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Optimization of hydrogen based hybrid renewable energy system using HOMER, BB-BC and GAMBIT

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ABSTRACT

Non-conventional energy sources contribute important role in the current environment world policy, assuring a competent way to reduce GHG emission causing a global warming. This work is based on simulation and optimization of non-conventional energy system of an auditorium of Police station Sagar at central India. For this hybrid system the meteorological data of solar insolation, hourly wind speeds are taken at the site considered. The pattern of load consumption is studied and suitably modeled for optimization of the hybrid energy system using HOMER software. The results are compared with that of BIG BANG CRUNCH (BBC) algorithm and GAME Theory based concept. Based on optimization result, it has been found that replacing conventional energy sources by solar-wind-Fuel Cell-Hydrogen tank energy system will be a feasible solution for distribution of electric power for standalone application. The paper employs GAMBIT software to optimize the system which is based on the GAME theory concept. At the last regression analysis to be to find out value of R-square, Durwin-Watson statistics.

Introduction

The increasing concern in the negative effects of conventional fuel on the environment has forced a more intensive use of Non-conventional sources which are considered as an important solution to the larger environmental pollution caused from fossil fuel consumption [1]. Non conventional energy sources such as wind and solar energy have made the public and private sectors interested to invest in energy generation from these sources extensively. Among wind and solar, wind energy system may not be technically viable at all sites as wind velocity is random in nature. Mixing of two or more resources in a proper combination to form a hybrid scheme, utilizing the intensity of one source to overcome the weakness of the other is a very good solution [2]. Combined model of solar and wind system is known as an integrated renewable energy system and is one of the best alternatives of oil produced energy [3].

In this article HOMER is used to plan the appropriate component where net present cost is the primary criteria. The outcomes are compared with that of BBC and GAME theory based concept. HOMER, MATLAB and GAMBIT software are used for analyzing net present cost of the system.

Agustin et al. demonstrate simulation and optimization of standalone HRES and listed the tools needed to simulate and design standalone HRES for the generation of electricity [4]. **Hochmuth et al.** proposed an optimum operational strategy

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for a hybrid system by carrying out a search through possible options for the system operation control along with sizing and operational control of hybrid PV system [5]. A feasibility analysis of a standalone system for large scale tourist operation is reported by **Delton et al.**, mentioning that wind energy system, rather than PVs is the most economically viable RES for large scale operation [6]. An optimal capacity allocation of standalone wind/solar/battery hybrid power system based on improving particle swarm optimization is presented by **Wang et al.** [7]. **Abber et al.** gave eco-design optimization of an autonomous hybrid wind, PV system with battery storage [8]. **Aien et al.** proposed a new methodology based on two point estimation method for probabilistic power flow of correlated hybrid wind–PV power system [9]. **Chen et al.** explain optimal contract capacities and the optimal installed capacities of the wind and PV generation system for a time of use rate for industrial user [10]. **Kusakana et al.** gave optimal scheduled power flow for distributed PV/Wind/Diesel generator with battery storage system [11]. **Hossein et al.** presents wind energy forecasting using echo state networks optimized by big bang crunch algorithm. The method is tested by real world hourly data to show the efficiency of the forecasting engine for prediction of both wind vector and wind power output of aggregated wind power production [12]. **Labbi et al.** presents big bang big crunch optimization algorithm for the maximum power point tracking in photovoltaic system [13]. The second preferred concept used in recent paper is GAME theory based GAMBIT software. **Street et al.** presents sharing quotas of a renewable energy hedge pool with the help of a cooperative game theory approach [14]. **Saad et al.** gave a coalitions game theory of cooperative micro-grid distribution networks of solar panels, wind turbines and PHEVs etc [15]. **Baeyens et al.** explains wind energy aggregation with the help of a coalition's game approach [16]. **Mei et al.** develop game approaches for hybrid power systems planning. Game theory is presented to model the planning of a grid connected hybrid power system comprised of wind turbines, PV panels and storage batteries [17]. **Sharp et al.** developed for industrial energy consumer several types of solar energy incentives. The incentives are formulated using Stackelberg game theory with the government as a leader offering incentives to the end user [18]. **Ogino et al.** present Non-cooperative game approach in an electric generating system which is related to public participation and resource supply [19]. **Lygeros et al.** design multiagent hybrid system using game theory. A methodology for designing a hybrid controller for the large scale multiagent system is presented. The paper present problem based on the optimal and timely investment on grids and that problem solved under the concepts of the Nash-Bayesian equilibrium [20]. **Wu et al.** develop demand side management for wind power integration in microgrid using dynamic potential game theory and analyzed and coordinated the interaction among users to efficiently utilize the available renewable and conventional energy sources to minimize the total energy cost to the system [21]. **Huang et al.** modeled fuel cell vehicle by assessing an electrolysis hydrogen production system powered by photovoltaic and wind energy system. MATLAB Simulink softwares are used to identify the effect of temperature on hydrogen flow and efficiency of the electrolyzer [22]. **Ghandeharium et al.** presented life cycle analysis of wind based hydrogen production in Western Canada. The key driver of life cycle analysis is the need to assess options for the energy industry to lower its carbon footprint by using hydrogen produced from renewable sources [23]. **Fazelpour et al.** examined economic analysis of standalone solar wind hybrid energy system to supply the energy needs for a house hold in Tehran Iran. Hydrogen is used for generation of electricity so as to ensure clean energy leading to little environmental impact and pollution free energy source [24]. **Mena et al.** present electrolyzer models for hydrogen production for wind energy system. Coupled operation of electrolyzer with wind turbine and four different electrolyzer models are presented and evaluated performance of renewable energy system [25]. All the previous research shows solar and wind energy system provide better energy producer from environment point of view and best alternative of electricity generation through fossil fuel. Fig. 1 shows comparative analysis of different optimization technique.

Standalone hybrid renewable energy system

Hybrid renewable energy system is a combination of different renewable energy source [26,28]. Solar and wind energy system and fuel cell are the principal ingredient in the proposed system. The battery is used for storage purpose, backup is provided by the diesel generator and hydrogen is used as an energy carrier [30–32]. Solar radiation and wind velocity data

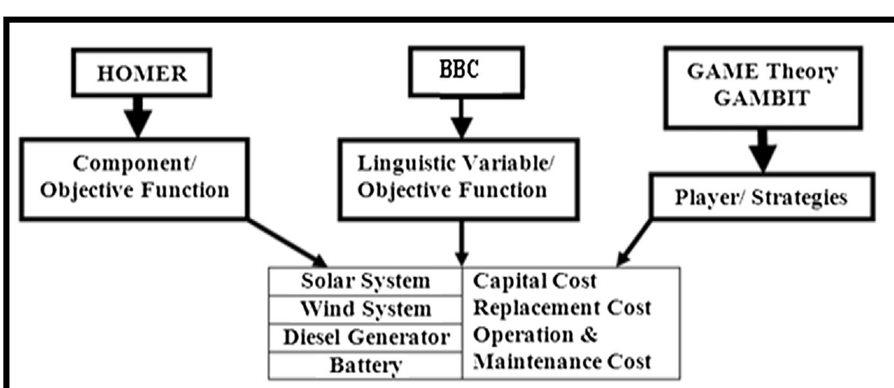

Fig. 1 – Comparative analysis of optimization technique.

of study area is presented in Table 1 [27]. As per the survey conducted to find out energy consumption, the site under consideration consumes around 18 kWh/d with a peak demand of 2.5 kW. Fig. 2 shows the proposed system which is implemented in the HOMER simulation tool.

The objective function of this research is to develop a standalone hybrid generation system, which is appropriately designed in terms of all economic aspects and measures subject to the operational constraints of the system [33]. The total cost ($/year) includes initial cost, operational and maintenance (OM) cost for each type of power source, and the salvage value of each equipment which should be deducted. Net present cost is the main criteria and the best optimum result obtained using HOMER is compared with a BBC and GAME theory based GAMBIT software [6]. The overall cost minimization function is given by Equation (1) [6,27].

$$\begin{aligned}\text{Total Cost of system} = {} & \sum_{i=1}^{N_{PV}} N_{PV}^{i} \times \left(C_{capital,PV}^{i} + C_{O\&M,PV}^{i} + C_{Replacement,PV}^{i}\right) + \sum_{j=1}^{N_{WT}} N_{WT}^{j} \times \left(C_{capital,WT}^{j} + C_{O\&M,WT}^{i} + C_{Replacement,WT}^{i}\right) + \sum_{j=1}^{N_{WT}} N_{Battery}^{j} \\ & \times \left(C_{capital,Battery}^{j} + C_{O\&M,WT}^{i} + C_{Replacement,Battery}^{i}\right) + C_{capital\ \ cost\_Generator} + C_{O\&M\ \ cost\_Generator} + C_{fuel\ \ cost\_Generator} \\ & + \sum_{i=1}^{N_{Electrolyzer}} N_{Electrolyzer}^{i} \times \left(C_{capital,Electrolyzer}^{i} + C_{O\&M,Electrolyzer}^{i} + C_{Replacement,Electrolyzer}^{i}\right) + \sum_{i=1}^{N_{FuelCell}} N_{Fuelcell}^{i} \times \left(C_{capital,Fuelcell}^{i}\right. \\ & \left. + C_{O\&M,Fuelcell}^{i} + C_{Replacement,Fuelcell}^{i}\right) + \sum_{i=1}^{N_{H_2\ \ Tank}} N_{H_2\ \ Tank}^{i} \times \left(C_{capital,H_2\ \ Tank}^{i} + C_{O\&M,H_2\ \ Tank}^{i} + C_{Replacement,H_2\ \ Tank}^{i}\right)\end{aligned} \tag{1}$$

Where N_{PV}, N_{WT}, $N_{Battery}$ are number of PV panel, a number of wind turbine and number of batteries respectively [27,35,36].

Hybrid renewable power generation component/ linguistic variable/player

Photovoltaic system

The solar system from suntech Ltd. is considered for the study. PV panel is position is considered horizontal axis, monthly adjustment. Capital, replacement and operation & maintenance cost of the solar system are $3150, $2500 and $125/year respectively.

Wind turbine

In this analysis SW Whisper 500 model is considered which has a rated capacity of 3 kW and the rotor diameter of 4.5 m. Capital, replacement and operation & maintenance cost of a wind system are $12,800, $11,000 and $150/year respectively.

Battery

Homer models the battery as a two tank energy storage device. Commercially available models such as Surrette battery S460 (6 V, 460 Ah, 2.76 kWh) are used for analysis. Capital, replacement and operation & maintenance cost of battery are $350/battery, $325/battery and $5/year/battery respectively.

Converter

A converter is required for a system in which DC component serves an AC load or vice versa. A converter can be an inverter (DC/AC), rectifier (AC/DC) or both. Capital, replacement and operation & maintenance cost of converter are $280, $150 and $2/year respectively.

Diesel generator

The capital, replacement and operation & maintenance cost of a commercially available diesel generator is $2800, $1700 and $0.2/hr. respectively.

Hydrogen tank & electrolyzer

The hydrogen tank stores the hydrogen for use at the time of generation. The cost of a tank with 1 kg capacity is assumed to be $800. The replacement cost and O&M cost are taken as $700 and $15/year. Five different sizes from 0 to 5 kg are included to extend the search space for a cost effective configuration. Current capital cost of electrolyzer is $2000/kW with improvement in polymer technology and power electronics. It is expected that costs would reduce much in next 5 years. Replacement cost and O &M cost of electrolyzer is $1200 & $20/year.

Table 1 – Solar radiation (kWh/m^2/day) and wind velocity (m/s) data of the study area.

Month	Solar radiation	Wind velocity
January	4.61	4.35
February	5.60	4.53
March	6.51	4.65
April	7.18	4.92
May	7.28	5.27
June	5.94	5.26
July	4.82	5.85
August	4.40	5.34
September	5.40	5.07
October	5.73	5.06
November	4.92	3.70
December	4.42	5.99

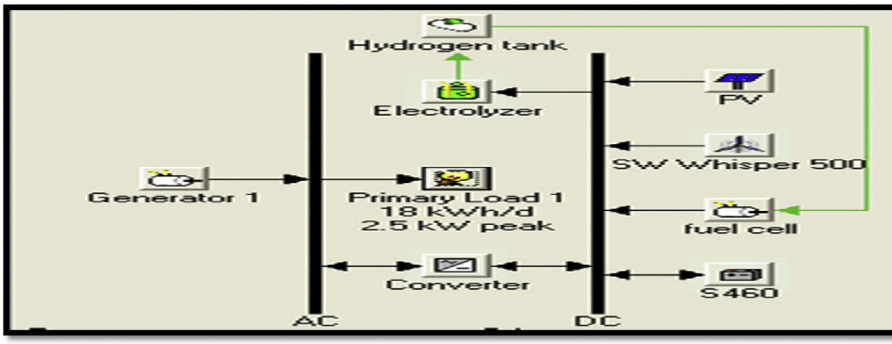

Fig. 2 – Hybrid system components in HOMER.

Fuel cell

Since the cost of fuel cell is one of the most significant issues in commercializing a hybrid energy system with hydrogen storage, a sensitivity analysis with varying cost is necessary. Considering these factors, the capital, replacement and operational costs are taken as \$1600, \$13,000 and \$0.020/h for 1 kW system, respectively. Fig. 3 shows that result when simulated using homer.

Big-bang big-crunch techniques

The big bang big crunch optimization algorithm is a new optimization method that relies on the big bang and big crunch theory, one of the theories of the evolution of the universe. BB-B-C theory is introduced by Erol and Eksin, which has a low computational time and high convergence speed. According to this theory, big bang phase energy dissipation produces disorder and randomness is the main features of this phase where in big crunch phase randomly distributed particles are drawn into an order. The BB-BC optimization generates random points in the big bang phase and shrinks these points to a single representative point via a center of mass in the big crunch phase [12,13]. The BB-BC method has been shown to outperform the enhanced classical GA for many benchmark test functions.

The Big Bang-Big Crunch approach takes the following steps:

1. Determine the center of mass which has global best fitness using Equation (2). The candidates are arranged in the ascending order of their fitness (fitness) and the first candidate will be the candidate with the best fitness (minimum loss).
2. Generate new candidates around the center of mass by adding/subtracting a normal random number according to Equation (3).
3. Calculate the fitness function values of all the candidate solution.

Find the center of mass according to the following equation (2).

$$\mathbf{x}^{\rightarrow c} = \frac{\sum_{i=1}^{N} \frac{1}{f^i} \mathbf{x}^{\rightarrow i}}{\sum_{i=1}^{N} \frac{1}{f^i}} \tag{2}$$

Where x_c = center of mass, x_i = is a point within a n-dimensional search space generated, f_i = is a fitness function value, N = population size in Big-Bang phase.

$$\mathbf{x}^{new} = \mathbf{x}^{c} + \mathbf{l} \cdot \frac{\mathbf{r}}{\mathbf{k}} \tag{3}$$

Where l = upper limit of the parameter, r = normal random number, k = iteration step.

GAME theory based GAMBIT software

Hybrid renewable energy system in strategic form

Game theory is the branch of decision theory concerned with independent decision. A game is given by $G = (N, S, U)$ in which the set of player is N, the set of strategies is S and the set of the payoff function (utility function) is U [37,38]. A payoff is a number, also called utility, which reflects the desirability of an outcome to a player, for whatever reason. When the outcome is random, payoffs are usually weighted with their probabilities.

If set of player N *is equal to* 4 = (solar system, wind system, diesel generator, battery is the set of player).

A. Set the strategies: S

- When the wind system is sufficient to fulfill the entire requirement. The solar systems are inactive even as the battery bank is in recharge mode.
- The wind system is not enough to satisfy the total demand and then solar system is set to supply the power in place of the wind system.
- The wind and the solar system are providing sufficient amount of energy and the battery is set to supply power to the load [39–41].

If power demand is higher than the power available from renewable energy sources and battery current is higher than maximum discharging current, the hybrid controller automatically turns on to the diesel generator to provide the extra

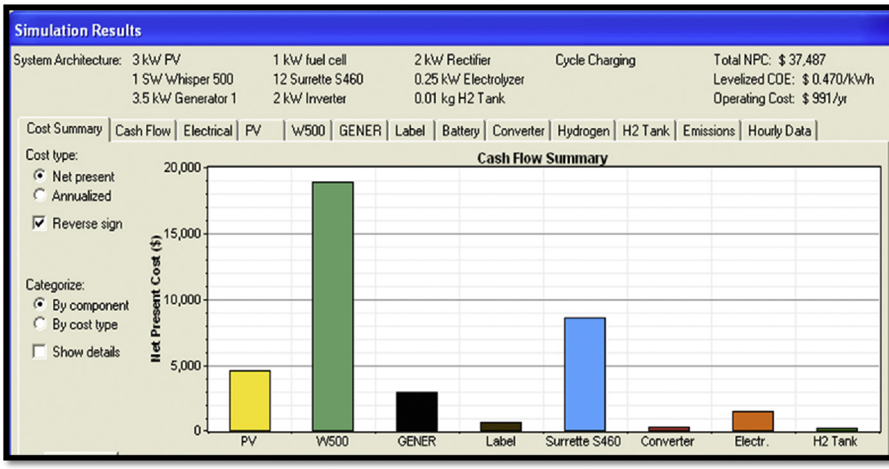

Fig. 3 – HOMER simulation result of hybrid system.

current. In this analysis 4 players and 12 strategic conditions are used, all 12 strategic conditions are shown in Equation (1).

GAME theory based GAMBIT software

GAMBIT is a software tool for GAME theory and it is a set of tool for doing computation on finite, non-cooperative games. This tool works in extensive or strategic form and uses Nash equilibrium and other solution concepts in games. Interactive cross platform graphical interface, command line tools for computing equilibrium and extensibility & interoperability is the main feature of GAMBIT software. The gambit tool read and write file formats which are textual and documented, making them portable across systems and able to interact with external instruments. The GAMBIT software is a framework for the definition and implementation of strategic interaction among player [40].

Fig. 4 presents the general architecture of GAMBIT software based hybrid renewable energy system. The frame presenting a game consists of two principle panels' main panel and player panel. The main panel to the right, display the hybrid system game graphically, to the left is the player panel, which lists the number of players in the game. In this paper Solar, wind, generator and battery are the players and the information is color coded, to match the color assigned to the players. Gambit stores all payoff's in games in an arbitrary-precision format. The payoff value which reflects the desirability of an outcome to a player entered as decimal numbers with arbitrary many decimal places.

In GAMBIT software simulink model considers 1 chance and 8 players are used. This software performs cost analysis of

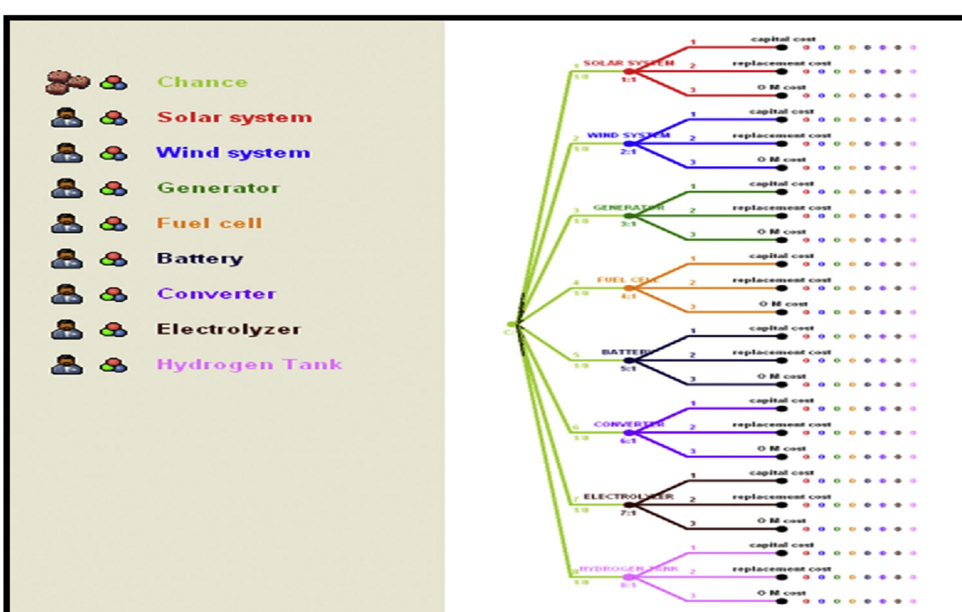

Fig. 4 – General architecture of Gambit.

Table 2 – Payoff function of hybrid renewable energy system.

	Total individual cost	Payoff value of individual system	Cost classification	Payoff function	Solar system
Solar system	4178	4178/39,895 = 0.104	C.C. = 3600	3150/4178 = 0.75	3150/3150 = 1
			R.C. = 880	880/4178 = 0.21	880/880 = 1
			O.M. = 45	120/4178 = 0.028	120/120 = 1
Wind system	20,147	20,147/39,895 = 0.505	C.C. = 12,800	12,800/20,147 = 0.63	3150/12,800 = 0.246
			R.C. = 4500	4500/20,147 = 0.22	880/4500 = 0.195
			O.M. = 2500	2500/20,147 = 0.124	120/2500 = 0.048
Generator	3599	3599/39,895 = 0.09	C.C. = 2100	2100/3599 = 0.583	3150/2100 = 1.5
			R.C. = 1500	1500/3599 = 0.416	880/1500 = 0.58
			O.M. = 180	180/3599 = 0.05	120/180 = 0.67
Fuel cell	2400	2400/39,895 = 0.06	C.C. = 1600	1600/2400 = 0.75	3150/1600 = 1.96
			R.C. = 1300	1300/2400 = 0.54	880/1300 = 0.67
			O.M. = 80	80/2400 = 0.034	120/80 = 1.5
Battery	9337	9337/39,895 = 0.23	C.C. = 4200	4200/9337 = 0.45	3150/4200 = 0.75
			R.C. = 4000	4000/9337 = 0.428	880/400 = 2.2
			O.M. = 180	180/9337 = 0.02	120/180 = 0.67
Converter	293	293/39,895 = 0.07	C.C. = 200	200/293 = 0.68	3150/200 = 16
			R.C. = 67	67/293 = 0.21	880/67 = 13
			O.M. = 26	26/293 = 0.08	120/26 = 4.8
Electrolyzer	2757	2757/39,895 = 0.07	C.C. = 2000	2000/2757 = 0.72	3150/2000 = 1.57
			R.C. = 700	700/2757 = 0.25	880/700 = 1.25
			O.M. = 250	250/2757 = 0.09	120/250 = 0.48
H_2 tank	1692	1692/39,895 = 0.0424	C.C. = 800	800/1692 = 0.47	3150/800 = 3.9
			R.C. = 600	600/1692 = 0.35	880/600 = 1.47
			O.M. = 170	170/1692 = 0.1	120/170 = 0.7

solar-wind hybrid renewable energy system. In this analysis chance is considered as a hybrid system. Solar system, wind system, generator, fuel cell, battery, converter, electrolyzer, and hydrogen tank by player 1, player 2, player 3, player 4, player 5, player 6, player 7, player 8 respectively. The cost analysis of hybrid systems of auditorium Sagar, India is done using it. According to HOMER simulation model the net present cost of solar-wind architecture is $37,487.

In Simulink model first chance is divided into 8 players, considering the payoff of different player by percentage of the cost of each player with respect to the total cost of the system. According to that concept Solar system, wind system, generator, fuel cell, battery, converter, electrolyzer, and hydrogen tank consume 10%, 50%, 9% & 6%, 23%, 0.7%, 7%, 4.2% of the total cost of the system. After these three strategies are considered for each player which is capital cost, replacement cost and O&M cost.

The observations gave out a payoff matrix for each player. Payoff matrix calculates the reliability and utility value of different player's w.r.t. a particular player. For example, in Table 2 gives the payoff matrix of the solar system as player 1. In sixth column second row the payoff value is 1 because it is the payoff value of solar system w.r.t. the player 1 as solar system. But in seventh, eighth and ninth column gives the payoff values of the solar system are w. r. t. wind, generator and fuel cell. In matrix such as 4.66 represent wind capital cost is 4 times to a solar system in our analysis. The same procedure is followed for the player 2, 3, 4, 5, 6, 7, 8. Table 2 presents the payoff function of a hybrid renewable energy system.

The result shows that net present cost and the operating cost of the whole system is $37,487 & $991/yr. respectively. The capital cost of wind system is drastically affecting the cost of the whole system because the cost of wind system is 50% of the capital cost of the whole system. Fig. 3 also shows that the average cost per kWh of useful electricity produced by the system is $0.470/kWh, which is also known as the levelized cost of energy. Fig. 5 shows that output of GAMBIT software. Data shows that the payoff value of wind system is much larger than PV system. Table 3 shows that comparative cost analysis of PV–Wind-Fuel cell system through different technique. HOMER result shows that simulation result of PV–Wind-Fuel cell HRES. Further simulated result, optimized with BB-BC & GAMBIT technique to minimize the cost function of the whole system in terms of capital, replacement and O&M cost of individual components. BB-BC and GAMBIT result provide better cost optimization result comparatively HOMER simulated result. The optimization results demonstrate the feasibility and effectiveness of the proposed method BB-BC and GAMBIT in minimizing cost of the hybrid system. The BB-BC and GAMBIT optimization has provide better cost minimization result due to simple algorithm and heuristic method with relatively few control parameters, and the ability to solve problems that depend on large number of variables.

The system designed is for the study area where in PV–Wind-Generator-Battery system is supposed to be the best option hence studied for these options only. However GAMBIT and BB-BC are also applicable in two player system such as Wind-Generator system, Solar-Generator system, Biogas-Generator system and Biogas-Solar system. The two player system also analyzes payoff function of individual player and finds optimal point of Nash equilibrium and with the help of centre of mass. This manuscript includes complete system which consist solar system, wind system, hydrogen tank, electrolyzer, generator, converter and fuel cell.

Wind system	Generator	Fuel cell	Battery	Converter	Electrolyzer	H_2 tank
12,800/3150 = 4.66	2100/3150 = 0.67	1600/3150 = 0.5	4200/3150 = 1.3	200/3150 = 0.63	2000/3150 = 0.63	800/3150 = 0.25
4500/880 = 5.11	1500/800 = 1.7	1300/800 = 1.47	4000/880 = 4.5	67/880 = 0.07	700/880 = 0.79	600/880 = 0.68
2500/120 = 20.8	180/120 = 1.5	80/120 = 1.5	180/120 = 1.5	26/120 = 0.2	250/120 = 2.08	170/120 = 1.41
12,800/12,800 = 1	2100/12,800 = 0.164	1600/12,800 = 0.125	4200/12,800 = 0.32	200/12,800 = 0.015	2000/12,800 = 0.156	800/12,800 = 0.0625
4500/4500 = 1	1500/4500 = 0.33	1300/4500 = 0.28	4000/4500 = 0.88	67/4500 = 0.0148	700/4500 = 0.0156	600/4500 = 0.13
2500/2500 = 1	180/2500 = 0.072	80/2500 = 0.032	180/2500 = 0.072	26/2500 = 0.01	250/2500 = 0.1	170/2500 = 0.068
12,800/2100 = 6.09	2100/2100 = 1	1600/2100 = 0.76	4200/2100 = 2	200/2100 = 0.09	2000/2100 = 0.95	800/2100 = 0.38
4500/1500 = 3	1500/1500 = 1	1300/1500 = 0.86	4000/1500 = 2.67	67/1500 = 0.04	700/1500 = 0.467	600/1500 = 0.4
2500/180 = 13.9	180/180 = 1	80/180 = 0.45	180/180 = 1	26/180 = 0.144	250/180 = 1.39	170/180 = 0.94
12,800/1600 = 8	2100/1600 = 1.31	1600/1600 = 1	4200/1600 = 2.625	200/1600 = 0.125	2000/1600 = 1.25	800/1600 = 0.5
4500/1300 = 3.46	1500/1300 = 1.15	1300/1300 = 1	4000/1300 = 3.07	67/1300 = 0.05	700/1300 = 0.53	600/1300 = 0.46
2500/80 = 31.25	180/80 = 2.25	80/80 = 1	180/80 = 2.25	26/80 = 0.325	250/80 = 3.125	170/80 = 2.125
12,800/4200 = 3.04	2100/4200 = 0.5	1600/4200 = 0.38	4200/4200 = 1	200/4200 = 0.047	2000/4200 = 0.47	800/4200 = 0.19
4500/4000 = 1.125	1500/4000 = 0.375	1300/4000 = 0.325	4000/4000 = 1	67/4000 = 0.016	700/4000 = 0.175	600/4000 = 0.15
2500/180 = 13.9	180/180 = 1	80/180 = 0.44	180/180 = 1	26/180 = 0.144	250/180 = 1.39	170/180 = 0.94
12,800/200 = 64	2100/200 = 10	1600/200 = 8	4200/200 = 21	200/200 = 1	2000/200 = 10	800/200 = 4
4500/67 = 67	1500/67 = 22	1300/67 = 19.4	4000/67 = 60	67/67 = 1	700/67 = 10	600/67 = 9
2500/26 = 96	180/26 = 7	80/26 = 3	180/26 = 7	26/26 = 1	250/26 = 10	170/26 = 6
12,800/2000 = 6.4	2100/2000 = 1.05	1600/2000 = 0.8	4200/2000 = 2.1	200/2000 = 0.1	2000/2000 = 1	800/2000 = 0.4
4500/700 = 6.42	1500/700 = 2.14	1300/700 = 1.85	4000/700 = 5.71	67/700 = 0.09	700/700 = 1	600/700 = 0.85
2500/250 = 10	180/250 = 0.72	80/250 = 0.32	180/250 = 0.72	26/4000 = 0.0065	250/250 = 1	170/250 = 0.68
12,800/800 = 16	2100/800 = 2.62	1600/800 = 2	4200/800 = 5.25	200/800 = 0.25	2000/800 = 2.5	800/800 = 1
4500/600 = 7.5	1500/600 = 2.5	1300/600 = 2.167	4000/600 = 6.67	67/600 = 0.111	700/600 = 1.167	600/600 = 1
2500/170 = 14.7	180/170 = 1.05	80/170 = 0.47	180/170 = 1.05	26/170 = 0.15	250/170 = 1.47	170/170 = 1

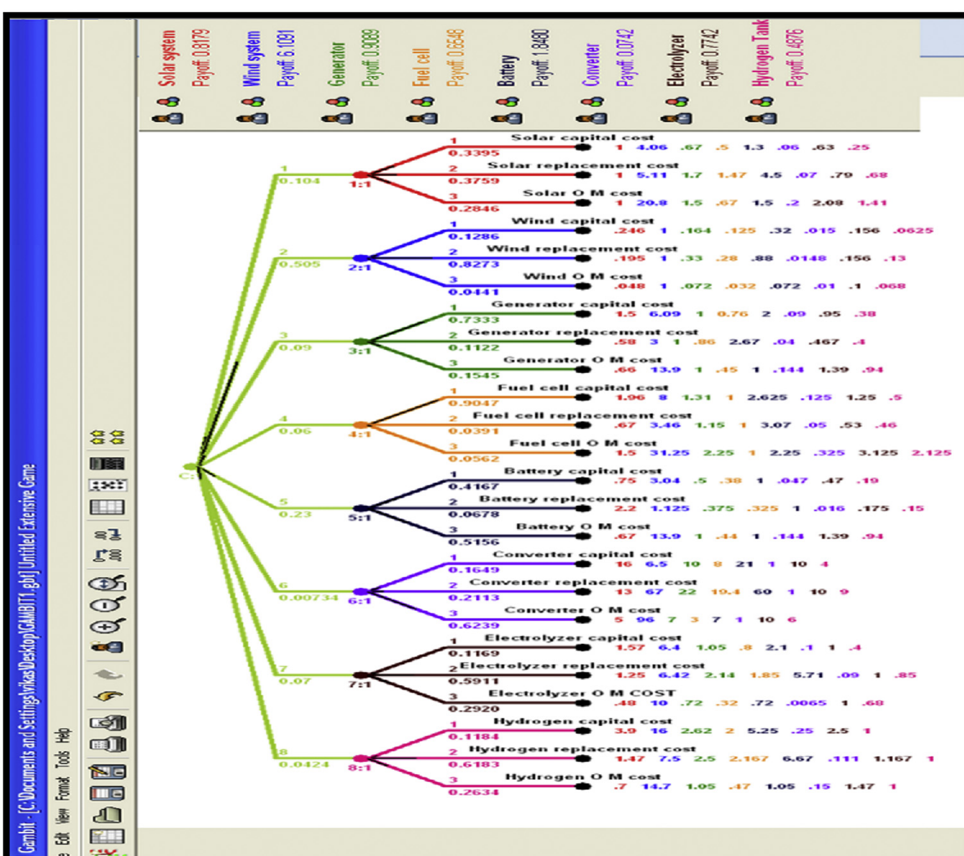

Fig. 5 – Output structure of GAMBIT technique.

Table 3 – Comparative cost analysis of PV–wind system.

Component	Cost	HOMER	BBC	GAMBIT
Solar system	Capital cost	3150	2850	2771
	Replacement cost	880	800	790
	O & M cost	120	90	88
Wind system	Capital cost	12,800	11,880	12,000
	Replacement cost	4500	4600	4218
	O & M cost	2500	1887	1900
Generator	capital cost	2100	1990	1870
	Replacement cost	1500	1450	1350
	O & M cost	180	160	157
Fuel cell	Capital cost	1600	1470	1400
	Replacement cost	1300	1117	1200
	O & M cost	80	67	45
Battery	Capital cost	4200	4167	4000
	Replacement cost	4000	3760	3750
	O & M cost	180	160	147
Converter	Capital cost	200	200	200
	Replacement cost	67	65	61
	O & M cost	26	20	12
Electrolyzer	Capital cost	2000	1870	1745
	Replacement cost	700	667	640
	O & M cost	250	210	200
Hydrogen tank	Capital cost	800	770	710
	Replacement cost	600	580	540
	O & M cost	170	165	165

Regression analysis

Linear regression calculates an equation that minimizes the distance between the fitted line and all of the data points. Technically, ordinary least squares (OLS) regression minimizes the sum of the squared residuals. In general, a model fits the data well if the differences between the observed values and the model's predicted values are small and unbiased. In this thesis regression analysis is done for cost analysis of solar wind hybrid renewable energy system which is calculated from HOMER, BB-BC and GAMBIT software. In this analysis R square, adjusted R square and F-Statistics are used as equation parameter. Where R-squared is a statistical measure of how close the data are to the fitted regression line. It is also known as the coefficient of determination, or the coefficient of multiple determination for multiple regression.

The definition of R-squared is fairly straightforward; it is the percentage of the response variable variation that is explained by a linear model:

$$R - \text{squared} = \text{Explained variation}/\text{Total variation}$$

R-squared is always between 0 and 100%:

- 0% indicates that the model explains none of the variability of the response data around its mean.
- 100% indicates that the model explains all the variability of the response data around its mean.

In general, the higher the R-squared, the better the model fits your data. In our cost analysis R squared and adjusted R squared value is **0.9995** and **0.9993** respectively, which shows all the variability of the cost data around its mean.

Table 4 – Regression parameter.

Regression parameter	
R squared	0.9995
Adjusted R squared	0.9993
Durbin-Watson statistic	3.265
Negative autocorrelation detected	0.81–1.69
Critical F-statistic – 95% confidence	3.112
Confidence to which analysis holds	86.00%

Table 5 – Multi-collinearity of different independent variable.

Multi-collinearity	
Adjusted R-squared against other indep.	Variables with RSQ at >90%
99.99%	CPSO,BB-BC,GAMBIT

In statistics, the Durbin–Watson statistic is a test statistic used to detect the presence of autocorrelation (a relationship between values separated from each other by a given time lag) in the residuals (prediction errors) from a regression analysis. A number that tests for autocorrelation in the residuals from a statistical regression analysis. The Durbin-Watson statistic is always between 0 and 4. A value of 2 means that there is no autocorrelation in the sample. Values approaching 0 indicate positive autocorrelation and values toward 4 indicate negative autocorrelation. In this analysis Durbin-Watson is 3.265, which shows negative autocorrelation. Table 4 represents a regression parameter related to the cost analysis of a hybrid renewable energy system which is calculated by HOMER, BB-BC and GAMBIT software. Table 5 shows Multi-Collinearity of different optimization technique.

Conclusion

An exhaustive study of the behavior of a BBC & GAMBIT applied to the design of hybrid system of electrical energy generation has been carried out. A PV–Wind-Generator-Battery system has been used, as this is one of the most complex systems possible to design. The performances of the cost function, membership, function, and payoff function of energy system have been studied. From the obtained result, it is possible to recommend the values of HOMER, BBC & GAMBIT valid for any hybrid system desirable to design. GAME theory and BB-BC provide better attribute because it provides a framework for assessing hybrid renewable energy system where the decision making entities respond to heterogeneous objectives and incomplete information. The study developed the application of game theory in hybrid renewable energy system and provides strategic decision to find out the best response from solar and wind energy system. The result from simulation of integrated renewable system in HOMER shows that PV–wind-Fuel cell battery-generator is the most economical solution to design integrated systems with minimum net present cost. From the simulation result, the total production of electrical energy is the combination of energy produced by solar system (34%), wind system (64%), diesel generator (1%) and fuel cell (1%). The net present cost of the hybrid renewable energy system is $39,557, operating cost is $977/yr. and levelized cost of energy is $0.505/kWh. In our cost analysis R squared and adjusted R squared value is **0.9995** and **0.9993** respectively, which shows all the variability of the cost data around its mean. Result shows renewable energy fraction is 99%, which present this system is better through environment point of view.

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