Chapter 4

HARNESSING SOLAR ENERGY

This chapter discusses Solar Energy's background, harnessing its potentials, and discusses challenges, cash flow, and limitations.

Solar Energy Background

4.1 Harnessing Solar Energy

Sun energy is energy generated by using glowing light and or high temperature from the solar using various knowhows. Solar energy has enormous potential. It is estimated the ground receives 174 peta watts (PW - 10^{15} watts) of incoming solar heat (insolation) at the higher environment, and 70% of that reaching the earth's side. The range of solar light at the ground's surface is mostly scattered across the obvious and near-infrared ranges with a small part in the near-infrared. The amount of sunlight absorbed by earth (oceans and landmasses) is estimated to be 3,850,000 exajoules (EJ) or 1.06944 x 10^{18} kWh annually. Harnessing solar energy will enhance Nation's energy security through reliance on an infinite and import-unbiased resource (Behi et al., 2020).

4.2 Benefits of Solar Power Generation

Here are some benefits of solar energy.

Global Benefits:

- Solar energy is viable and renewable. Unlike fossil fuels, renewable energy is always available
- Solar energy is almost pervasive throughout the earth – land, lakes, air, and ocean.

- Solar energy production is a silent and pollution-free with almost zero emissions method of generating energy. It can play a vital role in de-carburizing the global economy.
- Supports national power independence by reducing the need used for fossil fuels and keeping their prices under check.
- Unlike captive generation plants, solar generation can be in units of smaller sizes to bigger sizes. Can generate locally. Generation can be closer to the point of consumption, reducing the load on "grid" infrastructure.
- Can support DC micro-grids to create more efficient power systems and more compatible with electronic loads that are popular. Even remote villages can realize energy sustainability using solar.

Financial Benefits

- Solar energy can provide a lasting hedge against rising retail energy costs. Considering a typical life cycle of 25-30 years of a solar plant, it can be financially attractive provided shortcomings are managed better.
- No raw material costs: The creation of solar energy involves solar radiation, which is free input. No many moving parts and require very little maintenance. Hence operating costs are very low.
- Solar energy enables predictable pricing equal to or below retail energy rates (Iwafune et al., 2015).
- Solar energy can mitigate higher power costs due to peak hour pricing during day.
- Return on Investment is tricky, but it can be good if the right technologies are chosen.

4.2.1 *Trials / Challenges of conventional Solar Power Generation*

A large percentage of the Solar Power generation market in India uses fixed-tilt PV technologies and is facing tough challenges. Typical solar power generation using PV technologies suffers from;

- Lesser return on investment (RoI)
- Not able to compete with other energy generation technologies on true cost competitiveness
- Exceptionally long gestation periods despite government incentives

Several factors contribute to this scenario.

Challenges due to traditional PV Solar Technologies

- PV Solar cell efficiencies are poor, and they are in the range of 12%-15%.
- Over a day from dawn-to-dusk, energy generation characteristics resemble a “Bell Curve” resulting in reduced energy generation.
- Significantly high degradation due to temperature characteristics
- Due to aging, amazingly larger components of annual degradation

Even though trackers have helped, the net improvement is not sufficient. The generation proposition is still not attractive enough for many investors to get into solar power generation until and unless backed by Government subsidy/incentives.

Challenges due to Land Scarcity

The land is a scarce resource. In India, the Per capita land availability is significantly low. Even if available, securing them up for 25-30 years is also becoming a bigger concern.

Challenges due to EPC practices

- Generally, many solar generation plants suffer from the lack of applying best engineering principles in the engineering, procurement, and commission phases of the plant leading to high T&D losses, which would further bring down the net energy delivered. Optimal yield generation techniques are generally missing in many solar plants.
- Many Solar generation projects do not have “online monitoring” and “analysis”. Even in cases where “online monitoring” is deployed, it is limited to “overall measurement”. Detailed monitoring and analysis related to individual panels is missing.
- Failure of some electronic components or operating point drifts or site issues that might arise are not detected for a longer time, leading to further erosion in generation.
- EPC industry suffers from the non-availability of talented engineers with the right tools specializing and approaching all phases of EPC in a more scientific and engineering way.
- Many vendors in the balance of systems (BoS) sector suffer from the lack of collaborative working of BoS vendors with EPC and Solar panel manufacturers generally missing.
- Auditing and yield optimization programs are not good enough.

4.3 Technology Background

Concentrated Photovoltaic (CPV)

Multi-junction High Concentrated Photovoltaic solar panels are made up of multi-junction GaInP/GaInAs/Ge stack with refractive light concentrations of higher magnitude.

Multi-junction solar cells are solar cells with multiple p-n junctions manufacture of different semiconductor materials. Each material's p-n junction will deliver an electric current in response to a different wavelength of light. Using numerous semiconducting materials regularly absorb a high variety of wavelengths, thereby improving the cell's solar light to electrical energy transformation efficiency.

Cells produced from numerous materials have several band gaps. So, it will respond to multiple light wavelengths, and some of the energy that would otherwise be lost to relaxation as described above can be caught and transformed.

4.3.1 *Economics of solar system*

Finances of solar system relied on cost and benefit analysis of solar system. The expenses of solar energy system are- (Project & Report, n.d.)

- Capital cost- Solar energy utilizing will involve high investment cost because a large area needs to be used for PV installation
- Cost of operation is at a low level
- Refurbish, and maintenance will also be low
- Property tax will increase annually, so solar energy sources have rigorous cost

The advantages of solar energy system are:

If solar energy substitutes straw, then it is not profitable. Generally, solar energy installation is set to live an extended life span (about 40 years). These advantages are called substantial benefits; this means the benefits which can be converted into financial worth. At the same time, insubstantial benefits are reduced environmental emission, employment creation etc.

4.3.2 *Cash Flow diagram*

An illustrative representation of the cash flow of a project is used for economic analysis of the system. This description includes both cost and benefits, as shown in the *cash flow diagram* below.

Figure 4.1 Cash flow diagram for benefit – cost analysis

Money has minute value i.e. Value of money for the user fluctuates with time, value at t=T is less than value at t= T +ΔT because the same money can be spent over the time period of ΔT. Hence advantages or costs cannot be algebraically added over the total period in the cash flow diagram instead, bring benefits and costs in a standard time frame, then add all benefits together and add all costs together, then subtract total benefits with total costs.

Calculating Time value of money

With time, the value of money changes, if one invest 'X' at t = 0, then at an annual return of 'r', he will get back X (1 + r) after one year

X X {1 + r}

(At t=0) (At t=1)

Also buying power of money changes with time. So, if the yearly inflation rate be 'I', then after one year it will become (1 + I). To adapt these two factors in the cash flow diagram, we define the term 'discount rate' to express the time value of money from one reference frame to another reference frame.

If one invests 'X' at t = 0, then at a discount rate of 'd', it will become X (1 + d) after one year

So, $X(1 + d) = \frac{X(1+r)}{(1+I)}$

$$d = \frac{r-I}{1+I}$$

‘d’ value proves that value of money is the same at t=0 & t=1, taking into account the rate of price increases. Rupees 100 today in bank returned at a discounted rate of 10% would give 110, where both 100 & 110 hold values what 100 holds today.

Inflation rate ‘I’ varies from country to country and from time to time.

4.3.3 *Equivalence formula involving time value of money:*

A single cash flow at present (t=0) to

Corresponding ‘single’ cash flow at t=T in future

A ‘single’ cash flow expected in future at t=T to

An equivalent present (t=0) value of projected cash flow in future

A series of cash flows at regular periodic intervals of time between present t=0 and t=T in future to

A corresponding single value in future at t=T

A single cash flow expected in future at t=T to

An equivalent series of uniform cash flows from present (t=0) to time (t=T) in future

Equivalent value of ‘P’ at the end of 1st year = P (1+d)

Equivalent value of ‘P’ at the end of 2nd year = P (1+d) + P (1+d) d

= P (1+d) 2

Equivalent value of ‘P’ at the end of the year = P (1+d) T

Single cash flow compound amount factor, $\frac{F}{P} = (1+d)^T$

Single cash flow presents worth factor, $\frac{P}{F} = (1+d)^{-T}$

4.3.4 *Constraints of solar photovoltaic energy conversion*

- Elevated initial cost
- Abnormal supply of solar energy

- Require battery storage for the supply of power at night
- Minimal efficiency
- Require larger area
- Do not produce power during cloudy season

4.4 Types of Solar Technology

Photovoltaic (PV) Cell Technology:(Haffaf et al., 2020)

1. Crystalline Silicon type of solar energy
   - Mono-Crystalline
   - Poly Crystalline
2. Thin Film type of solar energy
   - Amorphous Silicon
   - CdTe
   - CIGS/CIS
3. Concentrated Solar PV

Basis of Function: Solar Radiation > Power Generation (Direct

Concentrated Solar Power (CSP) Technology:

1. Solar Trough
2. Parabolic Dish
3. Solar Power Tower
4. Solar Chimney

Basis of Function: Solar Radiation >Thermal Energy > Power Generation

Crystalline Silicon Technology;

1. Monocrystalline Silicon:

- Made from Single Crystal of Si (most purified Si), Three-axis deposition to form Si Ingots
- Most Expensive PV
- Most Efficient PV Cell: Research Eff. = 28 % Commercial Eff. = 16.5 %

2. Polycrystalline Silicon:

- Made from Multi Crystals of

  Si (less purified Si), Single-axis deposition to form Si Ingots
- Less Expensive PV
- Less efficient than Mono: Research Eff. = 24 % Commercial Eff. = 15.5 %

Thin-Film Technology

- Second Generation of Photovoltaic Cells

  Non-Crystalline Silicon (Amorphous Si) & various materials i.e. CdTe (Cadmium Telluride) / CIS (Copper Indium Selenide) / CIGS (Copper Indium Gallium Diselenide) are used
- Thin-film of the base material is deposited in vapor form over the glass substrate to form a cell
- Cheaper technologies with lower efficiencies & life than Crystalline Si PV
- Thickness ≈ 5 microns
- Research Efficiency: 19 %
- Commercial Efficiency: 6-9 %

4.4.1 *Pros and Cons of the Technologies* (Haffaf et al., 2020)

Table 4.1 Pros (advantages) and Cons (disadvantages) of the Technology

Technology	Pros	Cons
Crystalline Si – Mono	− High Efficiency − More Life	− Higher Module Cost
Crystalline Si – Poly	− Well developed & reliable − More Life	− High Module Level Cost
Thin Film - Amorphous Si	− Ease of Production & scalable − Road map to extend potency to 9-10% − Low Module cost	− Less Plant Life − Low Efficiency − Insufficient field reliability data − More Land Requirement
Thin Film – CdTe	− Low Cost & Scalable	− Raw material availability (Cd)
CPV	− High Efficiency, Less Area Required, most reliable, both active and reactive power are supplied.	− High variability
CSP - Solar Trough	− Mature & approved technology − Cost effective for large size application − Hybrid (solar/fossil) operation	− High Cooling Water Requirement − Aggressive & Expensive Storage material (Molten Salt)
CSP - Parabolic Dish	− High Efficiency − No Thermal Storage	− Still in Development Phase
CSP - Power Tower	− Dispatchable electricity − high conversion efficiencies − Hybrid (solar/fossil) operation	− High Cooling Water Requirement − Aggressive & Expensive Storage material (Molten Salt) − Higher Cost

4.5 Connection of Roof Top Solar System in Tata Power Delhi Distribution Limited, Delhi

We undertake this project. Planning and execution of a unified program on development and deployment of solar energy knowhows to achieve commercialization. We own, operate, and manage any type of power stations (both grid & off-grid). We promote research and development on various rooftop solar projects. We assist the Ministry of New and Renewable Energy in executing the Mission objectives through appropriate mechanisms.

The scope of this project is considering consumers in TPDDL's licensed area only. The minimum installed capacity is considered as 1 kWp. Because of cost-effectiveness and consumption pattern, only a "Without Battery" configuration is considered.

Approach

Figure 4.2 Stages of the project approach

Technical Parameters

Principle: Solar cell works on Photovoltaic principle, i.e., converting sunlight directly into electricity (Haffaf et al., 2020).

Electrical parameters and configuration: A module generally consists of 60 to 72 cells, connected in series to give approximately 8 A at 30-36 V**.**

Table 4.2 Technical Parameters

S/N	Parameter	Values
1	Solar Cell O/P	0.5V; 7-8 A
2	Rated Wattage	240-260 Wp
3	Efficiency	13-16%
4	Size	L-1.6 to 2 m; B-0.8 to 1 m; H- 0.03 m;
5	Area	2 sq m / 25 sq ft
6	Avg. Annual Generation (For 1 kWp)	1200-1500 Units
7	Tentative Cost (For 1 kWp)	W/o Battery: INR 1 Lakh With Battery: INR 2 Lakhs

Requirement for Plant design:

- Space needed for the 1 kW Solar PV system will range from 110 - 130 Square feet.
- Anticipated Annual generation of power will range from 1550 - 1650 units / KW installed capacity.
- Roof owner will get incentives of 2/kWh(unit) generated from the Solar Power System installed on his roof.
- Shadow free plain roof preferred

Optimal Size for 1 kWp System

Table 4.3 Size for 1 kWp System

S/N	Item	Description	Values
1	Solar Module	250 Wp Crystalline modules	4
2	1 phase Inverter	1 kVA, 1 PCU	1
3	Metering Arrangement	1 Net Meter, 1 Solar Energy Meter	1each
4	MM Structure	Fixed at 16 Degrees	As Per Site requirement
5	AJB/DCDB/ACDB	Array Junction Boxes	As Per Site requirement
6	Battery Bank	For off Grid Application	As Per Site requirement
7	Cables	PVC Copper Cables	As Per Site requirement
8	Lightening Arrestor & Earthing	Lightening Protection Units	As Per Site requirement
9	Miscellaneous	Accessories	As Per Site requirement

Rooftop Pictures.

Figure 4.3 Rooftop Solar Pictures

Illustration of the Revenue Generation by Rooftop Owner bearing in mind the shadow free roof:

Table 4.4 Illustration of Revenue Generation

Sr No.	Installed PV Capacity (kW)	Roof Size (Sq. Ft)	Expected Generation (Units/Year)	Expected Revenue for house owner (INR/Year)
1	5	650	7750	11500
2	10	1300	15500	31000
3	15	2000	23520	47040
4	25	3250	38750	77500
5	40	5200	62000	124000
6	50	6500	77500	155000
7	75	9750	116250	2325000
8	100	13000	155000	310000
9	150	19500	232500	465000
10	200	26000	310000	620000

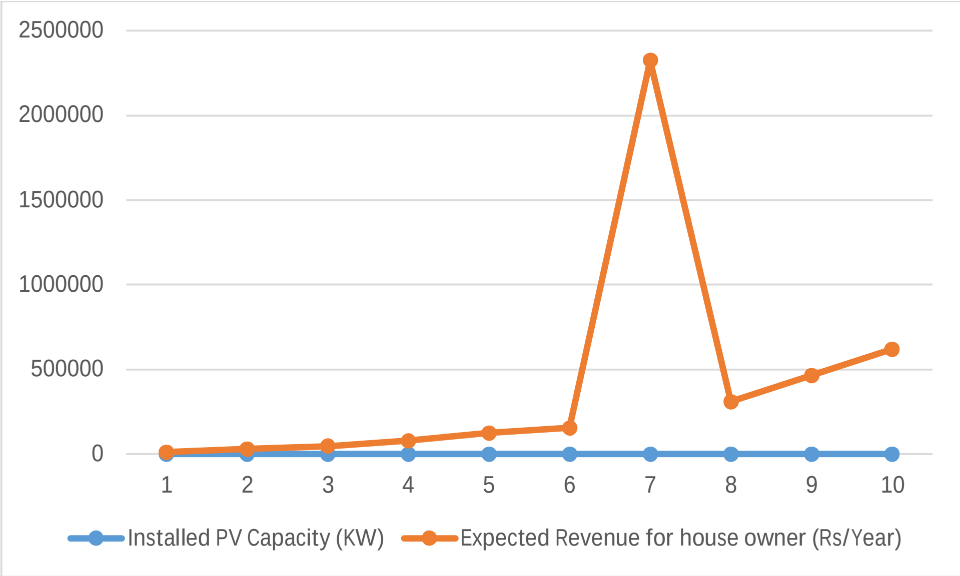

Figure 4.4 Illustration of Revenue Generation

4.5.1 *Benefits for Roof Top Owners* (S. Chopade et al., 2018)

- The roof top owner will have access to continuous revenue through a green motivation of INR 2/unit energy generated from the system installed on the roof.
- There is no capital investment & recurring cost for rooftop owner.
- Rooftop solar power system increase building thermal insulation, thus decreasing building temperature by about 5 degrees during day time.
- Above cooling effect results in the saving of electricity consumption by the cooling system of the building, thus providing an indirect saving of 3-5 % on electricity bills
- Increase in reputation and value of property by tagging it as a green building.
- Optimization of Rooftop area to deliver maximum value to house Rooftop Owner.
- Contribution to the environment by decreasing CO_2 Emissions at a rate of 1.5 tonne/kWh/Year.

4.6 Rooftop Solar Installations for Demand Side Management

Renewable energy options, especially solar energy, indicate a considerable potential to replace the generation of conventional fossil fuel-based electricity. Demand Side Management is a way of influencing electricity consumers' demand for electricity and reducing the load on distribution and generation companies. With Demand Side Management tools' help, consumers can modify their demand so that the installation of new power plants could be avoided. This paper studies the load pattern within the Jalgaon geographic area's industrial sector and their potential for upper side rooftop solar installations. The impact of rooftop solar on the consumption schedule is studied considering the TOD tariff in place.

Further, a storage system's importance is studied by comparing the daily savings for cases with and without storage availability. Once battery storage is in the market, a linear programming primarily based on improvement via the optimization model is employed to estimate the maximum possible savings from the installation. To achieve optimization, the simulation package used is MATLAB (Hussain et al., 2018).

Ever since employing conventional fuels for energy production has been realized, many have started to move towards renewable energy resources for their energy requirements. Humans have been using renewable energy forever, but using these resources for the major use of electricity generation has gained much importance. People have recognized the benefits of using renewables, such as low cost, less pollution, easy access, and the ability to replace fossil fuels. There have been significant advancements in technologies to convert renewable energies such as solar energy, wind energy, hydropower etc. Apart from developing new technologies to convert renewables, attempts have been made to improve the existing technologies' utilization. One such method applied to enhance the utilization of these energy resources is DSM (Martins, 1996)(Chauhan & Saini, 2016).

DSM focuses on managing the demands of the end customers of electricity to reduce the load on the power plant responsible for producing electricity, with the help of electricity produced from renewables and storing energy in battery systems. DSM influences the electricity requirement at the demand side. DSM focuses on techniques such as peak load shedding and relocating the demand in peak load period to off- peak periods(Project & Report, n.d.). In cases where the reduction in peak electricity demand is not possible, DSM utilizes the battery storage capacity to charge the battery during peak period and then use this energy in peak demand periods (Bakhshi Yamchi et al., 2019). 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 (Reddy, 1995).

In many places where the customer depends on the grid electricity, grid operators have implemented ToU or ToD tariff (Khalid et al., 2019). In ToU tariff, the customer is charged differently for power consumption during peak and off-peak hours. In peak hours, the price of electricity is considerably higher than that during the off-peak period. The price differential is high enough to motivate the customer to shift consumption from peak to off-peak period (Chauhan & Saini, 2016). One of the main objectives behind such systems is the electricity cost optimization of the customer. Although policies such as ToD tariff are new to the Indian electricity distribution market, some government organizations such as MAHADISCOM have realized the importance of such policies and started implementing them (Reddy, 1996). Apart from this, DSM has a vital role in energy management with renewable energy resources. Most of the renewable sources of electricity are intermittent, their availability is different throughout the day, and it does not always match with customer demand. For example, most solar irradiation is available during the afternoon period, when the electricity demand in the 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 (Bakhshi Yamchi et al., 2019).

Applications of DSM for various purposes such as peak load shedding and direct load control have been studied extensively. Such studies include the impact of renewable energy sources on such applications. Yao et al. have investigated the use of DSM to address the excessive voltage rise problem. They have proposed an autonomous energy consumption algorithm for scheduling of operation of loads, which are deferrable to simultaneously trim the peak load and reduce the reverse power flow to the grid. Byrne et al. discussed the peak shaving capability of grid-connected, PV-battery hybrid systems. The 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, focusing on the induced PV power losses due to these limitations. Et-Tolba et al. provided information about algorithms and modeling in smart grids to balance the supply and demand (Project & Report, n.d.). These models are scalable and can be applicable for larger or smaller grids.

Residential demand regulation with the help of DSM tools with PV systems has been studied extensively. Calpa et al. studied the PV-self utilization optimization with storage and active DSM for the housing sector(Project & Report, n.d.). The authors studied the effect of active DSM on the amount of consumed electrical system in case of a residential building (Project & Report, n.d.). To incorporate the impact of demand that varies continuously, Christopher studied the active demand balancing using DSM techniques in grid-connected fusion system(Yazid et al., 2014). This study focuses on proper switching techniques with electronic controllers to synchronize the operation of various devices with the goal of demand balancing. Various other approaches were also followed, considering the variability and uncertainties in demand. Some studies based on genetic algorithms work on the specific available data set, which are continuously trained with real-time data available. One such example is Canova et al, who applied a genetic algorithm for optimal electrical demand side(Project & Report, n.d.). Their study aims to show all the steps involved in optimal power management of domestic users. Similarly, Hu et al. provided a multi-objective genetic algorithm for DSM of smart grid (Project & Report, n.d.). A lot of research has focus on cost optimization for network-connected PV-battery hybrid systems. Many optimization models have been introduced with the objective of cost minimization. Wu et al. have studied DSM of the photovoltaic-battery hybrid system to explore solar energy and to benefit customers at the demand side. The authors have used a linear optimization model, which has been used in this project.

An optimal power flow management for network-connected PV systems with batteries has been investigated by Riffonneau (Project & Report, n.d.) et al. The main objective of this study is to help intensive penetration of PV production into the grid at the lowest cost. A similar research performed by Taleke et al. on rule-based control of battery energy storage for dispatching intermittent renewable sources focuses on developing a control strategy for optimal use of battery energy storage systems with PV(Project & Report, n.d.). 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 have studied sizing of residential PV battery systems (Project & Report, n.d.). 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 Photovoltaic (BIPV) systems are studied. The different factors associated with application of such systems in stand-alone as wells 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.

4.6.1 *Model Description*

In this research work, a single household connected to the grid with PV installation and battery storage system is considered. The system infrastructure and different power flow between various components of the system are presented in Figure 4.5.

Grid electricity tariff

To this analysis, the tariff schedule was taken from the Maharashtra Electricity Regulatory Commission Order for Tariff determination FY 2013-14. The base tariff varies for the mix of industrial connections involved in the analysis, but the TOD tariff schedule is the same. Table 4.5 shows the tariff variation throughout the day. The base tariff of ₹ 7.5/kWh is considered here.

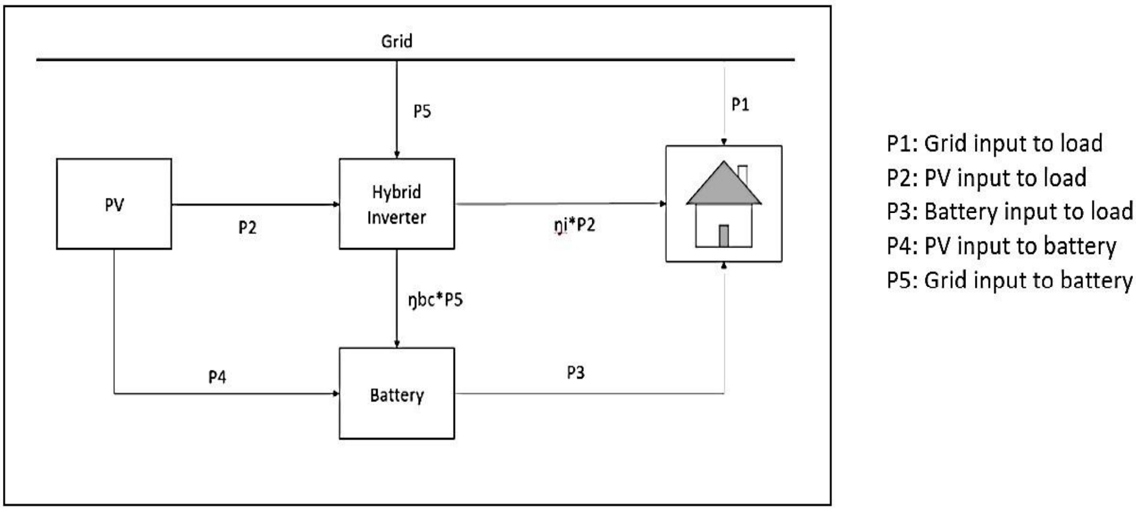

Figure 4.5 System infrastructure.

Table 4.5 Electricity tariff (time of day) schedule.

ToD	In addition to above base tariffs (in INR /kWh)
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

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 in a day (two shifts of 8 hours) is considered. Amongst these 16 hours, peak load has been observed from 11:00 am to 1:00 pm and 6:00 pm to 8:00 pm, which is about 20% more than the load during regular hours. The average consumption during every hour of the day is calculated from the monthly consumption and the consumption observations. The hourly demand profile of the customer for 24 hours is given in Table 4.6.

Battery and hybrid inverters

Based on market research regarding various energy storage technologies, the data for battery-based storage is acquired. The complete system includes battery 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 4.7

Table 4.6: Daily Average Consumption Profile

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

Table 4.7.: Details of battery storage system.

Inverter Battery charging efficiency	85%
Inverter Battery discharging efficiency	100%
Hybrid inverter efficiency	95%
Grid to Battery charge converter efficiency	95%

Photovoltaic generation estimation

Several methods are proposed for estimation of the 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.

Mathematical Modelling

For the analysis, as all the constraints and objective functions 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 optimization's objective is to obtain the minimum cost, which will be incurred at the consumer end. The total cost incurred by electricity customer includes the cost of electricity purchased from the grid and wearing prices 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.

$$Objective\ function\ (Z) = \sum_{t=0}^{23} C(t) \times (P_1(t) + P_5(t)) \quad (1)$$

Load balance constraints

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

$$P1(t) + \eta IP2(t) + P3(t) = Pload(t) \quad (2)$$

PV output constraint

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

$$P2(t) + P5(t) = PPV(t) \quad (3)$$

Battery state of charge constraint

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

$$SOC_n = SOC_{initial} + \sum_{i=1}^{n} \{\eta_c(P_{4i} + \eta_{bc}P_{5i}) - \frac{1}{\eta_d}(P_{3i})\} \quad (4)$$

$$SOC_{min} \leq SOC_n \leq SOC_{max} \quad (5)$$

Bounds on power flow

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

$$0 \leq P_i(t) \leq P_i^{max}, \qquad (i = 1,2, \dots ,5) \tag{6}$$

These sets 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.

4.6.2 ***Results and Discussion***

As discussed in the previous section, a linear programming problem has been set for a grid-connected household having a PV generation system and battery storage. Two cases are considered for a better understanding of the advantages of the proposed system. In the first case, the PV grid-connected installation without a storage option is explored. In this case, during the non-sunshine hours, the load required is satisfied with 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 4.7. The generation from the PV panels starts at around 7:00 am in the morning and closes at around 6:00 pm in the evening, with peak generation at noon. Because of the PV panels' installation, the average monthly savings in the electricity bill is INR 1359.7. If the generation from PV panels exceeds the demand for some period, the excess PV power remains unutilized.

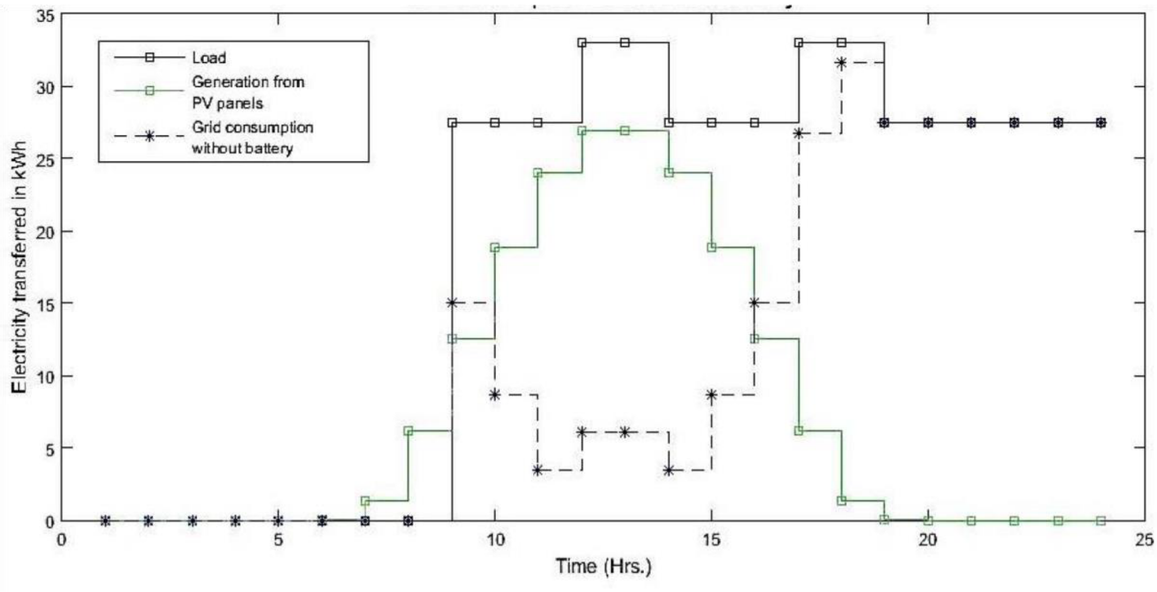

Figure 4.6 Power consumption profile without battery storage

The analysis results (Figure 4.6) show that the utilization of PV generation per day is 172.307 units compared to the total generation of 179.901 units, i.e. almost 95.78% utilization. This is mainly because the load in the concerned industrial building is concentrated in the PV generation duration on the contrary to any household consumption, where the load is concentrated in the morning and the evening with lower consumption during the daytime. Thus, high utilization of the PV panels is achieved even without having a storage system in place.

For the second case, the storage system is considered, and to optimize the system's output; the previously discussed optimization model is used. By solving the linear optimization problem, which is given in the previous section, we can 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. In this case, the PV utilization 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 is stored in the battery when the solar PV generation exceeds the load, and the energy is stored in 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 4.7.

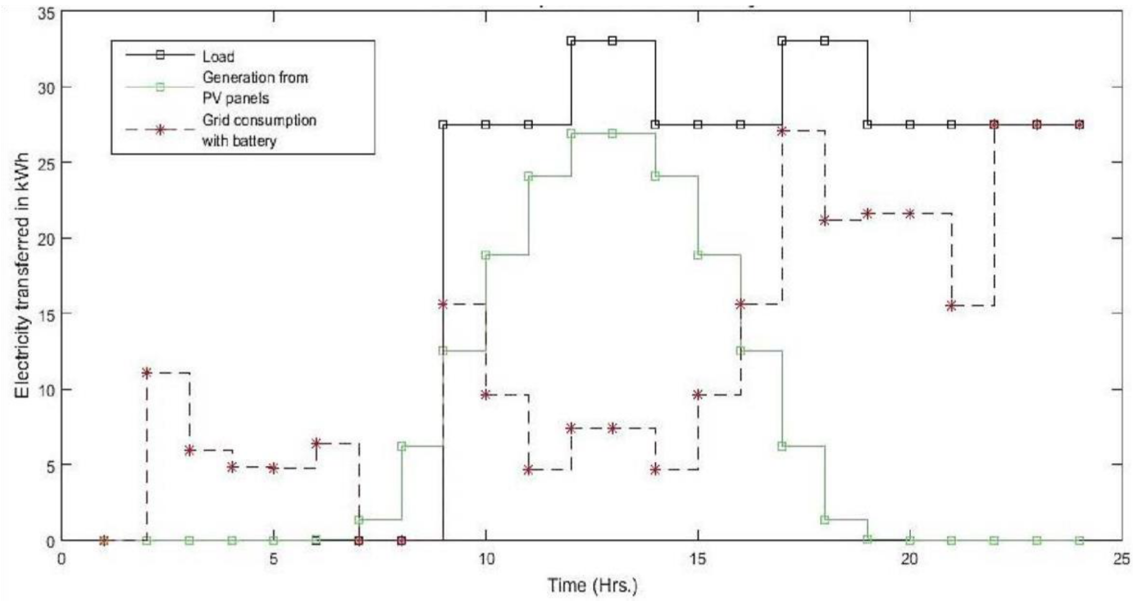

Figure 4.7 Power consumption profile with battery storage

4.6.3 *Conclusion*

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

- Customers can enjoy profits on the 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.
- Solar energy utilization through PV generation systems is higher when such a hybrid system is available compared to stand-alone systems without battery storage.

Future work related to this topic on the 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 because of the nature of the data available.

- The capital cost associated with an investment in PV-Battery hybrid system is to be considered. Based on this, the payback period for system installation is to be evaluated.
- The benefits associated with the relief on demand from the grid side to distribution companies and savings on eliminating the need for an additional power plant or some reduced generation capacity of newly proposed power plants are needed to be considered.
- The reduced carbon footprint of the newly introduced conventional power plants is an important aspect. Incentives for reduced carbon footprint are also an essential part of future work.