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# A Day-ahead Optimal Energy Scheduling of Grid-tied Residential Solar Power System using Particle Swarm Optimization

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## Abstract

This paper suggests the day-ahead optimal energy scheduling technique of grid-tied residential photovoltaic system in order to conform to the electricity tariff to optimize operational household benefit. The solution is conceived as optimization problem, with the objective of maximizing household energy benefit and the optimization variable being the dispatching ratio of electricity, which is the ratio of PV electricity sold to the grid to the additional PV energy after supplying load. After that, the formulated nonlinear optimization problem is solved using a Particle Swarm Optimization (PSO). The verification analysis is performed using a typical grid-tied solar powered system having solar photovoltaic system and battery energy storage system which is located in Lalitpur, Nepal. The findings indicate that the suggested energy scheduling strategy, in conjunction with a heuristic optimization approach, is successful for the optimal energy scheduling of the several energy sources to achieve maximum financial benefits under the time-of-day tariff.

## Keywords

Grid-tied Solar, energy scheduling, Particle Swarm Optimization (PSO), Time of Day tariff (TOD)

## 1. Introduction

The worldwide energy segment has been embracing renewable source of energy. The gigantic utilization of conventional fossil fuel assets has incited to utilize alternative source of energy. The concept of energy transition has been presented to convert the energy sector from carbon-based to zero-carbon energy. The decrease in utilization of fossil fuel resources is significant in arrange to moderate natural issues such as climate change, air pollution, greenhouse emissions etc. To decarbonize the energy sector, gigantic arrangement of renewable energy such as solar, wind, biomass, hydro, geothermal etc. is vital. Solar Photovoltaic energy resources have gained a lot of attention among renewable energy sources (RESs) because of their flexibility and low maintenance costs.

Solar photovoltaic energy resource is one of the basic resources of renewable energy that changes over sunlight into power. With efficiencies advancing, estimating being diminished each day, and new innovations being tested with, the fast development of solar industry is anticipated within the following couple of years. Solar energy is categorized as reasonable, endless, and renewable technology that can offer assistance to enhance sustainability, to advance sound and green environment, and to be energy-independent. The deployment of solar energy is cost effective in long-run and it has positive impact to decarbonize our environment and to mitigate environmental issues. The significant amount of solar PV power can be dispatched to the utility company in case grid is interconnected. The additional PV power could be used to charge batteries to utilize at night. If the right coordination is kept up between solar energy, battery storage and grid, the reliance on imported oil and fossil powers can be incredibly decreased. Apart from this, residential solar power framework can offer assistance to clients to save some money by introducing rooftop solar power system.

Solar power systems, nevertheless, due to their erratic existence and strong reliance on weather conditions, have some inherent drawbacks. As solar photovoltaic power generation does not follow the pattern of power demand and energy pricing, it is difficult to manage household power. To deal with the uncertainty and intermittency of solar power system, the integration of a battery energy storage system (BESS) with the grid connected solar power system is done. Because of the flexible charging-discharging capabilities of the battery storage system, it may store or release energy at any instant, and therefore can be utilized to provide mismatch energy in the electrical system. Although there are several advantages to using BESS in a system, one of the major drawbacks is the high initial capital cost. It also has a considerably shorter life duration than RESs, resulting in significantly higher replacement costs.

Many papers have been suggested various optimization methods for energy scheduling strategies. In [1] , the author illustrated the energy management optimization strategy in order to schedule multiple energy resources in residential household buildings under the time of use (TOU) and step tariffs. The energy management of community microgrids having multiple power sources is emphasized considering degradation cost of battery in [2]. The authors have proposed daily scheduling of energy storage system while considering the cost of degradation associated to charging and discharging cycles in [3]. In [4],the author created an optimization model to look at the revenue generated by feed-in tariffs for current and new PV production systems with energy storage.The optimization of a grid-connected Photovoltaic power plant by maximizing the amount of imported energy from the grid system is done in [5]. A stochastic programming approach is described in [6] to minimize operating cost for a day ahead scheduling of a residential energy management system utilizing a mix of electrical as well as thermal storage. In [7], the TOU of buying and selling electrical energy for a grid-tied microgrid is considered when solving a day ahead energy scheduling problem using interval optimization. The authors from [3]-[8] have analyzed the energy scheduling techniques in their respective available data under various input parameters and optimization techniques.

In this paper ,however, the day ahead energy scheduling is purposed to coordinate the multiple energy sources in such a way that the consumer will get the maximum benefit considering the case study of residential sector of Nepal . The energy scheduling strategy is stated as an optimization problem with the goal of reducing household energy cost, and this problem is solved by using particle swarm optimization (PSO) method. The optimization variable is the dispatching ratio which is the ratio of PV electricity sold to the grid to the extra amount of PV electricity available after feeding the load demand. For the verification purpose, a typical grid-tied residential solar powered system with battery storage was employed. Several scenario analyses have been done and demonstrated the rationality and effectiveness of the proposed energy scheduling strategy in scheduling the multiple power sources optimally to achieve optimum financial benefits under the TOD tariff.

The remainder of the paper is organized as follows. In Section II, the system modeling, which includes component models such as batteries and solar panels, is provided to assist analysis. Section III offers an objective function in terms of overall benefit to the residential user, subject to a variety of constraints. Section IV discusses the solution algorithm for the suggested energy optimization problem, and Section V concludes with the study's findings.

## 2. System Modeling

The grid-tied solar PV system consists of three power sources: solar photovoltaic system, battery storage, and the utility grid which is shown in figure 1. The use of an inverter creates a bi-directional link between the solar photovoltaic system and the utility grid system. When the electricity generated by the Photovoltaic cells exceeds the electricity needed by the users, the system's bi-directional platform allows the Photovoltaic panels' power to feed loads directly connected to the AC bus network while also exporting the surplus energy to the main. If the load demand is greater than the solar PV output, then the battery or utility grid will provide the deficit amount of energy to the load.

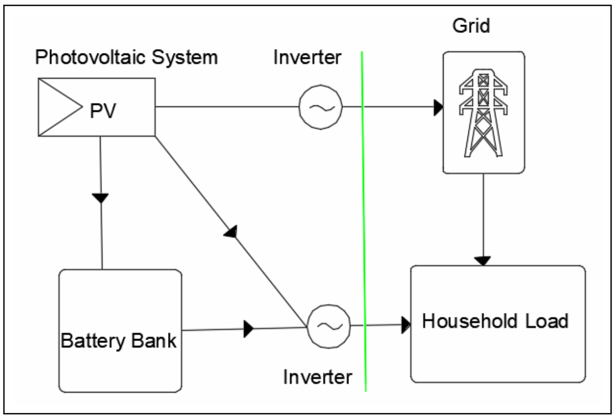


**Figure 1:** General Layout of Grid-connected Residential Photovoltaic System

## 2.1 Solar Photovoltaic System Modeling

Photovoltaic (PV) panels convert solar energy into usable DC power using sunlight. PV power generation is determined by size of solar array, solar irradiance and insolation. The solar output power is computed by array's size and the installed solar photovoltaic system's overall efficiency. The output power of a solar photovoltaic system is computed by [1]:

$$P_{PV} = \frac{P_{STC}G_C}{G_{STC}} + k\frac{P_{STC}G_C\left(T_C - T_{STC}\right)}{G_{STC}} \tag{1}$$

Where the $P_{STC}$ is the maximum PV output under standard testing condition (STC). $G_{STC}$ is an intensity of the sunlight under the normal testing condition which is set as 1 kW/m2. $G_C$ is the actual intensity of the light. The $T_{STC}$ is the temperature under standard testing condition at 250C. $T_C$ is the temperature of solar cell. The value k is the power temperature coefficient which is set to -0.0047°C. The cell temperature of frequently used glass encased solar photovoltaic modules may be calculated using the ambient temperature as,

$$T_C = T_a + 30 \times \frac{G_c}{G_{STC}} \tag{2}$$

Where $T_a$ is an ambient temperature.

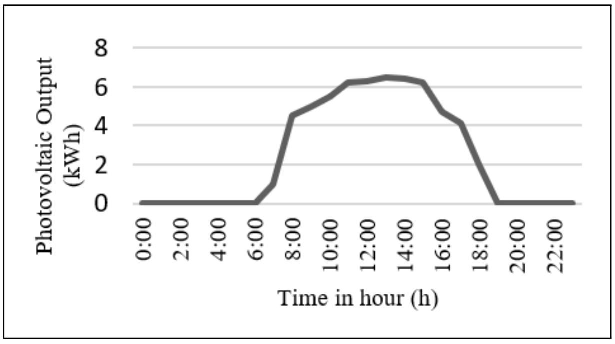


**Figure 2:** Forecasted daily PV output

The figure 2 shows the daily solar PV output of the standard residential grid-tied solar photovoltaic system which was located in Lalitpur, Nepal, which is considered as a case study for this work.

## 2.2 Battery Energy Storage Modeling

The energy storage devices such as batteries are usually employed in grid-connected residential PV systems. This is done to balance the energy production and consumption. The energy storage has the ability to accomplish peak shaving by charging during off- peak hours, and discharging during peak hours. The battery energy in the battery at time t, $E_{(bat,t)}$ can be obtained by[1] [2],

$$E_{bat,t} = \begin{cases} E_{bat,t-1} + (P_{pv,t} - \dfrac{p_{l,t}}{n_{inv}})n_{bat} \\ E_{bat,t-1} - (\dfrac{p_{l,t}}{n_{inv}} - P_{pv,t}) \end{cases} \tag{3}$$

Where, $E_{(bat,t-1)}$ is the energy stored in the battery at time t-1, $p_(pv,t)$ is the output of PV system, $p_{(l,t)}$ is the residential load demand. And $\eta_{inv}$ and $\eta_{bat}$ are the efficiency of inverter and battery respectively.

## 2.3 Household Load and Utility Grid

The daily household load profile is illustrated in Figure 3 whose peak demand is around 3 kW. This load data is taken from the case study which is conducted in a existing grid-tied solar PV system.

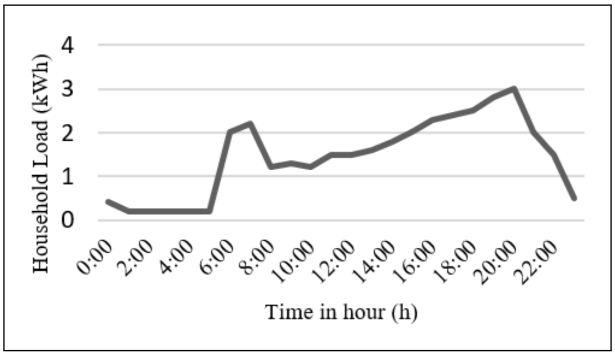


**Figure 3:** Forecasted Daily Consumer Load

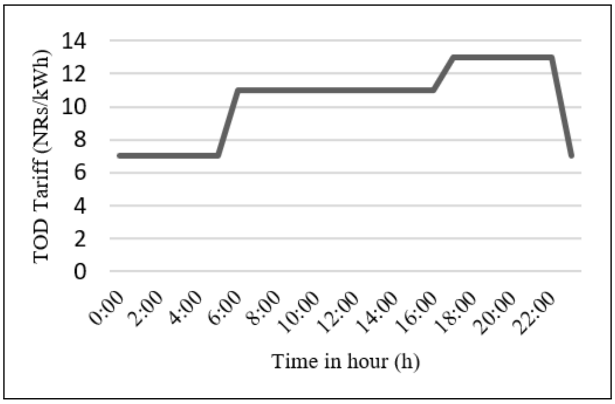


**Figure 4:** Residential Time of Day tariff structure

The time-of-day (TOD) tariff is taken as input which is shown in figure 4 where 24 hours a day are split into three cycles in terms of the TOD tariff, such as peak rate, standard rate and off-peak rate. The TOD tariff rate is assumed in this study with peak value 13

NRs/kWh, standard value 11 NRs/kWh, and off-peak value 7 NRs/kWh. The assumption is made based on the commercial TOD rate of Nepal Electricity Authority [9].

## 3. Proposed Objective Function

The objective function of this energy management optimization scheme is the maximize the daily operational energy benefit to the residential consumer. During a specified time interval, $[t_0, t_s]$, the total benefit of a grid-connected residential power system is as follows:

$$B_{TOD} = \int_{t_0}^{t_s} (C_{(sell,t)} - C_{(buy,t)})dt \tag{4}$$

Where $C_{(sell,t)}$ and $C_{(buy,t)}$ are the revenue from PV power sales, energy purchasing costs respectively. Since, it is the day-ahead energy optimization problem, the sampling interval, $t_s$ is taken as 24 hours.

When the solar power output exceeds the household consumer demand, the remaining excess part is either stored into the battery or injected into grid for selling purpose. The ratio of the PV power electricity sold to the grid to that rest part of solar photovoltaic electricity is defined as a 'dispatching ratio' $\omega$ which is depicted in equation 5. The dispatching ratio will have different values over the sampling time $t_s$.

$$\omega_t = \frac{p_{(n,t)}}{(p_{(pv,t)} - p_{(pl,t)})} \tag{5}$$

The electricity sale income, $C_{sell,t}$ is expressed as,

$$C_{(sell,t)} = p_{(pv,t)} - p_{(l,t)}\omega_t C_0 \tag{6}$$

Where $p_{(pv,t)}$ and$p_{(l,t)}$are solar photovoltaic power production and consumer household demand respectively; $C_0$ is the solar PV bench-marking price.

The cost of purchasing grid electricity, $C_{(buy,t)}$ is expressed as,

$$C_{buy,t} = p_{g,t} C_{price,t} \tag{7}$$

Where $p_{(g,t)}$ is the purchased grid electricity and $C_{(price,t)}$ is the electricity time of day tariff at time t.

Here, the total energy benefit, $B_{TOD}$ will be taken as the fitness function of the optimization problem. Optimizing $B_{TOD}$ produces the best possible result for the entire household PV power system.

## 3.1 Constraints

The following are the constraints for efficient energy scheduling optimization algorithms:

### 3.1.1 Dispatching ratio constraint

The 'dispatching ratio' is bounded to maximum of unity value that means selling all PV electricity to the grid, and to minimum value that means selling no PV electricity to the grid. The dispatching ratio should be between 0 and 1. It is bounded by,

$$0 \leq \omega_t \leq 1 \tag{8}$$

### 3.1.2 Power system balance

Power system balance means the total generation must be equal to the total load. The household electrical power system must be balanced at all times.

$$p_{(l,t)} = p_{(g,t)} + p_{(pv,t)} + p_{(bat,t)} - p_{(n,t)} \tag{9}$$

Where $p_{(n,t)}$ is the amount of solar photovoltaic power sold to the utility grid.

When PV output exceeds load demand i.e. $(p_{(pv,t)}) \geq p_{(l,t)})$, the battery storage enters a charging state, as determined by the scheduling rules. As a result, instead of acting as a power supply, the battery serves as a load. Hence, the power balance equation should be modified as,

$$p_{(l,t)} = p_{(pv,t)} - p_{(bat,t)} - p_{(n,t)} \tag{10}$$

When the output of the solar photovoltaic power is below the load profile, the energy storage is changed to discharging mode i.e. $(p_{(pv,t)} \leq p_{(l,t}$. To balance the load demand, additional power will most likely be acquired from the grid. The balance of the system is represented as follows,

$$p_{(l,t)} = p_{(g,t)} + p_{(pv,t)} + p_{(bat,t)} \tag{11}$$

### 3.1.3 Solar Power energy scheduling

When solar power output exceeds load demand, PV electricity is planned to fulfill the load demand first and foremost. Then, the rest part $p_{(pv,t)} - p_{(l,t)}$ is further dispatched through $\omega_t$ as

$$-p_{(bat,t)} = (p_{(pv,t)} - p_{(l,t)})(1 - t) \tag{12}$$

And,

$$p_{(n,t)} = (p_{(pv,t)} - p_{(l,t)})\omega_t \tag{13}$$

Where $p_{(bat,t)}$ is charging and discharging energy of the battery bank for a specified hour t.

### 3.1.4 Constraints for battery storage

Practically, deep discharge or overcharge reduces battery's service life, and brings extra maintenance cost. Hence, it is reasonable to set bounds for the energy stored in the battery as follow:

$$E_{(bat,min)} \leq E_{(bat,t)} \leq E_{(bat,max)} \tag{14}$$

Where $E_{(bat,t)}$ is the energy stored in the battery at time t, $E_{(bat,min)}$ and $E_{(bat,max)}$ form a bound for $E_{(bat,t)}$. Here, $E_{(bat,min)}$ and $E_{(bat,max)}$ are set as 20% and 80% of rated energy level of battery respectively. The rated energy level (E) of the battery storage is 20 kWh to meet the maximum power demand for one hour if the battery constraints are neglected.

### 3.1.5 Charging and discharging constraints for battery

Charging and discharging rates of battery are other issues affecting the safety and service life of battery packs. Thus, the bounds as follows are set for the charging and discharging rates.

$$\begin{cases} p_{bat+} \leq 0.2\frac{E}{\Delta t} \\ p_{bat-} \leq 0.2\frac{E}{\Delta t} \end{cases} \tag{15}$$

Where $p_{(bat+)}$ and $p_{(bat-)}$ are the charging and discharging power of battery respectively.

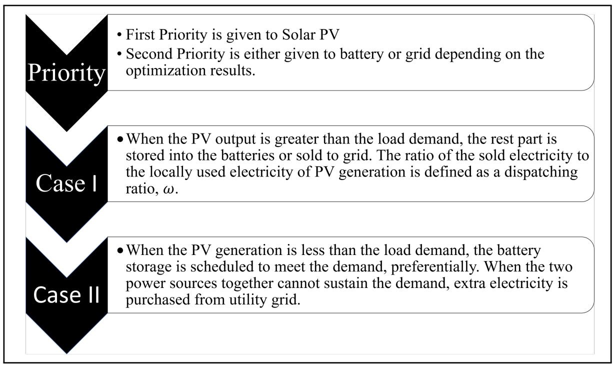
## 4. Solution Algorithm

The energy scheduling optimization is a constrained nonlinear optimization problem which is solved using Particle Swarm Optimization (PSO) methodology. The PSO computes a problem by creating the random population of potential solutions, called particles, and spreading particles along in the search area using standard mathematical expression based on their position and velocity. This methodology is motivated in the search space by social and cooperative actions shown by different organisms to satisfy their needs. The fact that the PSO method is easy and straightforward to implement, and can generate near-optimal schedules within less computational time making it the simplest and convenient optimization method and hence, has been used in this work.

### 4.1 Proposed methodology

#### 4.1.1 Energy Scheduling Rules

The energy scheduling rules for the three power sources of a residential power system are crucial to its energy scheduling management on order to augment the efficiency of the system. In particular, household loads preferentially consume the electricity produced by PV system; the remaining portion is then sold to the grid. Further details on energy scheduling rules is illustrated in figure 5.



- First Priority is given to Solar PV
- Second Priority is either given to battery or grid depending on the optimization results.

- When the PV output is greater than the load demand, the rest part is stored into the batteries or sold to grid. The ratio of the sold electricity to the locally used electricity of PV generation is defined as a dispatching ratio, $\omega$.

- When the PV generation is less than the load demand, the battery storage is scheduled to meet the demand, preferentially. When the two power sources together cannot sustain the demand, extra electricity is purchased from utility grid.

**Figure 5:** Energy Scheduling Rules [1]

In this methodology, the first stage consists of data collection work. The daily PV output, household load, and tariff rates are input to this optimization problem. After this step, the PSO parameters such as number of optimization variables, population size, number of generations, number of iterations etc. are initialized. The particle position that is the dispatching ratio and particle velocity is randomly initialized. After initializing particle position and velocity, the objective function is evaluated and calculate personal best, $p_{best}$ and global best $g_{best}$ values. Again, the particle position and velocity with constraints are updated. The major work of this problem is energy scheduling of the grid connected residential PV system. For one day optimization, when solar PV output is greater than load, the extra energy is scheduled to either charge battery or to sell to grid according to the dispatching ratio. When the solar PV output is less than the load, then the load demand is fulfilled by discharging battery alone if battery capacity is sufficient. If battery has not enough capacity, then remaining energy demand is fulfilled by purchasing electricity from grid. The purchase of electricity is associated with the energy buy cost $C_{(buy,t)}$. After energy scheduling formulation shown in figure 5, the fitness function in terms of cost of residential customer is formulated. The objective is to minimize this cost under Time of Day (TOD) Tariff. In this problem, the dispatching ratio is taken as optimization variable. The particle swarm optimization is employed to get the optimal solutions to this optimization problem. When the termination criteria satisfied with optimal solution, the optimal energy management instructions are obtained. According to this instruction, the consumer will operate the overall grid-connected residential system. The methodology under Particle Swarm Optimization is shown in figure 6.

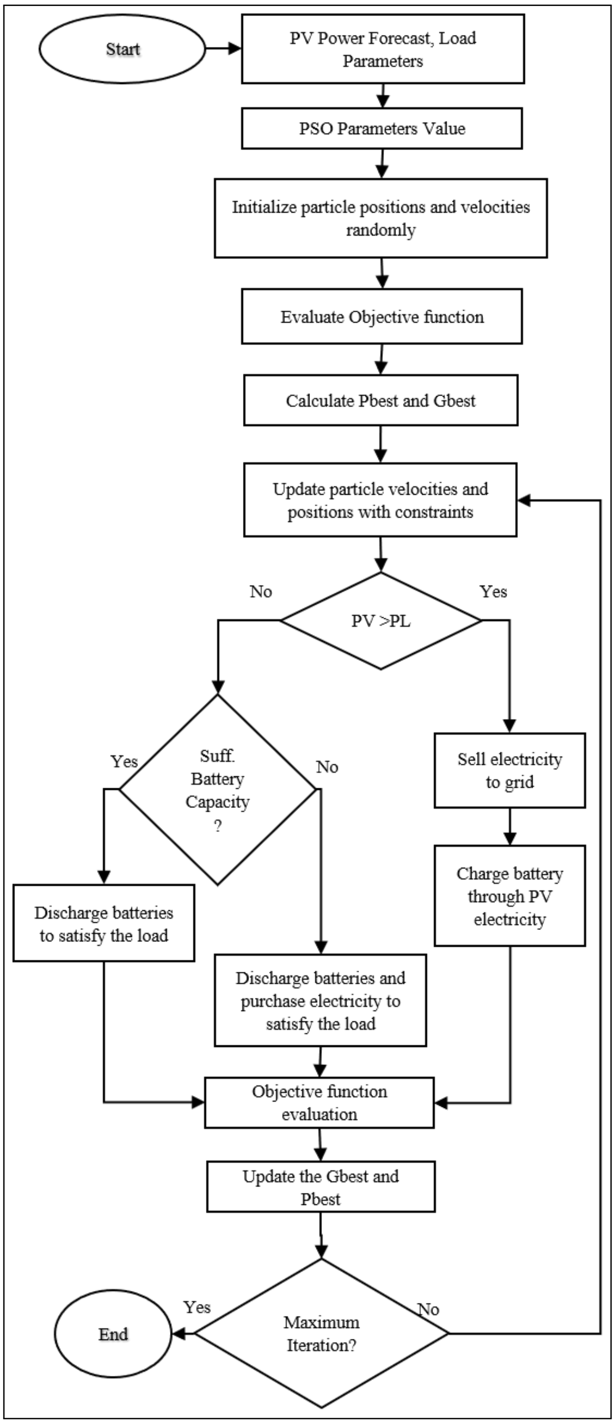


**Figure 6:** Proposed methodology

## 5. Experimental Result

### 5.1 Case Study

The study was conducted taking a case study of a standard residential grid-tied solar photovoltaic system which was located in Lalitpur, Nepal. The energy scheduling optimization will be done in the already existed system without considering the capital cost of the entire system. The size of the solar PV system is 8 kWp with standard crystalline module type and fixed roof mounted solar array. Table 1 lists the parameters utilized in this study.

**Table 1:** Hourly PV Performance Data

| | |
|---|---|
| Requested Location | Lalitpur, Nepal |
| Location | Pulchowk |
| Lat (deg N) | 27°40’44.90”N |
| Long (deg E) | 85°19’30.57”E |
| Elev (m) | 1300 |
| DC System Size | 8 kW |
| module Type | Crystalline |
| Array Type | Fixed |
| Array Tilt (deg) | 27 |
| Array Azimuth (deg): | 0 |
| System Losses | 5% |
| Inverter Capacity | 8 kW |
| Inverter Efficiency | 98% |
| Battery Capacity | 20 kWh |
| Maximum energy level | 16kWh |
| Minimum energy level | 4kWh |
| Initial energy level | 4kWh |

### 5.2 Optimal Operation of the Residential Solar PV System

First, the energy scheduling strategy is applied to the standard grid-connected residential power system mentioned above, which is formulated in compliance with the TOD tariff policy. The selling price of PV electricity is set at 7.30 NRs/kWh[9]. Given the above inputs and conditions, the PSO algorithm solves the energy scheduling problem. The grid-tied solar power system optimal operation is illustrated in Figure 7.

The working condition of the three sources of energy is described according to the scheduling rules. The dispatching ratio, or optimizer in the resource scheduling problem, economically dispatches the remaining solar power output to optimum profitability. The best operating instructions take full advantage of the TOD tariff according to optimization algorithms.

In this paper, as per figure 2 and figure 3, the solar PV output is not available during the period between 0:00 and 6:00, and the residential household load is fulfilled by purchasing electricity through grid. The time-of-day tariff has its off-peak rate during this interval, so purchasing electricity from grid is beneficial rather than discharging the battery. The load is also very less during this time interval. So, in this scenario, the load demand is met by the grid electricity.

During daytime between 9:00 and 18:00, the PV output is much larger than the load demand. The extra PV power output is dispatched to battery storage and also sold to grid based on dispatching ratio. The time-of-day tariff has its standard rate. However, the electricity is not purchased from utility grid.

During peak period between 18:00 and 21:00, there is no solar light intensity. At the same time, the TOD tariff rate is very high. As a result, the battery bank is set to serve as the primary power source to fulfill the load requirement. This optimal instruction avoids purchasing expensive grid electricity during peak interval. During standard period between 21:00 and 23:00, the TOD rate falls to standard rate and electricity is purchased from the grid to satisfy the load demand.

There is an optimal coordination between dispatching ratio and the TOD tariff. In the peak hours, the dispatching ratio is set to a reasonably high level. When the solar power output is sufficient, then the dispatching ratio is adjusted near to one, meaning that much of the PV electricity is sold to the grid. The dispatching ratio became useless when the solar intensity steadily declined to zero, so it was set to zero as well.

The battery capacity under TOD tariff is shown in figure 8. The battery has a rated energy level of 20 kWh. The battery must not get discharged below 20 percent of its rated capacity that is 4 kWh in order to maintain its lower bound. Similarly, the battery must not get charged above 80 percent of its rated capacity that is 16 kWh in order to maintain its upper bound. The initial battery status is at 4 kWh. The battery is charged when the solar PV output is sufficient, and it is discharged when there is high tariff rate and there is no solar PV available. Figure 9 shows the dispatching ratio of TOD strategy. The dispatching ratio is significantly high during the day time when there is sufficient solar PV output. The higher the dispatching ratio, the amount of energy selling to grid is high

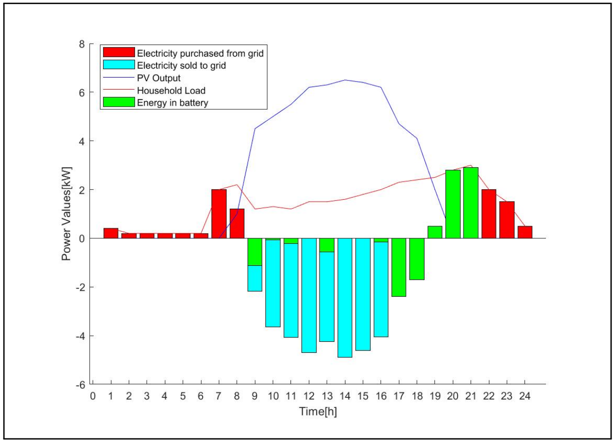


**Figure 7:** Optimal Operation of Residential Power System under TOD tariff

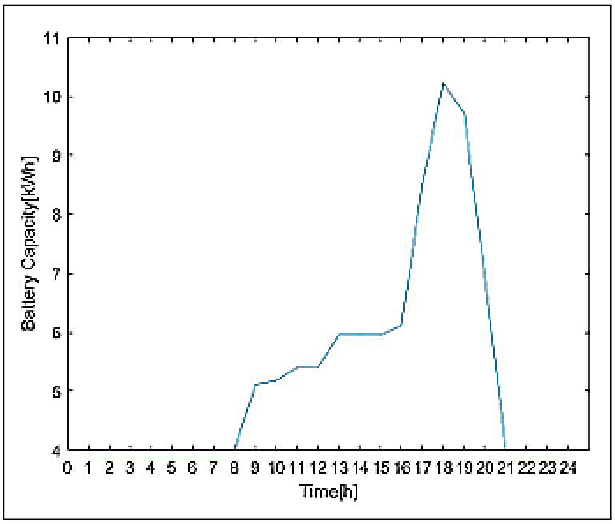


**Figure 8:** Battery capacity under TOD tariff

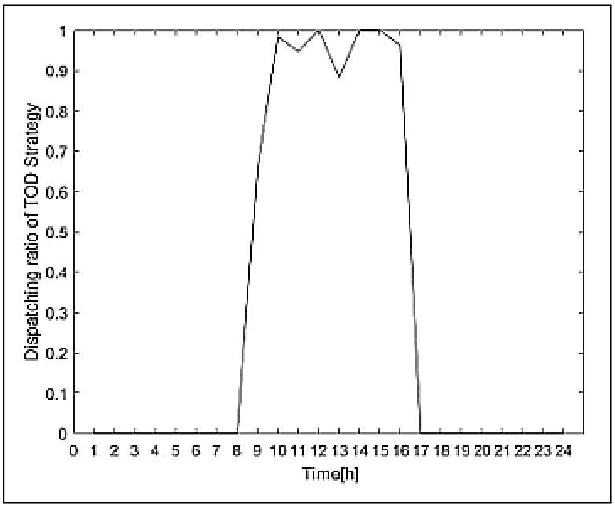


**Figure 9:** Dispatching ratio of TOD Strategy

having higher benefit to customer. During early morning time, late evening time, and night time, the dispatching ratio is zero as there is no solar energy available during that time.

## 5.3 Comparasion with Base Case Scenario

The optimal operation of residential solar power system can be compared with typical base case scenario. This scenario assumes the zero-dispatching ratio at first which means the battery will get charged at first, and when the battery is fully charged, then only after that the remaining PV will be sold to the main grid. The energy scheduling under the base case scenario is shown in figure 10. This base case scenario also considers the battery constraints avoiding battery undercharging and overcharging.

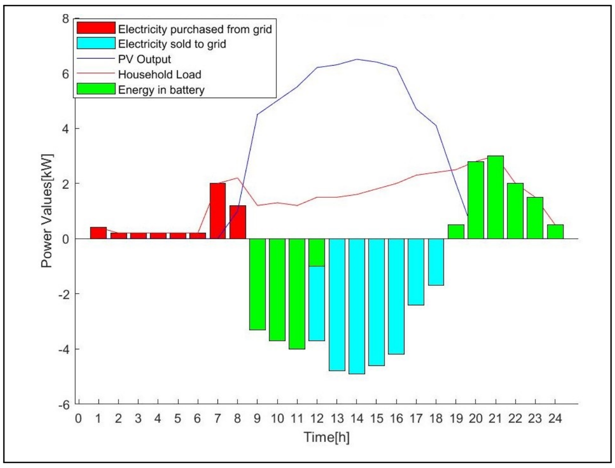


**Figure 10:** Energy Scheduling under base case scenario

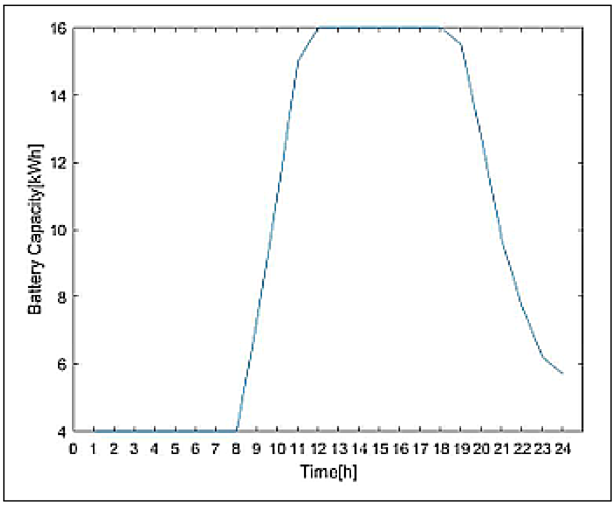


**Figure 11:** Battery Capacity under base case scenario

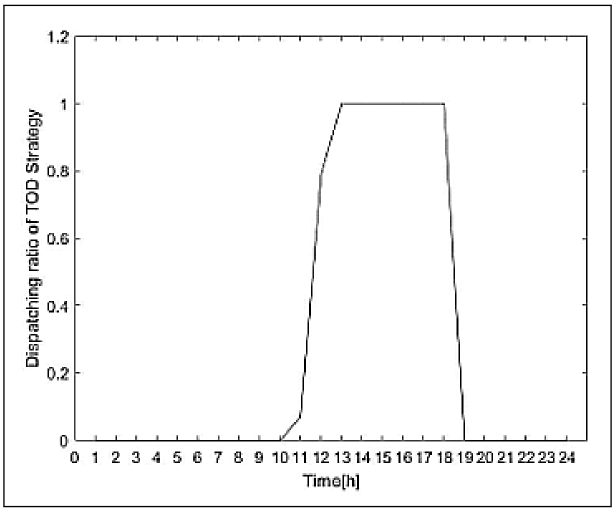


**Figure 12:** Dispatching ratio under base case scenario

Figure 11 shows the battery capacity under base case scenario. The battery get fully charged during the interval 8:00 to 12:00 and discharged when there is no PV output available. The dispatching ratio under base case scenario is also depicted in figure 12.

## 5.4 Financial Analysis and Economic Benefit

As per the aforementioned energy scheduling strategies, the solar power energy is used first by residential household appliances and to charge battery fully, with the remainder sold to the grid. Here, it is referred to as a base case scenario. This is a typical mode of service in a residential power system connected to the grid. The objective function of this paper gives the daily benefit of the system which is obtained under PSO methodology. The daily benefit obtained under EMOTD strategy is NRs 186.718, and the annual benefit is just calculated by multiplying daily benefit by 365. The annual average benefit is NRs. 68152.2. Under Base Case Scenario, the daily benefit obtained to consumer is NRs 149.18 and the annual benefit is NRs. 54450.7. The EMOTD strategy increases the annual financial benefit by 25.2 % as compared with the base case scenario which is shown in table 2.

**Table 2:** Comparison of EMOTD with base case scenario

| Operation Mode | Daily Benefit (NRs) | Annual Benefit (NRs) | Revenue Growth rate (%) |
|---|---|---|---|
| Base Case | 149.18 | 54450.7 | |
| EMOTD | 186.718 | 68152.2 | 25.2 % |

## 6. Conclusion

The two key concerns of grid-connected residential PV system are household benefit to the consumer and energy efficiency. Optimal energy scheduling strategies are required in order to effectively and economically leverage renewable solar energy. In this work, the optimal energy scheduling strategy under time-of-day tariff is proposed. The total operational energy benefit is considered as the objective function of the energy scheduling problem and the and the dispatching ratio is taken as the optimization variable. As long as all system constraints are met, the proposed optimization method has accomplished the maximum economic benefit to the residential consumers. The energy scheduling strategy under time-of-day tariff is formulated and modeled as an optimization problem, and particle swarm optimization (PSO) algorithm is applied to solve this scheduling problem. A standard grid-tied residential solar power system for verification study has been added to the proposed strategy. The proposed strategy can indeed achieve optimum benefits by optimization approach relative to the simple base case mode. The comparison on the financial benefit of the proposed energy scheduling strategy with base case scenario is done and calculated revenue growth which is around 25 %. Thus, there is a strong implementation scope for the suggested technique in the grid-connected residential PV generation system.

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