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# Optimal unidirectional grid tied hybrid power system for peak demand management

C.P. Vineetha* and C.A. Babu[a]

*Division of Electrical Engineering, Cochin University of Science and Technology, Kochi, Kerala, India*

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**Abstract.** A well designed hybrid power system (HPS) can deliver electrical energy in a cost effective way. In this paper, model for HPS consisting of photo voltaic (PV) module and wind mill as renewable energy sources (RES) and solar lead acid battery as storage device connected to unidirectional grid is developed for peak demand reduction. Life time energy cost of the system is evaluated. One year hourly site condition and load pattern are taken into account for analysing the HPS. The optimal HPS is determined for least life time energy cost subject to the constraints like state of charge of the battery bank, dump load, renewable energy (RE) generation etc. Optimal solutions are also found out individually for PV module and wind mill. These three systems are compared to find out the most feasible combination. The results show that the HPS can deliver energy in an acceptable cost with reduced peak consumption from the grid. The proposed optimization algorithm is suitable for determining optimal HPS for desired location and load with least energy cost.

**Keywords:** renewable energy; renewable energy sources; hybrid power system; peak load management; distributed renewable energy generation

## 1. Introduction

Renewable energy sources (RES) can supplement the present supply-demand gap and at the same time, can address the environmental and energy security issues (Priyanka *et al*. 2014, Anwar and Ibrahim 2014). Photovoltaic (PV) module and wind mill are accepted as alternative source of electrical energy now a days (Sankar *et al*. 2015, Nedim 2014). Easy availability of solar and wind with advancing technologies promotes their usage. The distributed renewable energy (RE) generation on the roof top of the building reduces technical and commercial (T&D) losses since the energy is generated at load point. One or more of storage devices like electrolyser with fuel cell, battery or conventional energy generation equipments like diesel generator are combined with RES in stand-alone HPS for minimal interruption, investment and green house gas emission (Abtin *et al*. 2015, Priyanka *et al*. 2014, Anwar and Ibrahim 2014, Nedim 2014, Khatib *et al*. 2012, Rajesh *et al*. 2013, Nitin *et al*. 2013, Kaldellis *et al*. 2012, Khatib *et al*. 2011, Abd El-Shafy A. Nafeh 2011, Salmanoglu and Cetin 2013, Sonali and Sayed 2014, Al-Badi *et al*. 2012, Suresh *et al*.

*Corresponding author, Ph.D. Student, E-mail: vineethacp@gmail.com
[a]Professor, E-mail: drcababu@gmail.com


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2011, Balamurugan *et al*. 2009, Kumaravel and Ashok 2012). Stand-alone or autonomous systems are to be optimized taken into account minimal loss of load probability or zero critical load rejection (Anwar and Ibrahim 2014, Nedim 2014, Khatib *et al*. 2012, Rajesh *et al*. 2013, Nitin *et al*. 2013, Kaldellis *et al*. 2012, Khatib *et al*. 2011, Abd El-Shafy A. Nafeh 2011). The individual RES stand-alone systems and diesel generator system were compared with stand-alone HPS to determine recommended configuration in a desired location for least energy cost or system cost (Priyanka *et al*. 2014, Khatib *et al*. 2011, Abd El-Shafy A. Nafeh 2011). This work aims to analyse grid connected distributed RE system.

Economic analysis of grid connected system is done by Turkay and Telli (2011) using HOMER by taking monthly average of input data for the fuel cell based system. In our paper the hourly solar irradiation, temperature of PV cell, wind speed and demand profile for one year are taken as input for analysis and software is developed using MATLAB coding for the development of HPS model and optimization algorithm.

Over all operation cost reduction of fuel cell is the aim of optimization of a grid connected hydrogen based PV-wind mill HPS for zero energy annual balance with peak load shaving, reactive power control and back up service by Aitor *et al*. (2010). An attempt to determine the reduction of peak load and energy cost of different types industries by the use of RES from independent power producers is done by Babu and Ashok (2009). Power scheduling algorithm is developed for grid connected solar PV system by proposing peak shaving service (Yann *et al*. 2011). Performance analysis of grid connected PV system is carried out using measured output data (Li *et al*. 2013, Kazema *et al*. 2014). Optimization of distributed RES is proposed for energy conservation and cost economization for integrated electric power and hot water supply incorporating PV system and solar water heaters with fuel cell for grid connected residential building by Xiangxiang *et al*. (2014). The grid must be dual directional to accept the energy from HPS in these works. The infrastructure must be strong and necessary protection circuitry are to be insisted by the authority for grid tied HPS.

In developing countries like India the infrastructure for electrical energy transmission and distribution is overloaded in many locations. The grid codes for on grid system installation are only in the draft stage in many states. The grid is to be strengthened to accommodate grid tied inverters. So HPS connected to unidirectional grid is only allowed in such countries for RE generation on the grid connected buildings. This system is to be modelled to analyse commercial feasibility and peak demand reduction. This paper is focused on this type of HPS for modelling and optimization.

The aim of this work is to determine optimal HPS on the roof top of the building connected to unidirectional grid for least energy cost satisfying the constraints appropriate for the proposed system and to reduce peak consumption from the grid. PV module and wind mill are taken as RES. Solar lead acid battery is taken as storage device for the proposed HPS. System model is developed to get the output of the RES for the life span of the project. The grid connected to the premises can deliver energy when there is shortage from HPS. The excess energy generated in the premises is stored in storage battery and if it is fully charged the excess energy generated is considered as dump load. The factors like State of charge (SOC) of the battery bank, dump load, renewable energy obligation (REO) etc are taken into account in the problem formulation. The individual RE systems are also analysed applying the same algorithm. The green energy credit (GEC) and peak energy credit (PEC) are considered in cost analysis. The RE generation, average SOC, dump load and energy peak reduction is also analysed in this work. Case studies are conducted in three locations for two types of loads with different annual consumption of energy.

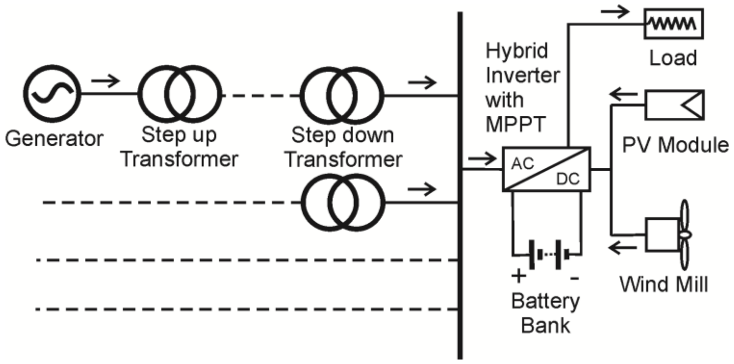



Fig. 1 One line diagram of HPS with power flow of grid

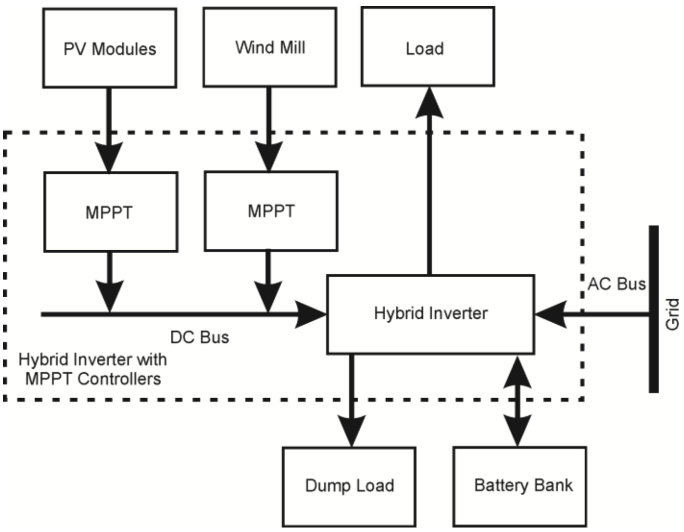



Fig. 2 Configuration of the proposed hybrid power system

This paper is organized as follows. In section 2 proposed system configuration is described. Section 3 presents the system component modelling. Section 4, 5 and 6 explain objective function, energy peak reduction and peak energy credit respectively. Constraints are explained in section 7. Section 8 and 9 describe simulation and case study. Results and discussion are presented in section 10. Section 11 concludes the work.

## 2. Description of the proposed system configuration

The HPS includes PV module and wind mill with solar lead acid battery as storage device. These are interconnected through hybrid inverter with maximum power point tracking (MPPT) controller. MPPT for each RES are included in the system configuration to extract maximum RE (Vineetha *et al* 2014). The load is fed through the inverter either from RES or battery bank or grid according to the availability and time of use. The one line diagram with power flow of grid is shown in Fig. 1 and the proposed HPS configuration is shown in Fig. 2.

The energy generated by RES is utilised to charge the battery during intervals when energy generation is less than demand. Under this condition the battery is fully charged the excess energy available is considered as dump load. The minimum SOC of battery is fixed in different values for peak hours and other times of the day to utilise maximum stored energy at peak hours. The priority of energy utilisation by the load is RES, battery and grid in the order of availability.

## 3. System component modelling

The modelling of each component plays an important role in system evaluation. A methodology with general description for modelling of HPS components both technical and commercial is described to determine optimal HPS. The symbols used in this paper are described in Appendix.

### *3.1 Technical modelling*

#### *3.1.1 PV module*

The irradiation received on earth is measured as global horizontal irradiance, global tilt irradiance, direct normal irradiance and diffuse irradiance. The irradiation obtained at a tilted PV module using mechanical MPPT is termed as global tilt irradiance. The mechanical MPPT is not widely used for roof top solar power plants due to its high cost and difficulty of maintenance. In this work PV module output power model is developed from hourly global horizontal irradiance in a location to account the absence of mechanical MPPT. The output of PV module is reduced with the increase in temperature of PV cell proportion to temperature coefficient of PV cell. That is also taken into account in the PV module output power modelling (Kazema *et al*. 2014, Skoplaki and Palyvos 2008). PV module output energy for the life span of the project is determined considering the energy reduction due to loss in inverter and ageing of PV module. The developed model can determine hourly output power of PV module (Vineetha *et al* 2014, Vineetha and Babu 2013, Vineetha and Babu 2014). That is

$$Ps_{dt_i} = Ps_r\left[1-(T_{dt}-25)*T_{cp}\right]*\gamma_{dt}*\eta_1*\frac{\omega}{2}*\left[2-(\omega-1)*\eta_2\right]*i \tag{1}$$

The energy reduction due to ageing of PV cell is taken into account in this paper. The $\eta_2$ is the percentage efficiency reduction due to ageing of PV cell for one year and $\omega$ is life span of project. Then $\frac{\omega}{2}*\left[2-(\omega-1)*\eta_2\right]$ is the net reduction percentage of the PV cell output energy for the life span of the project.

#### *3.1.2 Wind mill*

Wind mill coverts wind energy to electrical energy. Wind speed varies with height is also taken into account in the wind mill modelling. The wind mill is operated in a specific range of wind speed. The basic model of wind mill output power in terms of wind speed is developed by Arabali *et al*. (2013). As in the case of PV module the wind mill output power for the life span of the project is determined considering the efficiency of inverter with MPPT controller and energy reduction due to ageing of wind mills in this work. That is defined as

$$\left.\begin{aligned} Pw_{dt_j} &= 0 \text{ when } \mathrm{Sw}_{dt} < Sw_{ci} \text{ or } Sw_{dt} > Sw_{co} \\ &= Pw_r * \frac{Sw_{dt} - Sw_{ci}}{Sw_r - Sw_{ci}} * \eta_1 * \sum_{\tau=1}^{2} \frac{\omega_\tau}{2} * \left[2 - (\omega_\tau - 1) * \eta_2\right] * j \text{ when } \mathrm{Sw}_{ci} \le Sw_{dt} < Sw_r \\ &= Pw_r * \eta_1 * \sum_{\tau=1}^{2} \frac{\omega_\tau}{2} * \left[2 - (\omega_\tau - 1) * \eta_2\right] * j \text{ when } \mathrm{Sw}_r \le Sw_{dt} \le Sw_{co} \end{aligned}\right\} \quad (2)$$

### 3.2 Commercial modelling

#### 3.2.1 Hybrid power system components

The commercial modelling of PV module, wind mill and hybrid inverter with MPPT controller is conducted as in (Vineetha *et al* 2014). The net investment of PV module, wind mill and inverter with MPPT controller are $C_{s_i}, C_{w_j}$ and $C_{v_{ij}}$ respectively. These are determine as

$$C_{s_i} = A_{1s_i} + A_{2s_i} + A_{3s_i} - A_{4s_i} \quad (3)$$

$$C_{w_j} = A_{1w_j} + A_{2w_j} + A_{3w_j} - A_{4w_j} + A_{5w_j} \quad (4)$$

$$C_{v_{ij}} = A_{1v_{ij}} + A_{2v_{ij}} + A_{3v_{ij}} - A_{4v_{ij}} + A_{5v_{ij}} \quad (5)$$

The storage device used in the proposed system is solar lead acid battery. The commercial modelling of storage device is done as same as inverter with MPPT controller modelling as

$$C_{b_{ij}} = A_{1b_{ij}} + A_{2b_{ij}} + A_{3b_{ij}} - A_{4b_{ij}} + A_{5b_{ij}} \quad (6)$$

In the calculation of O&M cost and insurance charges escalation rate ($g$) and interest rate evolution ($h$) are taken into account. Salvage value and replacement cost are found out with general inflation rate ($q$) and interest rate evolution (Abd El-Shafy and Nafeh 2011, Vineetha *et al* 2014). Capital recovery factor (CRF) is applied to all cost including capital investment cost since the return of investment is monthly (Vineetha *et al* 2014, Vineetha and Babu 2013, Vineetha and Babu 2014). $C_{b_{ij}}$ and $C_{s_i}$ are proportional to the rating. So these can be expressed as

$$C_{b_{ij}} = \chi_b * k_{ij} \quad (7)$$

$$C_{s_i} = \chi_s * i \quad (8)$$

The investment for wind mill and inverter with MPPT controllers is not proportional to rating. These has one proportional components and another constant. These are expressed as

$$C_{w_i} = \chi_w * j + \sigma_w \quad (9)$$

$$C_{v_x} = \chi_v * x + \sigma_v \quad (10)$$

### 3.2.2 Grid energy cost

The shortage energy in the premises is met from the grid in the proposed system. The cost of shortage of energy is determined from hourly shortage of energy in the premises in the life span of the project. The energy cost is determined considering the time slot as normal, peak and off peak hours in the time of the day. The fixed charge imposed by the utility for the connected load of the premises is also taken into account in the energy cost modelling. It is expressed as

$$C_{e_{ij}} = C_{ex_{ij}} + C_{ey_{ij}} + C_{ez_{ij}} + C_f \tag{11}$$

That is determined as

$$C_{ex_{ij}} = \left[ \sum_{d=1}^{365} \sum_{t=t_1}^{t_2} \left[ +ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) - \phi dc_{dt_{ij}} \right] * r_x \right] * \omega \tag{12}$$

$$C_{ey_{ij}} = \left[ \sum_{d=1}^{365} \sum_{t=t_2}^{t_3} \left[ +ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) - \phi dc_{dt_{ij}} \right] * r_y \right] * \omega \tag{13}$$

$$C_{ez_{ij}} = \left[ \sum_{d=1}^{365} \sum_{t=t_3}^{t_1} \left[ +ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) - \phi dc_{dt_{ij}} \right] * r_z \right] * \omega \tag{14}$$

$$C_f = \partial * \delta * 12 * \omega \tag{15}$$

### 3.2.3 Green energy credit

Green energy credit (GEC) is the subsidy provided by the government to promote the RE. Subsidy is provided on the initial capital investment. The amount for the life span of project is determined as

$$C_{\mu_{ij}} = \left( A_{6s_i} + A_{6w_j} + A_{6v_{ij}} + A_{6b_{ij}} \right) * F(\alpha, \omega) * \omega * \varepsilon \tag{16}$$

Capital recovery factor (CRF), $F(\alpha, \omega)$ for the life span of project is taken into account in the GEC since subsidy is obtained at the starting of project and energy cost is paid monthly (Vineetha *et al* 2014).

### 3.2.4 Conventional energy cost

The premises energy cost for the utility supply for the life span of the project is found out considering peak, normal and off peak energy consumption and energy cost for each period in a day with fixed charge depending upon the connected load of the premises. This is expressed as

$$C_{eu} = \left[ \sum_{d=1}^{365} \sum_{t=t_1}^{t_2} Pl_{dt} * r_x + \sum_{d=1}^{365} \sum_{t=t_2}^{t_3} Pl_{dt} * r_y + \sum_{d=1}^{365} \sum_{t=t_3}^{t_1} Pl_{dt} * r_z + \partial * \delta * 12 \right] * \omega \tag{17}$$

## 4. Mathematical formulation

### 4.1 Objective function

The objective function is formulated to obtain energy cost of premises for the life span of the project for various combinations of HPS. These are determined to find out optimal HPS with minimum energy cost satisfying the constraints. The optimal ratings of PV module, wind mill, storage battery and inverter with MPPT controller are to be determined. The objective function is

Minimize:

$$C_{er_{ij}} = C_{s_i} + C_{w_j} + C_{v_{ij}} + C_{b_{ij}} + C_{e_{ij}} - C_{\mu_{ij}} \quad (18)$$

### 4.2 Energy peak reduction

There is a reduction in peak demand in premises due to RES generation and battery storage. Energy peak reduction is determined as

$$E_{mr_{ij}} = \left[ \sum_{d=1}^{365} \sum_{t=t_1}^{t_2} Pl_{dt} - \sum_{d=1}^{365} \sum_{t=t_1}^{t_2} +ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) - \phi dc_{dt_{ij}} \right] * \omega \quad (19)$$

The percentage reduction of peak energy is also determined to analyse the benefit of HPS.

$$E_{mr\%_{ij}} = \frac{E_{mr_{ij}} * 100}{\sum_{d=1}^{365} \sum_{t=t_1}^{t_2} Pl_{dt} * \omega} \quad (20)$$

### 4.3 Peak energy credit

The reduction of peak load is very beneficial for both grid and utility. The grid become stable and utility can reduce the investment for conventional generators to meet the peak load. The generators efficiency can also be improved due to peak load shaving. This benefit may be contributed to producers of RE with respect to peak demand reduction. This is termed as peak energy credit (PEC). The effect of PEC is also analysed in this paper. The PEC is

$$C_{\rho_{ij}} = E_{mr_{ij}} * \varphi \quad (21)$$

### 4.4 Constraints

The optimal HPS is determined for least life time energy cost with minimum RE generation with respect to REO. This is described as

$$E_{ge_{ij}} \geq \frac{El * u}{100} \quad (22)$$

Where

$$El = \sum_{d=1}^{365} \sum_{t=1}^{24} Pl_{dt} \quad (23)$$

Dump load reduction and minimum average SOC of battery are the other factors considered in this work. Dump load reduction is termed as

$$E_{dump_{ij}} < \beta * E_{ge_{ij}} \tag{24}$$

Where

$$E_{ge_{ij}} = \sum_{d=1}^{365}\sum_{t=1}^{24}(Ps_{dt_i} + Pw_{dt_j}) \tag{25}$$

Maximum and minimum SOC of the storage battery should be maintained within the limit to avoid depletion and overcharging. In this work minimum SOC is fixed at two values in peak and other times of the day to utilize maximum battery capacity at peak hours. Then the system should be satisfied at peak hours

$$SOC_{\min 1} \le SOC_{dt_{ij}} \le SOC_{\max} \tag{26}$$

At other times of the day

$$SOC_{\min 2} \le SOC_{dt_{ij}} \le SOC_{\max} \tag{27}$$

To ensure the life span of the battery the average SOC of the battery should be greater than a desired value. That is

$$SOC_{a_{ij}} > \lambda \tag{28}$$

To determine the rating of the storage battery in the iteration

$$k_{ij} = Round\left(\sum_{t=1}^{8760}\frac{+ve(Ps_{t_i} + Pw_{t_j} - Pl_t)}{300}\right) \tag{29}$$

The constraints to ensure the maximum and minimum rating of PV module and wind mill are not violated. These are expressed as

$$Rs_{\sigma} \le i \le Rs_{\tau} \tag{30}$$

$$Rw_{\sigma} \le j \le Rw_{\tau} \tag{31}$$

The HPS model is developed both technically and commercially to analyse the objective function with these constraints and optimal HPS is found out.

## 5. Simulation

The flow chart for optimization process is shown in Figs. 3 and 4. Model of HPS is developed to get hourly output power of RES for all combination and individual RES. The maximum rating of PV module and wind mill is the rating at which each alone can deliver the average consumption of the premises with average daily irradiation and wind speed. The roof top capacity of the premises is also a limiting factor for the maximum rating of RES. The rating of the PV Module and wind mill is limited by the excess energy generated in the premises in a year less than or equal to zero or the capacity of the roof top. The excess energy generated in the premises in a year is

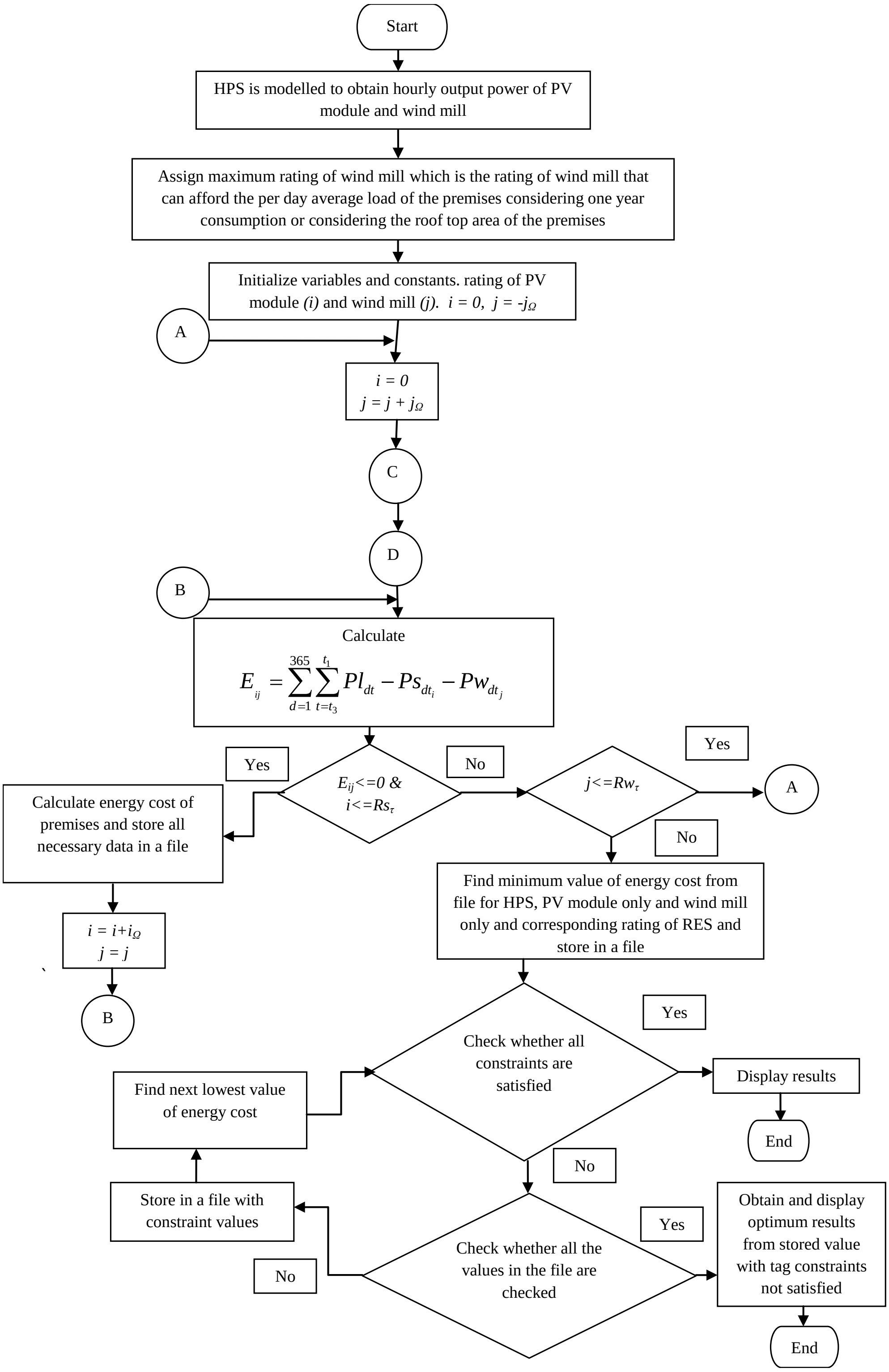



Fig. 3 Optimization flow chart 1

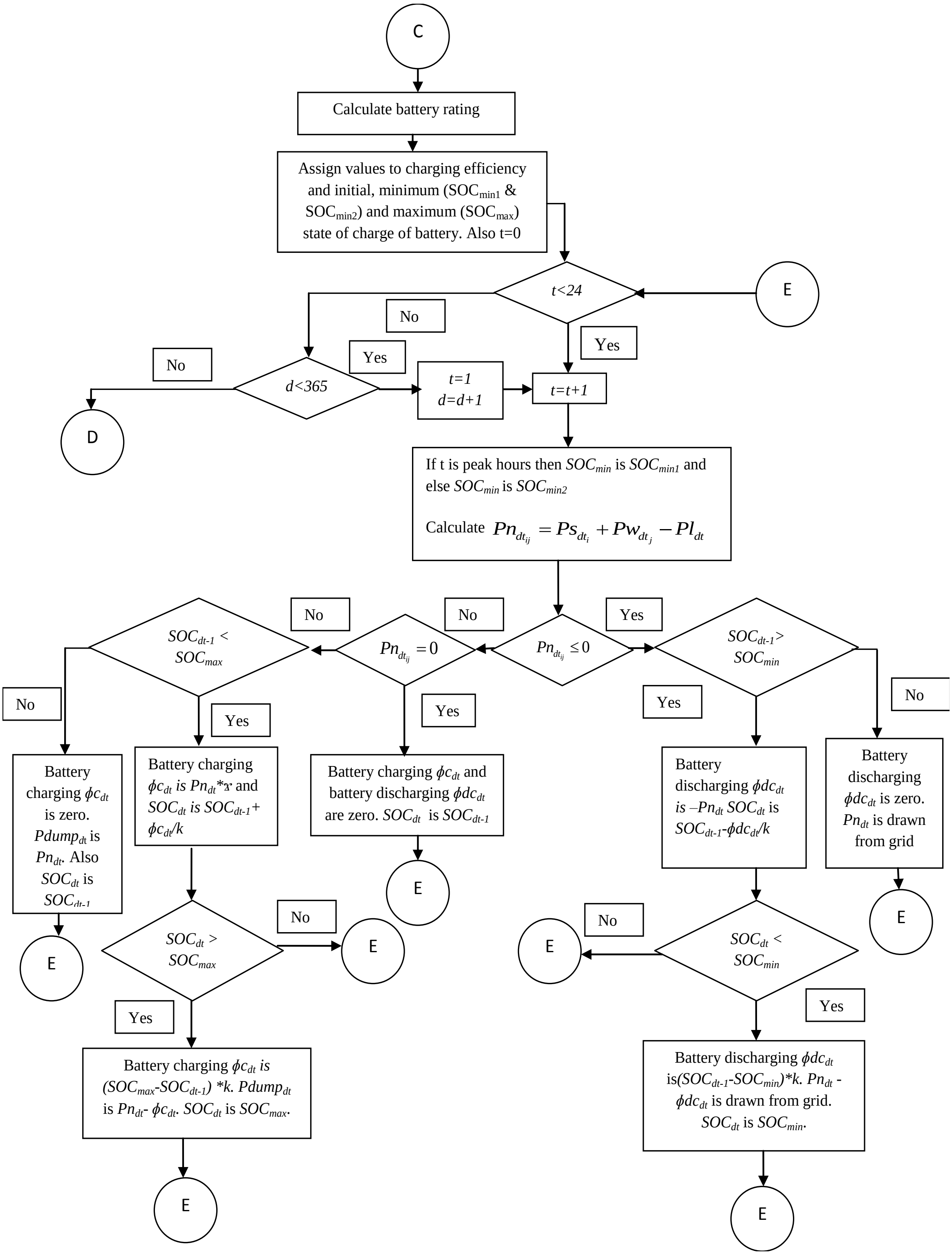



Fig. 4 Optimization flow chart 2

$$E_{ij} = \sum_{d=1}^{365}\sum_{t=1}^{24} Pl_{dt} - Ps_{dt_i} - Pw_{dt_j} \quad (32)$$

The technical modelling of storage battery is done by determining its SOC in each hour. Hourly SOC of the battery is determined considering SOC of the battery in the last hour and excess energy generated by the HPS in present hour. The minimum SOC of the battery is fixed in two levels in peak and other time of the day to utilise maximum stored energy at peak hours. The methods for determining hourly SOC, charge and discharge of the battery are detailed in Fig. 4.

There is loss in storage batteries. This is taken into account in battery modelling as charging efficiency (ϒ). The hourly excess energy generated is determined as

$$Pn_{dt} = Ps_{dt_i} + Pw_{dt_j} - Pl_{dt} \quad (33)$$

If $Pn_{dt}$ is less than zero, there is no excess generation in the premises. Then $-Pn_{dt}$ is the shortage of energy in the premises. If SOC of the battery is higher than $SOC_{min}$ the shortage of energy is met from the battery. The battery discharge is $\phi dc_{dt}$ and $SOC_{dt}$ is $SOC_{dt\text{-}1} - \phi dc_{dt} /k$. If $SOC_{dt}$ is less than $SOC_{min}$ the battery can discharge only $(SOC_{dt\text{-}1}\text{-}SOC_{min})*k$. $Pn_{dt}$- $\phi dc_{dt}$ is drawn from grid and $SOC_{dt}$ is $SOC_{min}$. If $SOC_{dt\text{-}1}$ is less than or equal to $SOC_{min}$, $\phi dc_{dt}$ is zero and $Pn_{dt}$ is drawn from grid (Abd 2011).

If $Pn_{dt}$ is greater than zero, the excess energy produced in the premises is utilised to charge battery if the battery in not fully charged. Battery charging energy $\phi c_{dt}$ is $Pn_{dt}$*ϒ and the $SOC_{dt}$ is $SOC_{dt\text{-}1}+ \phi c_{dt}/k$. If $SOC_{dt}$ is greater than $SOC_{\max}$, the battery charging energy $\phi c_{dt}$ is $(SOC_{\max}\text{-}SOC_{dt\text{-}1})*k$. The dump load $Pdump_{dt}$ is $Pn_{dt}$- $\phi c_{dt}$ and $SOC_{dt}$ is $SOC_{\max}$. If $SOC_{dt\text{-}1}$ is equal to $SOC_{\max}$, the dump load $Pdump_{dt}$ is $Pn_{dt}$ and $\phi c_{dt}$ is zero. If $Pn_{dt}$ is equal to zero, $\phi dc_{dt}$ and $\phi c_{dt}$ are zero and $SOC_{dt}$ is $SOC_{dt\text{-}1}$. In this way each hour SOC is determined with dump load and peak energy contribution from storage battery (Abd 2011).

The values of constants used for the simulation are summarised in Table 1.

Table 1 Values for simulation

| Sl. No. | Parameters | Unit | Values |
|---|---|---|---|
| 1 | $T_{cp}$ | %/$^o$C | 0.4 |
| 2 | $Sw_r$ | m/s | 11 |
| 3 | $Sw_{ci}$ | m/s | 3 |
| 4 | $Sw_{co}$ | m/s | 35 |
| 5 | $q$ | % | 8 |
| 6 | $h$ | % | 7 |
| 7 | $g$ | % | 10 |
| 8 | $\lambda$ | % | 50 |
| 9 | $\omega$ | years | 25 |
| 10 | $r_m$ | $ | 0.28 |
| 11 | $r_o$ | $ | 0.17 |
| 12 | $r_n$ | $ | 0.22 |
| 13 | $t_1$ | hr | 18 |
| 14 | $t_2$ | hr | 22 |
| 15 | $t_3$ | hr | 06 |
| 16 | $\delta$ | $ | 5 |
| 17 | ϒ | % | 80 |

Table 2 Details of premises

| Particulars | Unit | Load1 | Load2 |
|---|---|---|---|
| Demand of the premises | kWh | 589810.24 | 196603.40 |
| Conventional energy cost | $ in Thousands | 181.21 | 60.90 |

Table 3 Ratings of optimal systems

| Particulars | Unit | Load1 | | | Load2 | | |
|---|---|---|---|---|---|---|---|
| | | HPS | PV | Wm | HPS | PV | Wm |
| Location1 | | | | | | | |
| Optimal rating | kW | PV-2.35<br>*Wm-3.00<br>**B-16.00<br>***IC-5.00 | PV-6.45<br>B-16.00<br>IC-6.00 | Wm-5.00<br>B-22.00<br>IC-5.00 | PV-1.1<br>Wm-1.00<br>B-6.00<br>IC-2.00 | PV-2.15<br>B-5.00<br>IC-2.00 | Wm-2.00<br>B-9.00<br>IC-2.00 |
| Location2 | | | | | | | |
| Optimal rating | kW | PV-2.30<br>Wm-3.00<br>B-15.00<br>IC-5.00 | PV-6.45<br>B-16.00<br>IC-6.00 | Wm-5.00<br>B-20.00<br>IC-5.00 | PV-1.20<br>Wm-1.00<br>B-6.00<br>IC-2.00 | PV-2.15<br>B-5.00<br>IC-2.00 | Wm-2.00<br>B-9.00<br>IC-2.00 |
| Location3 | | | | | | | |
| Optimal rating | kW | PV-6.50<br>Wm-1.00<br>B-16.00<br>IC-8.00 | PV-6.80<br>B-16.00<br>IC-7.00 | Wm-9.00<br>B-3.00<br>IC-9.00 | PV-2.10<br>Wm-1.00<br>B-5.00<br>IC-3.00 | PV-2.25<br>B-5.00<br>IC-2.00 | Wm-9.00<br>B-5.00<br>IC-9.00 |

*Wm=Wind mill **B=Battery ***IC= Hybrid grid inverter with MPPT controllers

## 6. Case study

In this work one year hourly wind speed, irradiation and cell temperature of PV module are taken as the inputs to the model. The location selected for case study is Theni (location1) and Kayathar (location2) in Tamilnadu, India and Thrissur (location3), Kerala, India. Hourly wind speed and solar irradiation were obtained from National Renewable Energy Laboratory, USA and Centre for Wind Energy Technology, India. The temperature of PV cell was determined from the temperature data from climate data site. The hourly demand of the premises for one year was also obtained from Time of day (TOD) meter of the premises for analysis. The details of the premises selected for study are displayed in Table 2. The two loads are applied in three locations for analysing the algorithm.

The optimal HPS and optimal individual RES are determined for both loads in three locations and the results are displayed in Table 3. The average SOC, dump load, RE generation and energy peak reduction are found out. The optimal energy cost and optimal energy cost with PEC of all configurations are determined to compare it with conventional energy cost of the premises. These are explained in the next section.

## 7. Results and discussion

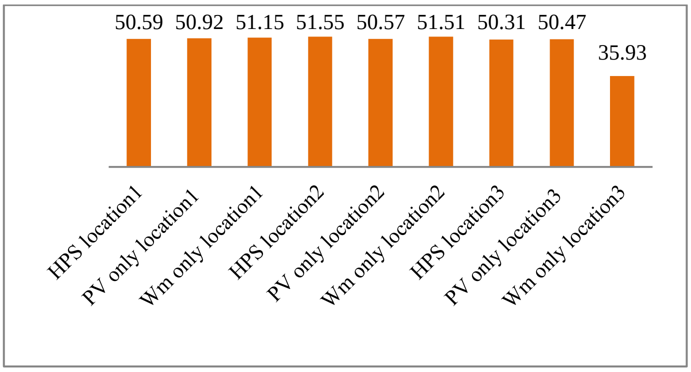



Fig. 5 State of charge of the premises for load 1 in three locations

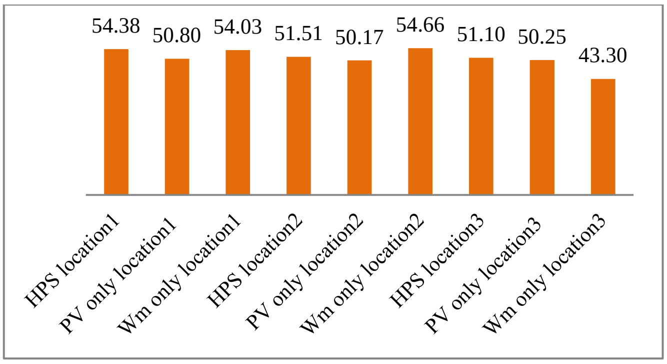



Fig. 6 State of charge of the premises for load 2 in three locations

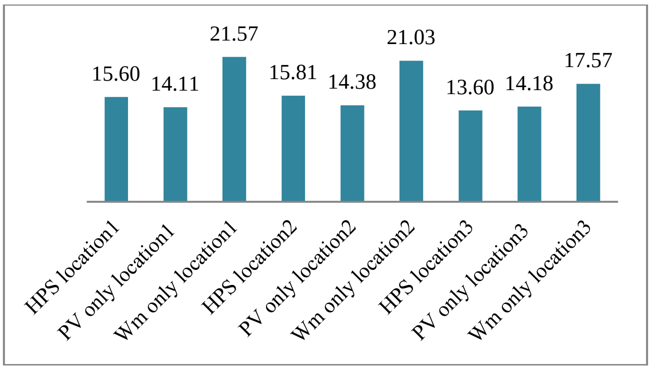



Fig. 7 Dump load of the premises for load 1 in three locations

The life cycle of the battery depends on the average SOC of the battery. Increase in average SOC of the battery ensures increase in the life span of the battery. The hourly SOC of each day is different due to the fluctuating nature of renewable energy and load. It is to be ensured that the average SOC of battery is higher than 50%. The percentage average SOC of the storage battery for load 1 and 2 in three locations for the optimal systems is shown in Fig. 5 and Fig. 6 respectively. The results show that except wind mill only optimal system at location 3 has average SOC more than 50%. The wind mill only optimal system at location 3 does not satisfy the Eq. (22).

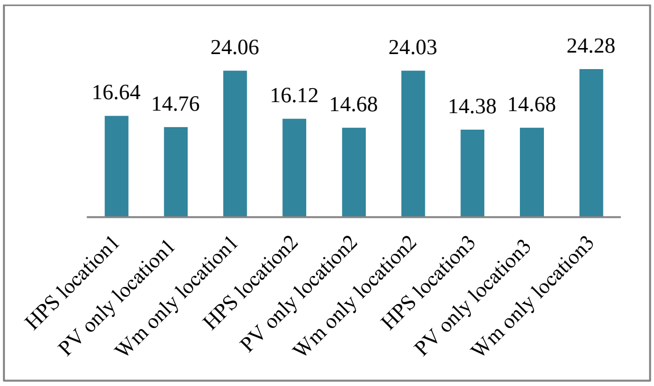



Fig. 8 Dump load of the premises for load 2 in three locations

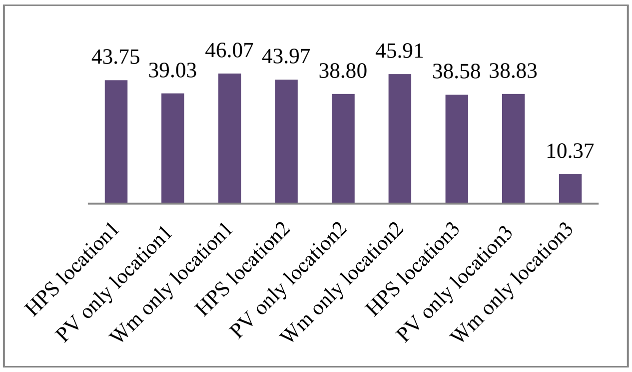



Fig. 9 Renewable energy consumption for load 1 in three locations

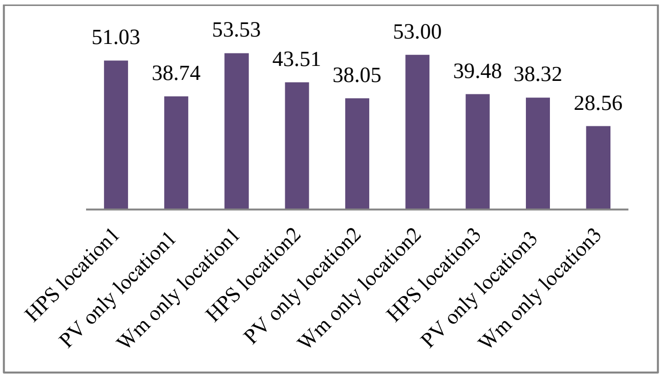
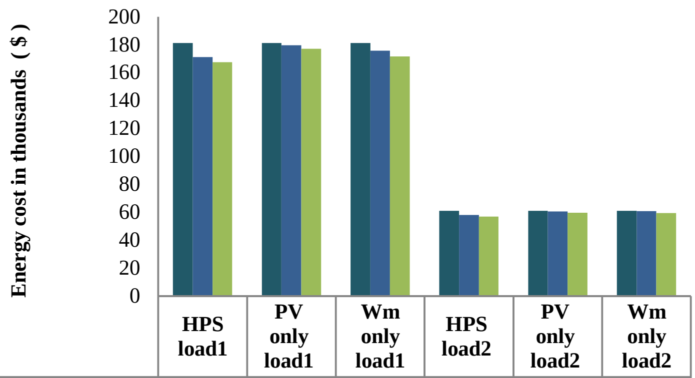



Fig. 10 Renewable energy consumption for load 2 in three locations

Fig. 7 and Fig. 8 show dump loads in percentage with respect to RE generated for load 1 and 2 respectively in three locations for combined and individual RES optimal systems. The results show that the dump load is less than 25% for all optimal systems. Wind mill only optimal system has high dump load compared to HPS and PV only optimal system in three locations for both loads. SO HPS or PV only systems are more preferable in terms of dump load reduction.

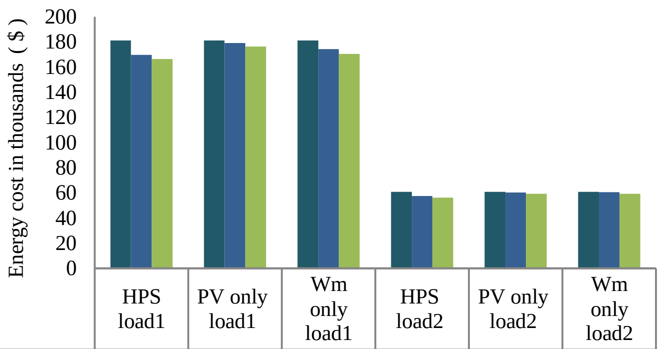
The RE generated in the premises cannot be fully utilised in this system. A part of RE generated has been lost in this system as dump load. So the RE consumption of premises is taken into account in the analysis. The percentage of RE consumption with respect to the demand of the premises in three locations for combined and individual RES optimal systems with load 1 and 2 are displayed in Fig. 9 and Fig. 10 respectively. The RE consumption of the premises is high for wind mill only and HPS optimal configuration for both loads in location 1 and 2. In location 3, optimal HPS and PV only optimal configuration have higher RE consumption for both loads compared to wind mill only optimal system.

The life time energy cost of the optimal system is determined in this algorithm to compare it with conventional energy cost. The life time energy cost for optimal system for all configurations is compared with conventional energy cost in Fig. 11, Fig. 12 and Fig. 13 in location 1, 2 and 3 respectively for both loads. The optimal energy cost is less than conventional energy cost for all configurations and demand profiles for location 1 and location 2. But in location 3 the optimal




| | HPS load1 | PV only load1 | Wm only load1 | HPS load2 | PV only load2 | Wm only load2 |
|---|---|---|---|---|---|---|
| **Conventional energy cost** | **181.21** | **181.21** | **181.21** | **60.90** | **60.90** | **60.90** |
| **Optimal energy cost** | **170.98** | **179.66** | **175.62** | **57.99** | **60.54** | **60.83** |
| **Optimal energy cost with PEC** | **167.44** | **176.96** | **171.64** | **56.82** | **59.68** | **59.35** |

Fig. 11 Comparison of optimal energy cost with or without PEC and conventional energy cost for location 1




| | HPS load1 | PV only load1 | Wm only load1 | HPS load2 | PV only load2 | Wm only load2 |
|---|---|---|---|---|---|---|
| Conventional energy cost | 181.21 | 181.21 | 181.21 | 60.90 | 60.90 | 60.90 |
| Optimal energy cost | 169.54 | 179.03 | 174.15 | 57.39 | 60.27 | 60.54 |
| Optimal energy cost with PEC | 166.23 | 176.22 | 170.48 | 56.13 | 59.36 | 59.16 |

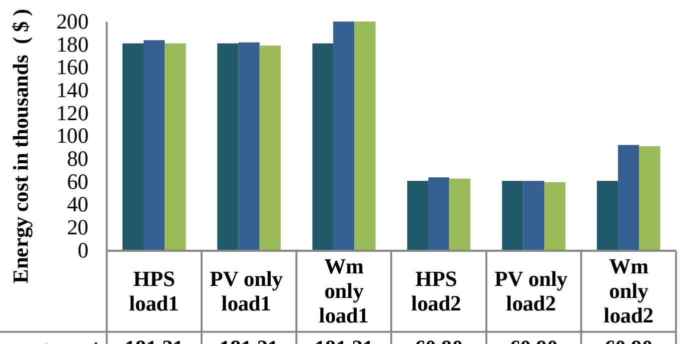
Fig. 12 Comparison of optimal energy cost with or without PEC and conventional energy cost for location 2

energy cost is less than conventional energy cost only for PV only optimal system for load 2.

The PEC can be taken into account in the determination of optimal energy cost if the utility is providing this considering peak energy consumption reduction of the premises. The optimal energy cost with PEC for all configurations are shown in Fig. 11, Fig. 12 and Fig. 13. Providing PEC reduces the optimal energy cost to less than conventional energy cost for load 1 at location 3 for PV only optimal system.

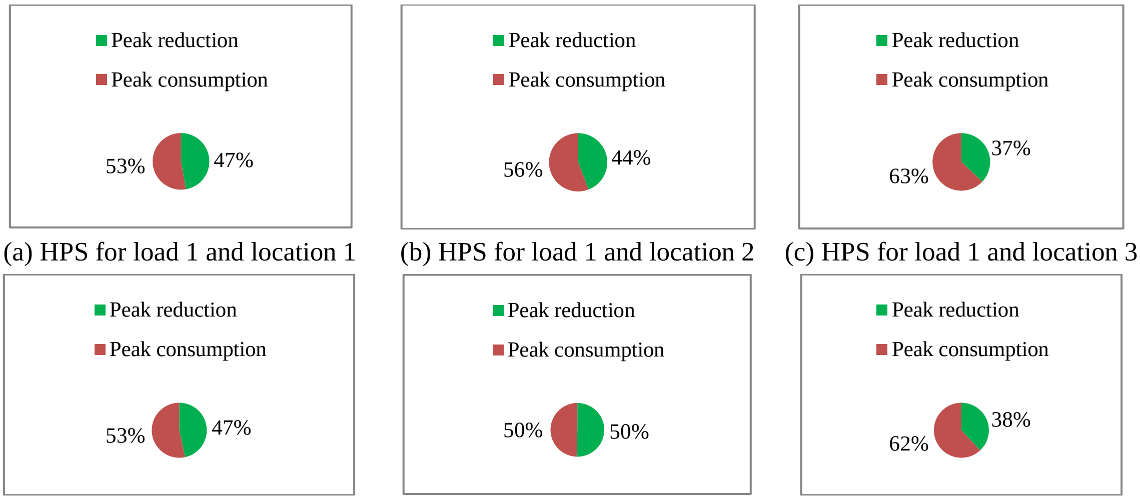
Comparison of combined and individual RES optimal systems is also carried out in terms of life time energy cost to determine most financially feasible system. The optimal energy cost is less for HPS for both demand profiles for locations 1 and 2 as seen in Fig. 11 and Fig. 12. The optimal energy cost with PEC is also less for the same system for both loads in location 1 and 2. Then optimal system for location 1 for load 1 is 2.35 kW PV module, 3 kW wind mill, 16 kW storage battery and 5 kW hybrid inverter with MPPT controllers. 1.1 kW PV module, 1 kW wind mill, 6 kW storage battery and 2 kW hybrid inverter with MPPT controllers are the optimal system in the same location for load 2. The optimal life time energy costs for load 1 and load 2 in location 1 are $171 thousands and $58 thousands respectively for location 1 which are less than life span conventional energy costs of $181 thousands and $61 thousands respectively. If PEC is provided by the utility as described in problem formulation, the optimal energy cost is $167 thousands and $57 thousands for location 1 with load 1 and 2 respectively. In location 2, the optimal system is 2.3 kW PV module 3 kW wind mill, 15 kW battery and 5 kW inverter with MPPT controllers and for load 1 and 1.2 kW PV module, 1 kW wind mill, 6 kW storage battery and 2 kW inverter with MPPT controller are the components of optimal HPS for load 2. The optimal life time energy costs are $170 thousands and $57 thousands for load 1 and 2 respectively for location 2 which are also less than respective conventional energy costs. The optimal energy cost with PEC is $166 thousands and $56 thousands for load 1 and 2 respectively for location 2.

In location 3, the optimal energy costs for load 1 and 2 are less for PV module only optimal system. The optimal energy cost is higher than conventional energy cost for PV only optimal system for load 2. The energy cost for load 2 at location 3 is less than conventional energy cost if PEC is provided. So PEC is to be provided by the utility to make the RES financially feasible in some locations and loads in the case of distributed RES connected to unidirectional grid. The




| | HPS load1 | PV only load1 | Wm only load1 | HPS load2 | PV only load2 | Wm only load2 |
|---|---|---|---|---|---|---|
| Conventional energy cost | 181.21 | 181.21 | 181.21 | 60.90 | 60.90 | 60.90 |
| Optimal energy cost | 184.02 | 181.87 | 208.56 | 63.92 | 60.85 | 92.25 |
| Optimal energy cost with PEC | 181.24 | 179.11 | 207.55 | 62.96 | 59.95 | 91.34 |

Fig. 13 Comparison of optimal energy cost with conventional energy cost for location 3




(a) HPS for load 1 and location 1 (b) HPS for load 1 and location 2 (c) HPS for load 1 and location 3

(d) HPS for load 2 and location 1 (e) HPS for load 2 and location 2 (f) HPS for load 2 and location 3

Fig. 14 Peak demand of the premises for optimal systems in six configurations

optimal system for location 3 and load 1 is 6.8 kW PV module, 16 kW storage battery and 7 kW inverter with MPPT controller. 2.25 kW PV module, 5 kW storage battery and 2 kW inverter with MPPT controllers are the optimal system for load 2 at location 3. The optimal energy costs are $182 thousands and $61 thousands for load 1 and 2 respectively. The optimal energy costs with PEC are $179 thousands and $60 thousands for load 1 and 2 respectively.

HPS is recommended for location 1 and 2 and PV module is suitable for location 3 with optimal configurations as above. The algorithm was applied to find out the peak demand reduction of the premises. Peak demand reduction and peak consumption from the utility of the optimal systems in three locations for both loads are displayed in Fig. 14. More than 37% reduction in peak demand can be achieved for all optimal systems. The investment cost of utilities for the conventional generators to meet the peak demand can be saved if peak load reduction is achieved by promoting these systems. Peak demand reduction also makes the grid healthier.

## 8. Conclusions

In many countries the grid is not capable to accept energy from distributed RE generation due to the shortage of grid capacity and the absence of advanced equipments for energy security and protection. So only way to promote distributed RE generation is using HPS connected to unidirectional grid. In this work model and algorithm of distributed RES connected to unidirectional grid are developed to determine optimal combination for least energy cost satisfying the constraints in a desired site condition and demand profile. The developed algorithm is applied at three different locations and in each location two demand profiles are considered. The results show that the RE consumption is more than 38% of the demand of the premises for the optimal systems. PEC is necessary for the implementation of financially feasible system in some locations. The peak demand can be reduced more than 37% with average SOC greater than 50%. The dump load can be limited to 18% for the optimal systems. It is established that the developed model and algorithm is applied to determine optimal system and to analyse technical, economical and environmental factors of unidirectional grid tied system.

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## Nomenclature

### *Symbols*

| | |
|---|---|
| $\beta$ | Allowable dump load in % |
| $\partial$ | Connected load in the premise in kW |
| $\delta$ | Fixed charge for grid energy for the connected load of 1kW in $ |
| $\omega$ | Life span of project in years |
| $\varepsilon$ | Subsidy on the initial capital investment of HPS in % |
| $\varphi$ | Per unit peak energy credit in $ |
| $\lambda$ | Desired value of average SOC in % |
| Ϫ | Efficiency of storage battery in % |
| $\eta_1$ | Efficiency of inverter with MPPT controller in % |
| $\eta_2$ | Efficiency of component of HPS due to ageing in % |
| $\chi_b$ | Net investment cost of 1kW battery for the life span of project in $ |
| $\omega_\tau$ | Life span of wind mill in years at $\tau^{th}$ replacement |
| $\gamma_{dt}$ | Global horizontal irradiance on day *d* and at time *t* in kW/m$^2$ |
| $\Psi_{ij}$ | Rating of inverter with MPPT controller for PV module rating *i* and wind mill rating *j* in kW |
| $\phi dc_{dt_{ij}}$ | Discharge of battery on day *d* and time *t* for PV module rating *i* and wind mill rating *j* in kWh |

| | |
|---|---|
| $\phi dc_{dt}$ | Discharge of battery on day *d* and time *t* in kWh |
| $\phi c_{dt}$ | Charge of battery on day *d* and time *t* in kWh |
| $d$ | Day of the year |
| $g$ | Escalation rate in% |
| $h$ | Interest rate evolution in % |
| $i$ | Rating of PV module in kW |
| $i_{\Omega}$ | Increment of PV module rating for simulation |
| $j$ | Rating of wind mill in kW |
| $j_{\Omega}$ | Increment of wind mill rating for simulation |
| $k_{ij}$ | Rating of battery for PV module rating *i* and wind mill rating *j* in kW |
| $q$ | General inflation rate in % |
| $r_x$ | Per unit grid peak energy cost in $ |
| $r_y$ | Per unit grid off peak energy cost in $ |
| $r_z$ | Per unit grid normal energy cost in $ |
| $t$ | Time in a day |
| $u$ | Renewable energy obligation in % |
| $-ve$ | Negative |
| $A_{1b_{ij}}$ | Capital investment of battery with CRF of rating $k_{ij}$ in $ |
| $A_{2b_{ij}}$ | Life time O&M cost of storage battery of rating $k_{ij}$ in $ |
| $A_{3b_{ij}}$ | Life time insurance charge of storage battery of rating $k_{ij}$ in $ |
| $A_{4b_{ij}}$ | Salvage value of storage battery of rating $k_{ij}$ in $ |
| $A_{5b_{ij}}$ | Replacement cost of storage battery of rating $k_{ij}$ in $ |
| $A_{6b_{ij}}$ | Initial capital investment of storage battery of rating $k_{ij}$ in $ |
| $A_{1s_i}$ | Capital investment of PV module with CRF of rating *i* in $ |
| $A_{2s_i}$ | Life time O&M cost of PV module of rating *i* in $ |
| $A_{3s_i}$ | Life time insurance charge of PV module of rating *i* in $ |
| $A_{4s_i}$ | Salvage value of PV module of rating *i* in $ |
| $A_{6s_i}$ | Initial capital investment of PV module of rating $i$ in $ |
| $A_{1v_{ij}}$ | Capital investment of inverter with MPPT controller with CRF of rating $\Psi_{ij}$ in $ |
| $A_{2v_{ij}}$ | Life time O&M cost of inverter with MPPT controller of rating $\Psi_{ij}$ in $ |
| $A_{3v_{ij}}$ | Life time insurance charge of inverter with MPPT controller of rating $\Psi_{ij}$ in $ |
| $A_{4v_{ij}}$ | Salvage value of inverter with MPPT controller of rating $\Psi_{ij}$ in $ |
| $A_{5v_{ij}}$ | Replacement cost of inverter with MPPT controller of rating $\Psi_{ij}$ in $ |

| | |
|---|---|
| $A_{6v_{ij}}$ | Initial capital investment of inverter with MPPT controller of rating $\Psi_{ij}$ in $ |
| $A_{1w_j}$ | Capital investment of wind mill with CRF of *j* rating in $ |
| $A_{2w_j}$ | Life time O&M cost of wind mill of *j* rating in $ |
| $A_{3w_j}$ | Life time insurance charge of wind mill of *j* rating in $ |
| $A_{4w_j}$ | Salvage value of wind mill of *j* rating in $ |
| $A_{5w_j}$ | Replacement cost of wind mill of *j* rating in $ |
| $A_{6w_j}$ | Initial capital investment of wind mill of rating *j* in $ |
| $C_f$ | Fixed charge for the life span of the project in $ |
| $C_{eu}$ | Conventional energy cost for the life span of the project in $ |
| $C_{\mu_{ij}}$ | Green energy credit in $ |
| $C_{\rho_{ij}}$ | Peak energy credit in $ |
| $C_{b_{ij}}$ | Net investment of storage battery for the life span of project for $k_{ij}$ rating in $ |
| $C_{e_{ij}}$ | Cost of energy from grid for the life span of project with PV module rating *i* and wind mill rating *j* in $ |
| $C_{s_i}$ | Net investment of PV module for the life span of project for PV module rating *i* in $ |
| $C_{v_{ij}}$ | Net investment of inverter with MPPT controller for the life span of project for battery rating $\Psi_{ij}$ in $ |
| $C_{w_j}$ | Net investment of wind mill for the life span of project and wind mill rating *j* in $ |
| $C_{e\Delta_{ij}}$ | Net energy cost of premises with PV module rating *i* and wind mill rating *j* in $ |
| $C_{ex_{ij}}$ | Life span peak grid energy cost of premises with PV module rating *i* and wind mill rating *j* in $ |
| $C_{ey_{ij}}$ | Life span off peak grid energy cost of premises with PV module rating *i* and wind mill rating *j* in $ |
| $C_{ez_{ij}}$ | Life span normal grid energy cost of premises with PV module rating *i* and wind mill rating *j* in $ |
| $E_{ij}$ | Excess energy generated is a year in the premises for PV module rating *i* and wind mill rating *j* in kWh |
| $El$ | Demand of the premises in kWh |
| $E_{mr}$ | Reduction of peak load in kWh |
| $E_{ge_{ij}}$ | Green energy generated for PV module rating *i* and wind mill rating *j* in kWh |
| $E_{dump_{ij}}$ | Dump load of the premises for PV module rating *i* and wind mill rating *j* in kWh |
| *INR* | Indian rupees |
| $Ps_r$ | Rated power output of PV module in kW |
| $Pw_r$ | Rated output power of a wind mill in kW |

| | |
|---|---|
| $Pl_{dt}$ | Load of the premises on day *d* and time *t* in kW |
| $Ps_{dt_i}$ | Output power of PV module of rating *i* on day *d* and time *t* in kW |
| $Pw_{dt_j}$ | Output power of wind mill of rating *j* on day *d* and time *t* in kW |
| $Pn_{dt_{ij}}$ | Excess or shortage of energy of the premises on day *d* and time *t* for PV module rating *i* and wind mill rating *j* in kW |
| $Rs_\sigma$ | Minimum rating of PV modules in kW |
| $Rs_\tau$ | Maximum rating of PV modules in kW |
| $Rw_\sigma$ | Minimum rating of wind mill in kW |
| $Rw_\tau$ | Maximum rating of wind mill in kW |
| $Sw_r$ | Rated wind speed in m/s |
| $Sw_{ci}$ | Cut in wind speed in m/s |
| $Sw_{co}$ | Cut out wind speed in m/s |
| $Sw_{dt}$ | Wind speed on day *d* and time *t* in m/s |
| $SOC_{a_{ij}}$ | Average SOC of the storage battery for PV module rating *i* and wind mill rating *j* in % |
| $SOC_{\max}$ | Maximum SOC of the storage battery in % |
| $SOC_{\min 1}$ | Minimum SOC of the storage battery at peak hours in % |
| $SOC_{\min 2}$ | Minimum SOC of the storage battery at other times of the day in % |
| $SOC_{dt_{ij}}$ | SOC of the battery at time t and on day d for PV module rating *i* and wind mill rating *j* |
| $T_{cp}$ | Temperature coefficient of PV module in %/$^o$C |
| $T_{dt}$ | Temperature of the PV cell on day *d* and time *t* in $^o$C |