[Singh, 5(9): September 2018]
DOI- 10.5281/zenodo.1407058

ISSN 2348 – 8034
Impact Factor- 5.070

GLOBAL JOURNAL OF ENGINEERING SCIENCE AND RESEARCHES

EFFICIENT ENERGY TRANSACTIONS USING AN INTELLIGENT HOME ENERGY MANAGEMENT SYSTEM

Paramvir Singh[*1] & Nisha Tayal[*2]
[*1&2] Department of Electrical and Electronics Engineering, UIET, Panjab University, Chandigarh, India

ABSTRACT

Smart grid being the future of the current electric grids, provides the residents with the opportunities to control the use of their home's energy for minimising their energy expenses. In this study, a mixed integer linear programming (MILP) problem has been formulated for efficiently using the load and power generating units in a home that integrates renewable energy sources, a battery bank and an electric vehicle. Moreover, to include the effects of the intermittent weather, four scenarios each for the solar irradiation and wind speed are taken. Combining these scenarios, six different test cases have been obtained and simulated using an Intelligent Home Energy Management System (IHEMS) in the MATLAB software. The results from these test cases show that with the incorporation of IHEMS in the home, all the units operate efficiently according to the Time of Use (ToU) prices to bring the home's energy expense value to its lowest. Further, to evaluate the annual energy expense, the results from each of these test cases are replicated for a particular number of days as according to their frequency of occurrence in a year. The results from the annual study show that with the optimal operation of the home's units, the energy expense has been reduced significantly.

Keywords*: Energy management, renewable energy sources, MILP, MATLAB software.*

I. INTRODUCTION

The increase in the energy requirement has led to the fast deployment of electric vehicles (EVs) and the non-conventional energy sources [1, 2]. But the intermittent nature of these resources is the main hurdle in their integration into the electrical power system. Hence, the optimum operation of EVs and renewable energy resources is necessary for the efficient operation of the smart grid [3, 4]. Various researches are undergoing to develop efficient energy management systems to integrate the EVs and renewable energy sources into the electric grid as well as the residential buildings.

In [5], a load scheduling system was presented that integrates conventional and non-conventional energy resources for minimising the energy expense as well as the emission of green house gases. In [6], a photovoltaic system, a battery storage system along with an EV has been employed in a single residential building and a coordinated operation of all these has been done using mixed integer linear programming (MILP) technique. In [7], the efficient operation of a smart household has been done with the objective of reducing the total energy expenditure using the MILP technique while taking into account every feasible bidirectional energy transfer. In [8], the EVs' scheduling behaviour due to the demand based tariffs has been assessed without integrating the renewable sources.

The residential load demand has been mathematically formulated with multiple objective functions in [9], considering only a photovoltaic system and excluding the wind turbine system. In [10], a particle swarm optimization technique has been employed for solving the energy management problem over a time period of 24 hours. A Bluetooth employed network system has been used in the smart energy management system in [11] for minimizing the peak load requirement and for maintaining the user comfort.
The above studies have not considered the intermittent nature of the weather over a complete year. To address its impact on a smart home's energy management problem, the study undertaken has been done for different weather conditions. The contributions made by the study are as follows:

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[Singh, 5(9): September 2018] ISSN 2348 – 8034
DOI- 10.5281/zenodo.1407058 Impact Factor- 5.070

1. Efficient management of the smart home's energy by incorporating an MILP technique for minimising its energy expenses.
2. Performing the energy management simulation for six test cases that are obtained by combining different scenarios of solar irradiation and wind speed.
3. Evaluation of the home's energy expense over a complete year on the basis of the frequency of occurrence of each of the six cases in that year.

The remaining sections are described as follows. In section II, the architecture of the smart home has been described while it is mathematically formulated in the section III. The section IV has been used for discussing the results and the study has been concluded in the section V.

II. ARCHITECTURE OF SMART HOME

The smart home consists of a photovoltaic (PV) system, a wind turbine system, a battery bank and an EV which are collectively referred to as the Distributed Energy Sources (DESs). The modelling of the smart home architecture has been done using the MILP technique. The integration of all the components of the home has been done by incorporating an Intelligent Home Energy Managing System (IHEMS) while their coordinated operation has been done according to the Time of Use (ToU) power pricing policy. For the intermittent nature of the weather, four different scenarios each of the solar irradiation and wind speed have been considered. Combining these scenarios, the smart home's simulation has been done for a total of six test cases. The time period of the simulation of each test case has been taken to be 24 hours.

Based on the frequency of occurrence of these cases in a year, an annual study has been conducted. The smart home's architecture has been shown in the Fig. 1 while its working has been explained through a flow chart in the Fig 2.

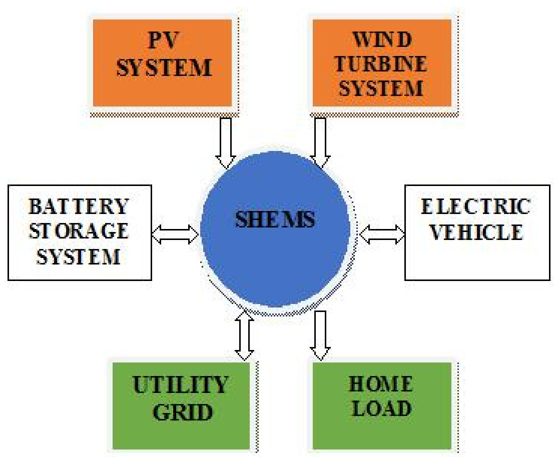

Fig. 1 Smart Home Architecture

III. PROBLEM FORMULATION

The energy management problem for the smart home has been mathematically formulated and solved using the MILP technique. The equations and constraints describing the operation of all the components of the smart home have been explained in this section.

A. Power Balance Equation

The power in the smart home is needed to be balanced at all times and is done using the following constraint:

DOI- 10.5281/zenodo.1407058 Impact Factor- 5.070

$$\left(P_{utility}(t) + P_S(t) + P_W(t) + P_{V2R}(t) + P_{B2R}(t) \right) = \left(D_{Load}(t) + P_{R2V}(t) + P_{R2B}(t) + P_{sell}(t) \right)$$

(1)

where $P_{utility}(t)$, $P_S(t)$ and $P_W(t)$ are the power from the utility grid, PV system and wind turbine system respectively at time t while $P_{sell}(t)$ is the power sold to the utility grid at time t. $P_{R2B}(t)$ and $P_{B2R}(t)$ are the power required for charging and discharging the home battery bank respectively at time t while $P_{R2V}(t)$ and $P_{V2R}(t)$ are the power required for charging and discharging the EV battery respectively at time t. $D_{Load}(t)$ is the home load demand at time t.

B. Electric Grid

The power is imported from the utility grid at any time t whenever the demand exceeds the power supplied by DESs in the home. It is done according to the following constraints:

$$0 \leq P_{utility}(t) \leq P_{utility}^{\max} \quad (2)$$

$$P_{utility}(t) \leq P_{utility}^{\max} \times B_{G2R}(t) \quad (3)$$

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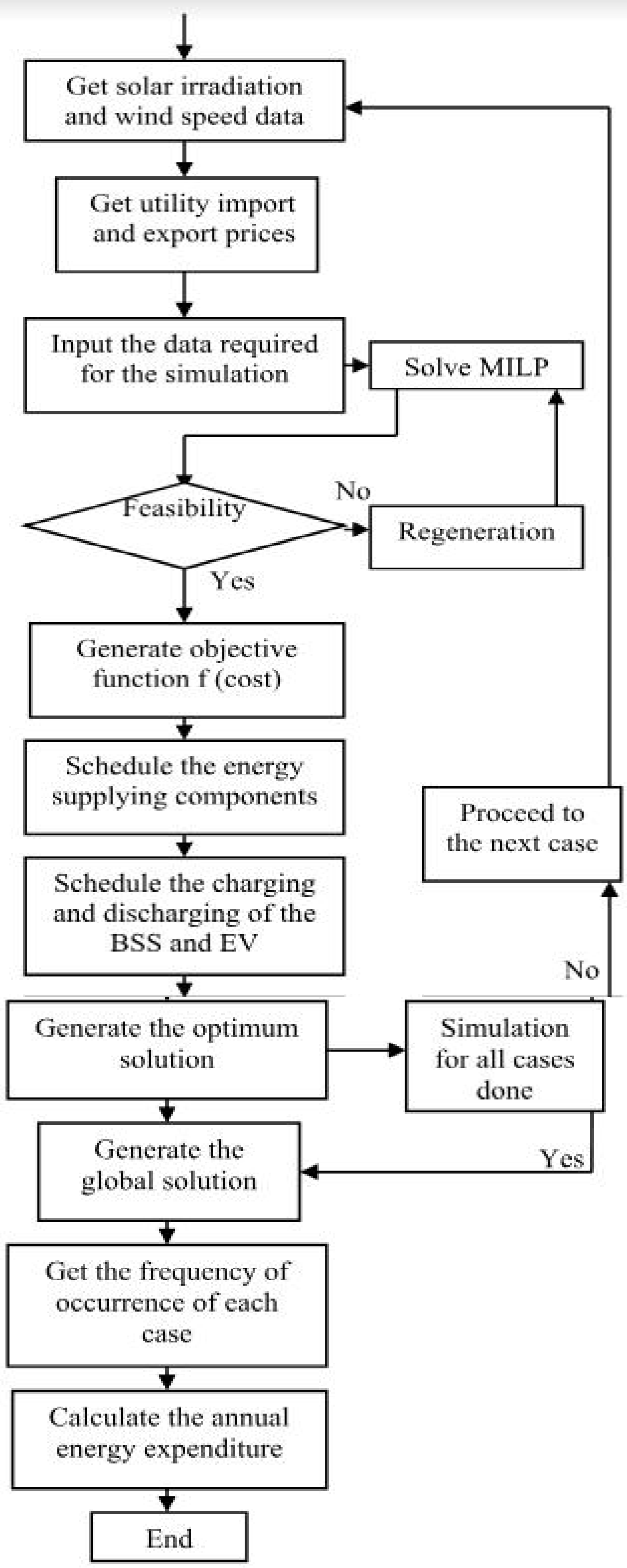

Fig. 2 Flow Chart of MILP technique for all cases

where $P_{utility}^{\max}$ is the maximum power that could be imported from the utility at any time t. $B_{G2R}(t)$ is a binary variable (=1 means power is imported and = 0 otherwise).
If the power generated by the DESs at any time t is greater than the home load demand then it is exported to the grid using the following constraints:

$$0 \leq P_{sell}(t) \leq P_{sell}^{\max} \quad (4)$$

$$P_{sell}(t) \leq P_{sell}^{\max} \times B_{R2G}(t) \quad (5)$$

where $P_{sell}^{\max}$ is the maximum power that could be exported to the utility at any time t. $B_{R2G}(t)$ is a binary variable (=1 means power is exported and = 0 otherwise).

C. Photovoltaic System

The PV system generates the power according to the solar irradiation received by it. The bound within which it generates the power is given by:

$$0 \leq P_S(t) \leq P_S^{\max} \quad (6)$$

The output power from the PV system is according to the following inequality constraint [12]:

$$P_S(t) \leq A_S \times \rho \times S_{rad}(t) \quad (7)$$

where $P_S^{\max}$ is the max power that could be generated by the PV system at any time t. A_S and ρ are the total surface area and efficiency of the PV system respectively while $S_{rad}(t)$ is the solar irradiation received by it at time t.

D. Wind Turbine System

The power generated by the wind turbine system according to the wind speed at time t is as follows [13]:

$$\begin{cases} P_W(t) = 0 & if\ V_f < V_{ci} \text{ and } V_f > V_{co} \\ P_W(t) = P_{rated} & if\ V_r \leq V_f \leq V_{co} \\ P_W(t) = \dfrac{V_f - V_{ci}}{V_r - V_{ci}} \times P_{rated} & if\ V_{ci} \leq V_f \leq V_r \end{cases} \quad (8)$$

where V_f, V_r, V_{ci}, V_{co} are the forecasted, rated , cut-in and cut-out wind speeds respectively. P_{rated} is the rated power that could be generated by the wind turbine system.

E. Home Battery Bank

The home battery bank gets charged and discharged according to the ToU prices. The bounds for the power charging and discharging respectively are as follows:

$$0 \leq P_{R2B}(t) \leq P_{R2B}^{\max} \quad (9)$$

$$0 \leq P_{B2R}(t) \leq P_{B2R}^{\max} \quad (10)$$

where $P_{R2B}^{\max}$ and $P_{B2R}^{\max}$ are the upper limits of the power that could be charged and discharged respectively out of the home battery at time t.

The inequality constraints defining the charging and discharging of the battery respectively at time t are as follows:

$$P_{R2B}(t) \leq P_{R2B}^{\max} \times B_{R2B}(t) \quad (11)$$

$$P_{B2R}(t) \leq P_{B2R}^{\max} \times B_{B2R}(t) \quad (12)$$

where $B_{R2B}(t)$ and $B_{B2R}(t)$ are the binary variables describing the charging and discharging states of the battery bank respectively at time t. The simultaneous operation of the battery bank in the charging and discharging modes is not allowed:

$$B_{R2B}(t) + B_{B2R}(t) \leq 1 \qquad (13)$$

The energy stored in the battery bank at the initial time period is:

$$N_{BC} \times SC_B(1) = I_{BC} + \left(\frac{P_{R2B}(1) \times dt}{e_c} - (e_d \times P_{B2R}(1) \times dt)\right) \qquad (14)$$

While the energy stored in the battery bank at time $t > 1$ is given by [14]:

$$N_{BC} \times SC_B(t) = N_{BC} \times SC_B(t-1) + \left(\frac{P_{R2B}(t) \times dt}{e_c} - (e_d \times P_{B2R}(t) \times dt)\right) \qquad (15)$$

where N_{BC} and I_{BC} are the total and initial capacity of the battery bank. $SC_B(t)$ is its State of Charge (SoC) at time t while dt is the time step of the simulation period.
The bound for the SoC of the battery bank is given by:

$$0.2 \leq SC_B(t) \leq 1 \qquad (16)$$

The battery is not allowed to charge beyond its total capacity using the following constraint:

$$N_{BC} \times SC_B(t-1) + \left(\frac{P_{R2B}(t) \times dt}{e_c}\right) \leq N_{BC} \qquad (17)$$

F. Electric Vehicles

The EV takes part in the energy transactions when it is present at home. The bounds for the EV's power charging and discharging respectively are as follows:

$$0 \leq P_{R2V}(t) \leq P_{R2V}^{\max} \qquad (18)$$

$$0 \leq P_{V2R}(t) \leq P_{V2R}^{\max} \qquad (19)$$

where $P_{R2V}^{\max}$ and $P_{V2R}^{\max}$ are the upper limits of the power that could be charged and discharged respectively out of the EV at time t.

The inequality constraints defining the EV's charging and discharging respectively are as follows:

$$\begin{cases} P_{R2V}(t) = P_{R2V}^{\max} \times B_{R2V}(t) & \forall t \in T_{home} \\ P_{R2V}(t) = 0 & \forall t \in T_{drive} \end{cases} \qquad (20)$$

$$\begin{cases} P_{V2R}(t) = P_{V2R}^{\max} \times B_{V2R}(t) & \forall t \in T_{home} \\ P_{V2R}(t) = 0 & \forall t \in T_{drive} \end{cases} \qquad (21)$$

where $B_{R2V}(t)$ and $B_{V2R}(t)$ are the binary variables describing the charging and discharging states of the EV battery respectively at time t.

The simultaneous operation of the EV in the charging and discharging modes is not allowed:

$$B_{R2V}(t) + B_{V2R}(t) \leq 1 \qquad (22)$$

[Singh, 5(9): September 2018] ISSN 2348 – 8034
DOI- 10.5281/zenodo.1407058 Impact Factor- 5.070

The energy stored in the EV battery at the initial time period is:

$$N_{EVC} \times SC_{EV}(1) = I_{EVC} + \left(\frac{P_{R2V}(1) \times dt}{e_c} - (e_d \times P_{V2R}(1) \times dt) \right) \qquad (23)$$

While the energy stored in the EV battery at time t >1is given by [14]:

$$N_{EVC} \times SC_{EV}(t) = N_{EVC} \times SC_{EV}(t-1) + \left(\frac{P_{R2V}(t) \times dt}{e_c} - (e_d \times P_{V2R}(t) \times dt) \right) \qquad (24)$$

where N_{EVC} and I_{EVC} are the total and initial capacity of the EV battery. $SC_{EV}(t)$ is its SoC at time t while e_c and e_d are the charging and discharging factors respectively for both the home battery bank and EV battery.

The bound for the SoC of the EV battery is given by:

$$0.2 \leq SC_{EV}(t) \leq 1 \qquad (25)$$

The EV battery is not allowed to charge beyond its total capacity using the following constraint:

$$N_{EVC} \times SC_{EV}(t-1) + \left(\frac{P_{R2V}(t) \times dt}{e_c} \right) \leq N_{EVC} \quad (26)$$

G. Objective Function

The objective of the study is to minimise the energy expense of the home while satisfying the system constraints. The objective function f (cost) for the MILP problem is as follows:

$$\text{Min } f(cost) = \sum_{t=1}^{T} \left(\begin{array}{l} \left[P_{utility}(t) \times dt \times C_{utility}(t)\right] + \left[P_S(t) \times dt \times C_S(t)\right] + \\ \left[P_{wind}(t) \times dt \times C_W(t)\right] + \left[P_{B2R}(t) \times dt \times C_B(t)\right] + \\ \left[P_{V2R}(t) \times dt \times C_{EV}(t)\right] - \left[P_{sell}(t) \times dt \times C_{sell}(t)\right] \end{array} \right)$$

where T is the time period of the simulation. $C_{utility}(t)$ and $C_{sell}(t)$ are the cost of the power that is imported and exported to the utility grid at interval t. $C_S(t)$, $C_W(t)$, $C_B(t)$ and $C_{EV}(t)$ are the expenditure due to the maintenance and power generated from the PV system, wind turbine system, home battery bank and EV battery respectively at time t.

The annual energy expense evaluation of the home is done by summing the energy expense value of each case taken for a particular number of days according to its frequency of occurrence in the year. The formula related to it is described as follows:

$$C_{annual} = \sum_{i=1}^{6} \left(C_{day}(i) \times N(i) \right) \qquad (28)$$

where C_{annual} is the annual energy expense of the home. $C_{day}(i)$ is the energy expense of the i[th] case and $N(i)$ is the number of days for which the weather conditions are similar to that of the i[th] case in the year.

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IV. RESULTS AND DISCUSIONS

A. System Parameters

A total of four scenarios each for the solar irradiation and wind speed are taken and are shown in the Fig. 3 and Fig. 4 respectively. The six test cases obtained from the combination of these solar and wind scenarios are shown in the Table 1. The table also contains the time span for which each case is taken in a year to conduct an annual study. The 3.5 kW PV system has a total surface area of 25 m^2 with an efficiency of 18.6% [12]. The wind turbine system has a rated power generation of 2.1 kW and the cut-in, cut-out, rated wind speeds for it are taken to be 4m/s, 25m/s and 14m/s respectively [13].

The home battery bank has a total capacity of 10 kWh with its initial energy value taken to be 6kWh. The EV battery has a total capacity of 24kWh with an initial energy value of 16 kWh. The power charging and discharging rate for home battery is taken to be 1 kW while for the EV battery, this value is taken to be 3.3 kW.

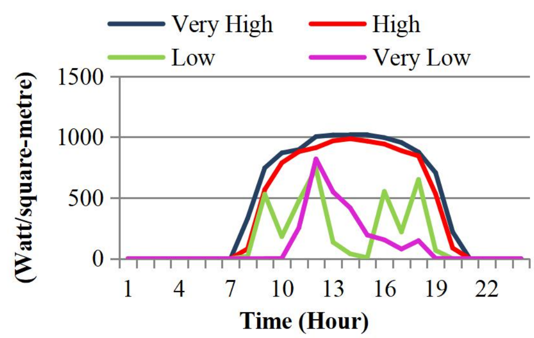

Fig. 3 Solar Irradiation scenarios

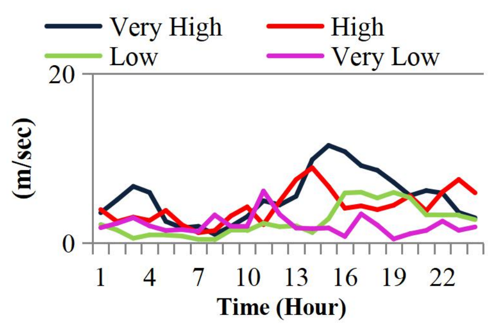

Fig. 4 Wind Speed Scenarios

The EV is assumed to be out of the home for driving during the intervals 9 to 17. For the purpose of driving, the SoC of EV battery is taken to be 50% at the start of the driving period. While it is also assumed that at the end of the driving period, the EV battery has the same value of SoC as at the start of the driving period. The charging and discharging factor for both EV and home battery is taken to be 1.1 and 0.9 respectively. The upper limit of the power that could be imported and exported to the grid is taken to be 5kW and 10kW respectively. The value of $C_S(t)$, $C_W(t)$, $C_B(t)$ and $C_{EV}(t)$ is taken to be 0.01€/kWh while the hourly cost of the power imported and exported to the utility grid has been shown in the Fig. 5.

 ISSN 2348 – 8034
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Table 1 Different Cases of weather conditions

Case	Combination	Weeks	Wind	Solar
1	Spring + Sunny	8	Very High	High
2	Summer + Sunny	12	Very High	Very High
3	Summer + Cloudy	6	High	Low
4	Summer + Rainy	6	Low	Very Low
5	Autumn + Sunny	8	High	High
6	Winter + Sunny	12	Very Low	Low

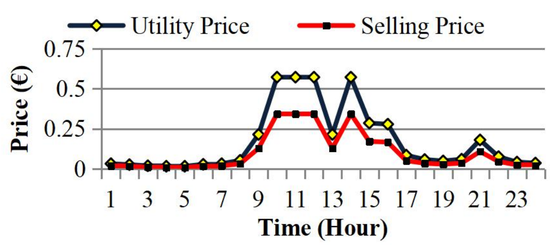

Fig. 5 Hourly Electricity Prices

B. Case Studies

The simulation for the test cases has been done using MATLAB 2018a software. The primary motive of doing the simulation is to minimise the home's energy expenses. The results of the case studies have been shown in the Table 2. The variation in their energy expenses is due to the different weather conditions taken for each case.

Table 2 Simulation results for each case

Case Number	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Energy Expense (€/day)	-2.32	-2.51	2.94	4.13	-1.75	3.75

As has been noted in the table, the case 4 has the highest energy expense due to poor solar and wind power generation. While the case 2 has the lowest expense as it has the highest power generation from the renewable sources. The negative value of the energy expense in the Table 2 illustrates that the home has managed to generate profits through the energy optimization. The power imported and exported hourly for the case 2 has been shown in the Fig. 6. The hourly home load, as shown in the figure, is taken the same for all the cases. The PV system's and wind turbine system's power generation for the case 2 has been shown in the Fig.7.

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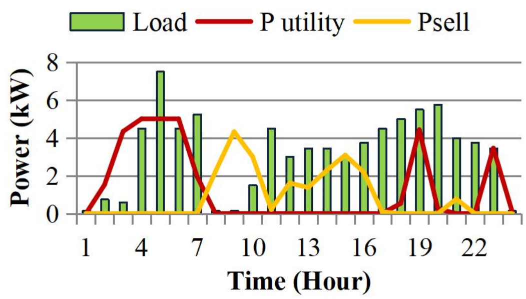

Fig. 6 Hourly power transfer between home and utility (Case 2)

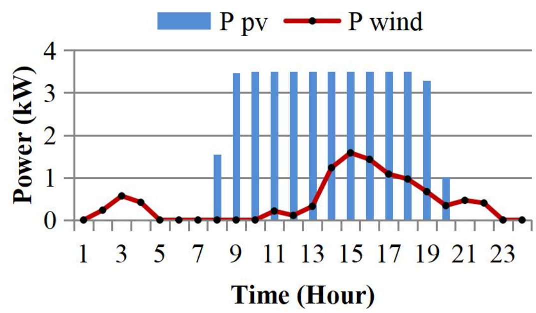

Fig. 7 Hourly renewable power generation (Case 2)

The home battery and the EV have actively participated in the energy management and have significantly contributed in the reduction of the home's energy expenses. The Fig.8 and Fig.9 show the power charged and discharged out of the home battery and EV respectively for the case 2. It has been observed that the charging of both the EV and home battery has been done during the off-peak period. While these discharge their power in the peak load periods, as the profit from exporting the power to the grid during these periods is high.

The hourly energy expense for all the cases has been shown in the Fig.10. From the figure it is observed that with the planned integration of the renewable energy sources, home battery and EV, it is possible to reduce the energy expenses without compromising the home load demand. It is also observed that when the weather conditions are favourable home expenses are lower. The energy expense for each case during the yearly simulation has been shown in the Fig.11. Using all values of the figure, the annual energy expense of the home is calculated to be 173.14€. This value is approximately equal to the expense occurred during the case 4 over a period of 6 weeks. This shows that with the home's proper energy management, it has been able to minimise its annual expenses significantly.

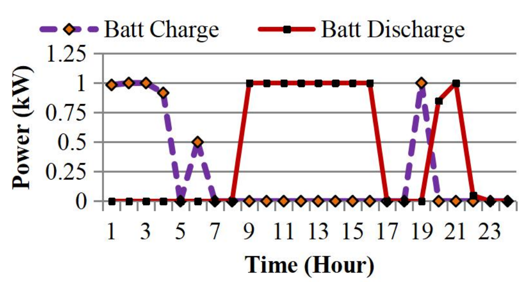

Fig. 8 Hourly power flow in the home battery (Case 2)

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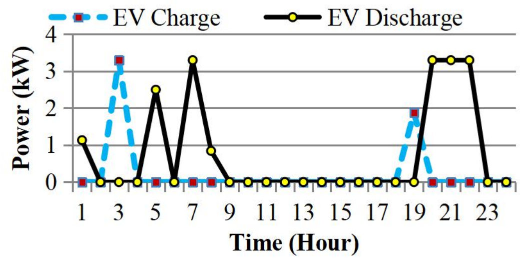

Fig. 9 Hourly power flow in the EV (Case 2)

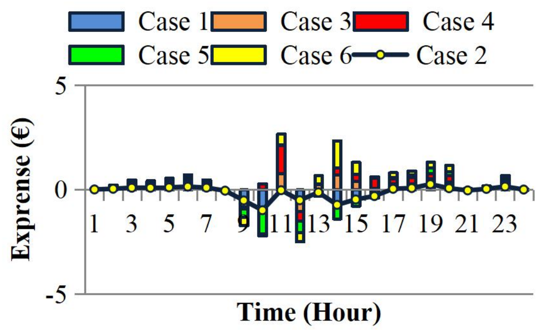

Fig. 6 Hourly home energy expense for all the cases

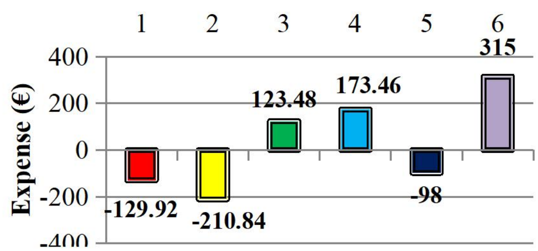

Fig. 7 Total expense of each case in a year

V. CONCLUSION

An energy management has been done for a single home consisting of a PV system, a wind turbine system, a battery bank and an EV. This has been done by modelling the home's architecture using the MILP technique. Considering the intermittent weather conditions, six different test cases have been simulated, each with different solar and wind power generation. The results of the simulations show that the intelligent home energy management system has been able to efficiently manage all the units' operation. Moreover, after comparing the results of all the cases, it has been observed that the energy expenses are lower during favourable weather conditions. Further, the annual energy expense evaluation done using the results of all the six cases show that the home expenses have been significantly reduced due to the optimal energy management.

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