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# Optimal Planning of Hybrid Energy Conversion Systems for Annual Energy Cost Minimization in Indian Residential Buildings

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**Abstract**

The increasing interest in renewables has encouraged power system planners to include the concept of hybrid energy systems in modern power industry. Besides, the modern power consumers are becoming more concerned about their energy bills which has led to the concept of hybrid energy management systems (HEMSs) for buildings to monitor, control and optimally manage energy consumptions without any waste. In this study, an optimal planning framework is proposed to determine optimal capacities and sharing of hybrid energy conversion systems (HECS) such as wind turbine, solar photovoltaic, battery energy storage and the utility grid. The objective is to maximize the net present value of the project/system which includes the cost of annual investment, operation and maintenance costs of HEMS expected to have incurred in the planning period. All the costs and parameters are considered in the Indian context, and Genetic Algorithm (GA) is adopted to solve this proposed planning framework. The simulation results obtained are compared with same obtained for conventional houses in India. The comparison shows that the proposed framework effectively reduces the electricity bills while improving its reliability.



*Keywords:* Hybrid energy conversion systems, renewables; smart homes; genetic algorithm

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## 1. Introduction

The recent advancement in energy conversion, information, and communication technologies have led to the concept of smart homes. These technologies help residents to monitor, control and manage energy consumption and house environment while enhancing comfort, convenience, security, and entertainment. The Home Energy Management System (HEMS) plays crucial role to attain goals of smart energy homes in most of the countries [1].

**Nomenclature**

| | |
|---|---|
| $C_{Inst}^{PV}$ / $C_{OM}^{PV}$ | Investment and O&M cost of solar photovoltaic system |
| $C_{Inst}^{WT}$ / $C_{OM}^{WT}$ | Investment and O&M cost of solar photovoltaic system |
| $C_{Inst}^{BESS}$ / $C_{OM}^{BESS}$ | Investment and O&M cost of solar photovoltaic system |
| $d$ | Discount rate |
| $h$ | Hour |
| $K_E$ | Grid energy price |
| $n_{B,y}$ | Number of BESS units deployed in year $y$ |
| $y$ | Year |
| $\varphi$ | Daily to annual conversion factor |
| $T_p$ | Planning horizon |
| $P_r^{WT}$ / $P_r^{PV}$ / $P_r^{BESS}$ | Rated capacity of WT/PV/BESS |
| $P_G^{WT}$ / $P_G^{PV}$ / $P_{G/D}^{BESS}$ | Power generation from wind system, solar PV system and BESS |
| $P_D^H$ / $P_D^S$ | Load demand of house in a given hour and sanctioned load demand |

Like in other countries, the smart homes market is fast growing in the Indian context. Initially, it is progressing in emerging areas such as lighting, gas outflow & fire detection, entertainment and energy efficiency systems [2]. According to this report, the high-income families with better economic condition having an outlay of more than 50,000,000 Indian National Rupee (₹) want to have smart homes with primary motivations of security, suitability, and energy efficiency. However, it may be observed that the majority of Indian population cannot afford costly automation for their homes. Only middle-income families with an annual income around 1 million ₹can accept energy efficient solutions to reduce their monthly electricity bills. The Indian utilities are now allowing net-metering solutions for their customers to promote the integration of solar roof-tops to the grid [3]. In these promotions, the governments have exempted the payment of electricity duty payable by a person on the consumption of energy generated by the customer.

In literature, some smart home frameworks have been suggested and investigated to achieve primary objectives of owners across the globe. In [4], a comprehensive and case studies on smart home policies currently adopted in Singapore is presented to save energy. A HEMS framework is presented in [5] for leveling/balancing household consumption by using Battery Energy Storage System (BESS). A multi-agent based HEMS is proposed in [6] to improve the efficiency and to optimize the energy utilization of smart homes. The smart appliances are considered as the agents, and then an optimization technique has been adopted in decision-making process. In [7], the pedagogical based smart home test-bed is proposed for graduates to understand smart grid aspects, like peak load shaving, demand response, real-time pricing, wireless communication, and sensors, etc. An intelligent infrastructure is developed in [8] for contemporary homes to provide security based on audio visuals, smart and secure handling of selected appliances, and HEMS comprised of wind and solar energy sources. In [9], three-fold optimization framework is proposed for smart interface control, energy management, and efficient operating time control of electronic appliances. A HEMS is proposed in [10] for smart homes having different load profiles with photovoltaic generation, energy storage, and DC loads. Basit *et al*. [11], proposes an autonomous energy management-based cost reduction solution for peak load times using HEMS. It may be observed that the most of literature work is focused on the optimal operation of energy conversion resources. However, the optimal planning of Hybrid Energy Conversion Systems (HECSs) for smart home applications is not yet explored much.

In this study, an optimization framework is developed for optimal planning of HECSs, in smart homes, in the Indian context. The HECSs considered are wind turbine (WT) and photovoltaics (PVs) along with BESSs. The objective is to maximize the Net Present Value (NPV) of the investment which includes the annual cost of grid energy transactions, investment, and operation & maintenance, etc. The effectiveness of the proposed model is implemented for a house with peak load demand of 5 kW in the located in India. A comparative cost analysis is carried-out with conventional house bills to demonstrate the economic feasibility of proposed model. The comparison shows that the proposed model generates more economical and reliable solutions for smart homes in Indian middle-class family groups.

## 2. Proposed Planning Framework for HECS

In this section, the proposed optimization framework is presented for optimal planning of HECS for smart home applications in the Indian context. The NPV is considered as the objective function for optimal planning of WTs, PVs, and BESSs. The NPV calculation converts all future costs into their corresponding present values. The objective function considered for this planning is expressed as follows:

$$NPV = PVC^{b}_{Outflows} - PVC^{a}_{Outflows} \tag{1}$$

$$PVC^{b}_{Outflows} = \sum_{y=1}^{T_P} \frac{\varphi}{(1+d)^y} \sum_{h=1}^{24} K_E(h) P^{b}_{Grid}(h) \tag{2}$$

$$PVC^{a}_{Outflows} = P_r^{WT} C_{Inst}^{WT} + P_r^{PV} C_{Inst}^{PV} + n_{B,1} C_{Inst}^{BESS} + \sum_{y=1}^{T_P} \frac{1}{(1+d)^y} \left[ \begin{pmatrix} P_r^{WT} C_{OM}^{WT} + P_r^{PV} C_{OM}^{PV} + \\ (n_{B,1} + n_{B,y}) C_{OM}^{BESS} + n_{B,y} C_{Inst}^{BESS} \end{pmatrix} + \varphi \sum_{h=1}^{24} K_E(h) P^{a}_{Grid} \right] \tag{3}$$

*subject to*

$$NPV \geq 0 \tag{4}$$

$$P_G^{WT}(h) + P_G^{PV}(h) \leq 0.8 P_D^S \qquad \forall\ h \tag{6}$$

$$P^{b}_{Grid}(h) = P_D^H(h) \qquad \forall\ h \tag{7}$$

$$P^{a}_{Grid}(h) = P_D^H(h) - P_G^{WT}(h) - P_G^{PV}(h) \pm P_{C/D}^{BESS}(h) \qquad \forall\ h \tag{8}$$

Equations (4)–(8) are representing NPV, power balance, grid power transaction before and after HECS installation respectively. In proposed optimization framework, the NPV is maximized subjected to the constraints expressed in (4)–(8). The size of BESS is determined by balancing (8) for minimum daily grid transaction whereas the capacity of PV and WT are determined by an optimization method. Equation (6) is adapted to limit the HECS penetration as per the regulation provided by Indian utilities which says that the amount of DG penetration should not exceed the 80% of the sanctioned load of the house, $P_D^S$ [12] or sanctioned load would have to be increased.

## 3. Wind, Solar PV and BESS modeling adopted in Proposed Model

The wind speed and solar irradiation are highly intermittent and uncertain by nature. Therefore, appropriate hourly modeling of wind and solar power generation has to be done and is adapted from [13, 14] in this study. Besides, the BESS is very different from DGs due to its changing behavior as generator or load. Further, the availability of state of charge (SOC) of BESS is also an issue in HEMSs. Therefore, in optimal energy management considering BESS, it may be an essential to maintain SOC level and utilized whenever needed. In this study, it has been recommended that BESS is charged when total power generation from renewable units is found be more than the load demand, generally observed during light load hours. The modeling and constraints of BESS are adopted from [13,14].

## 4. Case Studies

In order to demonstrate the effectiveness of proposed HECS model for smart homes, it is implemented on a middle-income group Indian house with peak load demand of 5 $kW_p$. In solar PV system, 60-cell multi-crystalline solar PV modules, i.e., TP250 by TATA power are adopted [15]. For BESS, discover tubular flooded RE series batteries are adopted due to superior deep cycling performance and reliability for demanding commercial, industrial and residential applications [16, 17]. The details of solar PV system, wind system and BESS used in the proposed model are presented in Table 1. The multiplying factors used for solar power generation, wind power generation and load demand are adopted from [13, 14]. In order to solve the proposed planning framework presented in Section 2, a powerful nature inspired meta-heuristic optimization technique, i.e.; genetic algorithm is adopted due to its ability to solve the complex engineering optimization problems. It is inspired from the process of natural selection. An improved variant of GA proposed in [18] is adopted except heuristic spark. To show the effectiveness of the proposed model, the simulation results obtained are compared with the base case in which no hybrid energy system was present. The comparison of various parameters/factors is presented in Table 2. The simulation is carried out for $T_p$ = 5 yrs period as the BESS will be replaced after this. The table shows the optimal sizing of different resources like solar PV system, WT system, and BESS. It also includes the cost of initial investment, the present value of the O & M cost charged in this period.

Table 1. Technical and economical specification of hybrid energy conversion system

| Parameter(s)/System(s) | Value | Parameter(s)/System(s) | Value |
|---|---|---|---|
| Capital cost of solar PV system, $C_{Inst}^{PV}$ [16] | 53000₹/kW | O & M cost of 3kWh BESS unit, $C_{OM}^{BESS}$ [16,19] | 700₹ /year |
| O & M cost of solar PV system, $C_{OM}^{PV}$ [16] | 700₹ /kWDC/yr | Discount Rate ($d$) [13] | 5% |
| Capital cost of wind system, $C_{Inst}^{WT}$ [16] | 61980₹/kW | Annual load growth rate [13] | 3% |
| O & M cost of wind system, $C_{OM}^{WT}$ [16] | 1124₹/kWDC/yr | Daily to annual conversion factor (φ) [13] | 365 days |
| Capital cost of BESS unit of 3kWh, $C_{Inst}^{BESS}$ [16,19] | 22000₹/unit | Lifetime of renewables ($T_p$) [13] | 20 year |

From the table, it may be observed that the cost of investment is recovered in 5 years. Besides, the cost of initial investment is not too much with reference to middle-income group family in India. According to proposed strategy, the capacity of the BESS, in first year, is determined by restricting the amount of energy feeding to utility grid. The minimum load deviation in the load demand is also ensured as the second objective.

Table 2. Simulation results obtained by the proposed model

| Case | Optimal sizing of WT in $kW_p$ | Optimal sizing of PV in $kW_p$ | Optimal sizing of BESS in $kWh_p$ | Initial investment (Year = 1) (₹) | Present value of O & M cost | Present value of the cost paid to the grid in 5 years (₹) | NPV (₹) | Pay-back time (approx. years) |
|---|---|---|---|---|---|---|---|---|
| I Base case | — | — | — | 00.00 | - | 677162 | - | - |
| II HECSs | 2.000 | 4.185 | 11.231 | 428125 | 35450 | 212172 | 1415.6 | 5 |

Fig. 1 shows the hourly load demand curve of the house, solar PV system output, wind system output and BESS dispatch for first year. The wind and solar systems simultaneously supporting the house load along with the BESS as can be observed from Figs. 1(a), 1(b), 1(c) and 1(d). It can be analyzed that the BESS charged when there is an excess power generation from solar and wind or price is low. Similarly, it discharged during peak load hours, approx. from to 12 PM to 8 PM. The comparison of these HECSs and load demand is shown in Fig. 2 to shows that the HECS reduces the variation the power drawn from the grid.

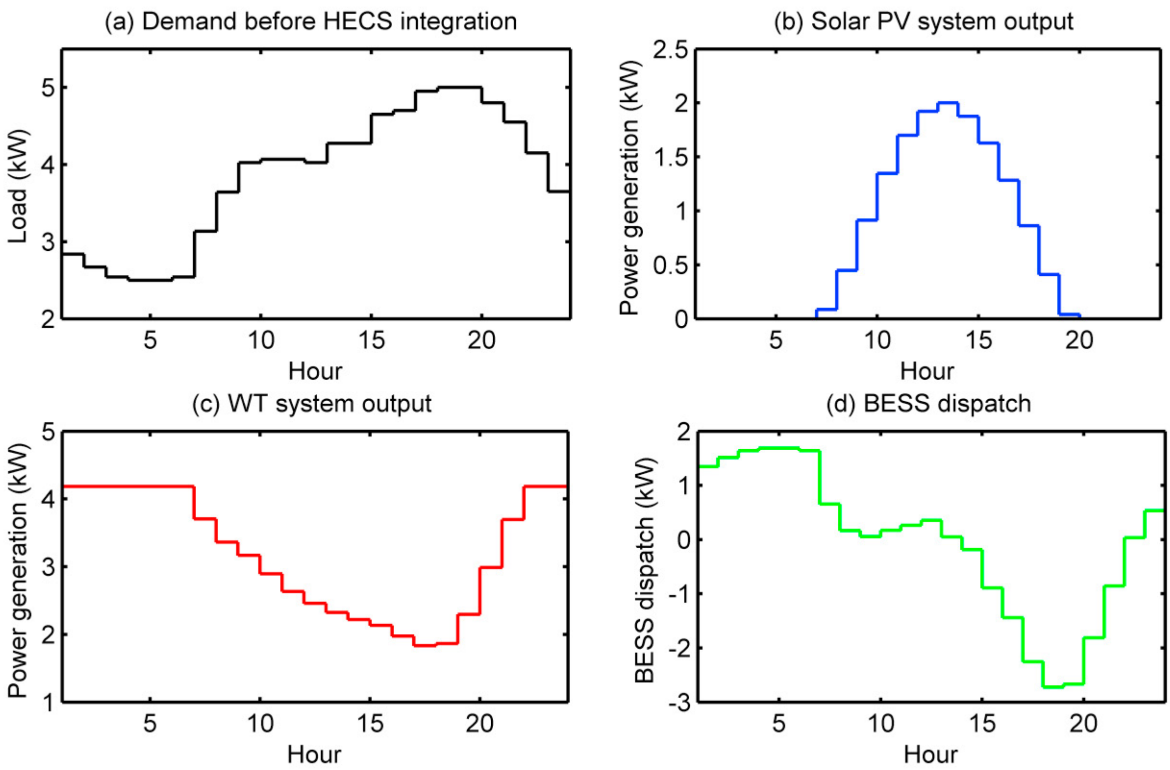


Fig. 1 Load demand curve, solar PV power generation, WT system power generation, and BESS dispatch

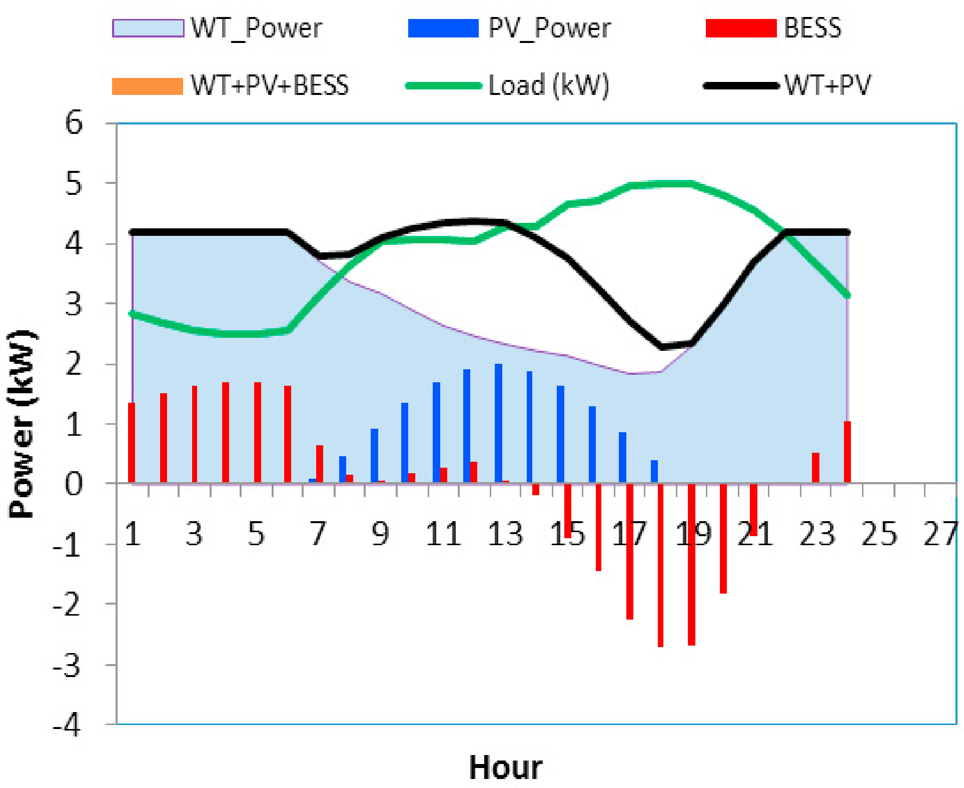


Fig. 2 The comparison of various HECSs and load demand of the house

## 5. Conclusion

The paper presents an optimization framework for optimal energy management of smart homes, having hybrid energy resources, in the Indian context. The cost of hybrid energy resources is considered form the Indian market and the house of a middle-class income group family is adopted. In order to motivate the house owner to integrate HECS in his house, the economic analysis is carried out and the payback time and the benefits are discussed. The NPV calculation is also shown to show the monetary benefits in the present time. The simulation results revealed that a middle-class family with outlay of 1 million ₹could manage to pay for the smart energy management system which can reduce their huge annual energy bills. It has been observed that the cost of such system is recovered in 5 years. In future, the proposed framework may be extended for optimal energy management in smart houses considering the modeling of variance appliances.

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