with the customer demand. For example, most solar irradiation is available during the afternoon period, when the electricity demand in average household is lower; and in the evening and night when the actual demand is realized the production from solar sources is low. In such cases, DSM with help of energy storage solutions can be used to make the use of renewables more practicable [4, 12-14].

Applications of DSM for various purposes such as peak load shedding and direct load control have been studied extensively. Such studies include impact of renewable energy sources on such applications. Yao et al. [6] have studied the use of DSM to address the excessive voltage rise problem and have proposed an autonomous energy consumption algorithm for scheduling of operation of loads, which are deferrable to simultaneously shave the peak load and reduce the reverse power flow to the grid. Byrne et al. [7] discussed about the peak shaving capability of grid-connected, PV-battery hybrid system. Effect of grid feed-in reducing of a PV generation system with thermal or electricity storage (battery) is simulated as a function of system dimensioning with a focus on the induced PV power losses (due to this limit) and on cost balance. Et-Tolba et al. [12] provided information about algorithms and modelling in smart grids to maintain balance between the supply and the demand. These models are scalable and can be applicable for larger or smaller grids.

Residential demand regulation with the help of DSM tools with PV system has been studied extensively. Calpa et al. [15] study the PV-self consumption optimization with storage and active DSM for residential sector. The authors studied the effect of active DSM on the amount of consumed electrical system in case of a residential building. To incorporate the effects of demand that varies continuously, Christopher [16] studied the dynamic demand balancing using DSM techniques in grid connected hybrid system. This study focuses on proper switching techniques with electronic controllers for synchronizing the operation of various devices with ultimate goal of demand balancing. Various other approaches were also followed considering the variabilities and uncertainties in demand. Some studies based on genetic algorithm work on certain available set of data, which are continuously trained with the help of real time data available. One such example is of Canova et al. [17], who applied a genetic algorithm for optimal management of electrical demand side. The purpose of their study is to show all the steps involved in optimal power management of domestic user. Similarly, Hu et al. [18] provided a multi-objective genetic algorithm for demand side management of smart grid. A lot of research has its focus on cost optimization for grid connected PV-battery hybrid systems.

Many optimization models have been introduced with objective of cost minimization. Wu et al. [10] have studied DSM of photovoltaic-battery hybrid system to explore solar energy and to benefit customers at demand side. The authors have used a linear optimization model, which has been used in this project. An optimal power flow management for grid connected PV systems with batteries has been investigated by Riffonneau et al. [19]. The main objective of this study is to help intensive penetration of PV production into grid at the lowest cost. A similar study performed by Taleke et al. [20] on rule-based control of battery energy storage for dispatching intermittent renewable sources focuses on development of a control strategy for optimal use of battery energy storage system with PV. When considering cost optimization, optimum sizing is equally important. Considering installation costs and estimating payback period is objective of any economic problem. To address this, Weniger et al. [21] have studied sizing of residential PV battery systems. The study analyses residential PV battery systems in order to have more knowledge about their sizing along with economic assessment of PV battery systems.
In this study, some of the existing models of rooftop PV generation systems along with some new techniques such as Building Integrated Photovoltaics (BIPV) systems are studied. The different factors associated with application of such systems in stand-alone as well as grid connected modes are considered. Apart from various models for DSM implementation, system infrastructure including various controllers required for them and their working are studied. A linear optimization model is used to find a cost optimal solution for a standard industrial, commercial and household electricity consumer having installed rooftop/installation potential along with available storage system, based in Jalgaon district in Maharashtra, India. The hourly demand profile for electricity consumer is obtained based on the average consumption of all such customers in the concerned area.

2. Model Description
In this research work, a single household connected to grid with PV installation along with battery storage system is considered and the system infrastructure along with different power flows between various components of the system is presented in Figure 1.

A. Grid electricity tariff
For the purpose of this analysis, the tariff schedule was taken from MERC Order for Tariff determination FY 2013-14. The base tariff is varying for the mix of industrial connections involved in the analysis, but the Time of Day (TOD) tariff schedule is the same. Table 1 shows the tariff variation throughout the day. The base tariff of ₹ 7.5/kWh is considered here.

| TOD (In addition to above base tariffs) (in ₹/kWh) | 06:00-09:00 hours | 09:00-12:00 hours | 12:00-18:00 hours | 18:00-22:00 hours | 22:00-06:00 hours |
|---------------------------------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 06:00-09:00 hours                                 | 0.00              |                   |                   |                   |                   |
| 09:00-12:00 hours                                 |                   | 0.80              |                   |                   |                   |
| 12:00-18:00 hours                                 |                   |                   | 0.00              |                   |                   |
| 18:00-22:00 hours                                 |                   |                   |                   | 1.10              |                   |
| 22:00-06:00 hours                                 |                   |                   |                   |                   | -1.00            |

B. Hourly load profile
The analysis is being done for industrial buildings in Jalgaon. The data collected includes the connected load of several industrial establishments and their monthly consumption. Based on observations of their consumption behavior, the load for 16 hours period in a day (two shifts of 8 hours) is considered. Amongst these 16 hours, peak load has been observed during 11:00 am to 1:00 pm and 6:00 pm to 8:00 pm, which is about 20% more than the load during normal hours. The average consumption during every hour of the day is calculated from the monthly consumption and the observations regarding the consumption. The hourly demand profile at the customer for 24 hours is given in Table 2.
C. Battery and hybrid inverters

Based on a market research regarding various technologies of energy storage, the data for battery-based storage is acquired. The complete system includes components like battery for storage, inverter, and charge controller for storing PV energy into battery and charge converter to store grid electricity into battery. A hybrid PCU (inverter) is an electrical device encompassing inverter and charge converters in a single component. The battery system specifications are reported in Table 3.

| Time                  | Consumption (kWh) |
|-----------------------|-------------------|
| 12:00 am to 08:00 am  | 0                 |
| 08:00 am to 11:00 am  |                   |
| 01:00 pm to 04:00 pm  | 27.53             |
| 06:00 pm to 12:00 am  |                   |
| 11:00 am to 01:00 pm  |                   |
| 04:00 pm to 06:00 pm  | 33.04             |

Table 3: Details of battery storage system.

| Component                          | Efficiency |
|------------------------------------|------------|
| Battery charging efficiency        | 85%        |
| Battery discharging efficiency     | 100%       |
| Hybrid inverter efficiency         | 95%        |
| Grid to Battery charge converter efficiency | 95%       |

D. Photovoltaic generation estimation

There are several methods proposed for estimation of output of solar panels based on daily normal irradiation, which is obtained from NREL site (source: https://maps.nrel.gov/nsrdb-viewer/). The area for rooftop installation is derived from the connected load. The PV installed capacity is assumed to be 1.5 times of the connected load. The rooftop area required for 1 kW of solar installation is approximately 1 square meter for panel efficiency of 15% based on the specifications of commercially available panels.

3. Mathematical Modelling

For the analysis, as all the constraints and objective function come in the form of simple linear equations, a linear optimization model is proposed here. The objective function and constraints of the studied model are explained in detail below.

Objective function

The objective of the optimization is to obtain the minimum cost, which will be incurred at the consumer end. Total cost incurred by electricity customer includes the cost of electricity purchased from the grid and wearing costs of PV-battery system. While calculating the cost, revenue earned by selling electricity to the grid is also needed to consider. Thus, the objective function takes the form as given by the following equation.

\[ \text{Objective function (Z)} = \sum_{t=0}^{23} C(t) \times (P_1(t) + P_5(t)) \]  \hspace{1cm} (1)

Load balance constraint

The equality constraint gives a relationship between all the power flows, which are responsible for supplying the demand faced by the customer. These power flows include power coming from PV system, battery and the grid.

\[ P_1(t) + \eta P_2(t) + P_3(t) = P_{load}(t) \]  \hspace{1cm} (2)

PV output constraint

The power generation from the PV system is fed to the household to meet the load requirement during daytime. Excess generation is stored into the battery.

\[ P_2(t) + P_5(t) = P_{PV}(t) \]  \hspace{1cm} (3)
Battery state of charge constraint

The battery’s state of charge is restricted between upper and lower bounds in order to have safe and prolonged operation of the battery. Draining the battery below certain limit hampers its life.

\[
SOC_n = SOC_{initial} + \sum_{i=1}^{n} \{\eta_c(P_{Pi} + \eta_{bc}P_{Si}) - \frac{1}{\eta_d}(P_{Si})\}
\]  
(4)

\[
SOC_{min} \leq SOC_n \leq SOC_{max}
\]  
(5)

Bounds on power flow

For the safe operation of all the components and to avoid power surges at each moment, every power flow has to take a value between \(0\) to \(P_i^{max}\). In this report value of \(P_i^{max}\) is predefined at 5 kW.

\[0 \leq P_i(t) \leq P_i^{max}, \quad (i = 1,2,...,5)\]  
(6)

These set of equations and previously defined values for various system component specifications give us the system structure and solved with the help of linear optimization solver on MATLAB software.

4. Results and Discussion

A linear programming problem has been set, as discussed in the previous section, for a grid-connected household, having a PV generation system and battery storage. Two cases are considered for better understanding the advantages of proposed system. In first case, PV grid-connected installation without storage option is explored. In this case, during the non-sunshine hours, the load required is satisfied from grid electricity. During the sunshine hours, some portion of the load is provided by the power generated from the PV panels. The result of the case is presented in Figure 2. The generation from the PV panels starts at around 7:00 am in the morning and ends at around 6:00 pm in the evening with peak generation at noon. Because of installation of the PV panels, average monthly savings in the electricity bill is ₹ 1359.7. If the generation from PV panels exceeds the demand for some period, the excess PV power remains unutilized.

![Figure 2](image_url)

Figure 2. Power consumption profile without battery storage.

It evident from the analysis results (Figure 2) that the utilization of PV generation per day is 172.307 units compared to total generation of 179,901 units, i.e. almost 95.78% utilization. This is mainly due to the fact that the load in the concerned industrial building is concentrated in the PV generation duration on contrary to any household consumption, where the load is concentrated in the morning and the evening with lower consumption during the daytime. Thus, a high utilization of the PV panels is achieved even without having a storage system in place.
For second case, the storage system is considered and to optimize the output of the system, the previously discussed optimization model is used. On solving the linear optimization problem, which is given in the previous section, we are able to obtain a result, which gives total reduced cost incurred by the electricity customer. The monthly savings in this case was ₹ 1587.8, which is 16.77% higher. The PV utilization in this case is of 179.901 units, which implies 100% utilization of PV power generated. These observations are caused by two main factors, availability of storage system and Time of Day tariff being in place. Electrical energy from the PV panels gets stored into the battery at the times when the PV generation exceeds the load and the energy is stored into the battery when the cost of purchasing electricity from the grid is low and is utilized when the grid electricity cost is high. This reasoning is supported by the results of various power flows shown in Figure 3.

![Figure 3. Power consumption profile with battery storage.](image)

**5. Conclusion and Future Prospects**

The major outcomes of the present research work are as follows:

- Customer is able to enjoy profits on implementation of Grid connected load with PV-Battery hybrid system.
- Profits are higher when policies such as feed-in tariff and Time of Day (TOD) tariff are available.
- Utilization of solar energy through PV generation system is higher when such hybrid system is available compared to stand alone systems without battery storage.

Future work related to this topic on following aspects is to be done

- Analysis based on actual data for an average Indian scenario is needed to be done.
- Some modifications will be required in the existing model to incorporate the inverter and some other factors. Also changes are needed on the basis of nature of the data available.
- Capital cost associated with investment in PV-Battery hybrid system is to be considered. Based on this, payback period for system installation is to be evaluated.
- The benefits associated with the relief on the demand from the grid side to distribution companies and savings on elimination of need for an additional power plant or some reduced generation capacity of newly proposed power plants are needed to be considered.
- Reduced carbon footprint of the newly introduced conventional power plants is an important aspect. Incentives for reduced carbon footprint are also an important part in future work.
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