Optimization of an autonomous hybrid renewable energy system using reformed electric system cascade analysis

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Abstract—**This paper presents reformed electric system cascade analysis (RESCA) technique for optimization of hybrid renewable energy system (HRES) comprising of wind energy conversion system (WECS), photo-voltaic system (PV), battery energy storage system (BESS) and non-intermittent source (NIS). Optimization constraints of final excess energy (FEE), energy generation ratio (EGR), cost of energy (COE), net present cost (NPC) and renewable energy fraction (REF) are considered for the optimization of the system. This optimization is realized for an isolated load comprising of the 10 households in Malaysia with a daily consumption of 84.5 kWh. On successful implementation of RESCA with different constraints it is found that the optimum size of energy sources for the HRES varies depending on the chosen constraints. Also, the net present cost (NPC) of the system can be considerably reduced on introduction of NIS to the HRES. RESCA provides the user with better insight into the influence of variation of PV and WECS power generation while identifying the optimal size of energy storage unit. The optimized results obtained are also compared with benchmark HOMER software to validate the methodology.**

Index Terms—**Batteries, design optimization, hybrid power system, iterative algorithm, solar energy, wind energy.**

I. INTRODUCTION

Due to the ever-increasing demand of energy in the world along with greater awareness towards the harmful impacts of the convention fossil fuels, has brought acute attention to renewable energy generation in past two decades. Among renewable sources the most popular resources are wind and PV [1]. PV system has ease of installation and lower maintenance cost, PV installation capacity of the world at the end of 2017 is 397 GW which is projected to increase to 489 GW by 2020 and 1760 GW by 2030 [2]. Wind energy is also a fast growing green energy source with worldwide installation capacity of 540 GW at the end of 2017 which is expected to increase to 800 GW by 2020 and 2000 GW by 2030 [2]. Penetration of renewable energy into to the current grid reduces the energy demand from the conventional energy sources, but recently stand-alone hybrid systems with high renewable energy penetration has gained popularity for complete pollution free energy generation, especially for isolated loads which are not connected to the grid [3]–[6]. Due to uncertainty in renewable sources like solar and wind it is prudent to add storage unit to the isolated system. Addition of storage unit increases the cost and control complexity of the system but provides higher reliability of power supply [7], [8]. Multiple energy sources and storage unit control complexity creates the problem of optimal sizing of the system components. There are many techniques

adopted by researchers for optimization of Hybrid Energy System (HES), e.g., Upadhyay et al. [9] have found the most economic configuration of HES with diesel generator using Particle Swarm Optimization (PSO). Maleki et al. [10] have found PSO to be the most effective technique among other Artificial Intelligence (AI) techniques for optimization of HES with battery and fuel cell as storage systems. Katsigiannis et al. [11] have used Simulated Annealing (SA) and Tabu Search (TS) techniques to find optimum scheduling of small autonomous power system to reduce the cost of energy. Paliwal et al. [12] have carried out the reliability analysis of isolated HRES in a rural area using PSO. Koutroulis et al. [13] used Genetic Algorithm (GA) for optimization of a HES comprising of PV, WECS and diesel generator feeding a desalination system. Bahramara et al. [14] have presented literature review of various studies for optimal planning of isolated HRES using HOMER. Hove et al. [15] using RETScreen presented economic analysis of a HES consisting of PV and diesel generators based on renewable energy fraction. Singh et al. [16] have compared grid connected and isolated mode of operation of a HRES feeding a residential load in Mumbai based on COE using HOMER. The software tools which can be used for the optimization process as presented in [17] and the application AI techniques for optimization of HES are presented in [10]. The major drawbacks of software tools like HOMER, RETScreen, HYBRID2, etc. are, that the user has to input the size of the various components and the software provides results based on only the input range, whereas, the optimum solution can lie outside the input range of the user. HOMER considers only a single objective function to minimize the NPC and it does not consider intra hour variability [17]. HYBRID2 has limited access to the system parameters [17]. iHOGA can simulate loads limited to average daily consumption of 10 kWh and sensitivity and probability analysis is not included [17]. These software basically provide the most feasible solution based on economics and does not guide the user to a predefined type of solution based on performance parameters. The underlying optimization process is hidden from the user, who gets no idea or feedback to why the solution obtained is the best. For Artificial Intelligence (AI) techniques, prior knowledge of the working of these techniques is required. It is somewhat difficult to correlate and find analogues parameters and functions for these techniques to optimize HRES. For GA approach, finding the best solution is not guaranteed, as it depends on the maximum generation set and the optimal solution may not be analyzed. For neural network techniques, the solution depends on the training process and after the system is trained introducing flexibilities in evaluation is

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problematic [18]. For fuzzy logic approach, estimation of membership function is a difficult and time consuming process [18]. The major drawbacks of AI techniques are that for complex system with several system components the solution complexity, convergence time and computation power required increase [18].

Therefore, a novel RESCA technique is introduced in this paper. It is a systematic and simple technique for the optimization of HRES which provides better insight into the sizing of energy sources and storage unit with its cascade table and its graphical representations.

RESCA is a technique which is primarily based on pinch analysis, used during optimization of raw material like heat, mass, carbon and gasses [19]. Wan et al. [20] implemented this method to minimize the outsourced electricity for a grid connected load. Bandyopadhyay [21] implemented power pinch analysis (PoPA) for the design and optimization of battery storage unit of an isolated energy system. Ho et al. [22] further improved upon this technique and introduced a new iterative method of ESCA which could optimize both the non-intermittent source of biomass and energy storage unit for distributed generation system. Ho et al. [23] further extended the research to optimize an isolated system with intermittent source of PV and BESS. All these works provide a deep insight into the successful implementation of PoPA and ESCA in optimization of the renewable energy system. RESCA is therefore developed as an extension to the work of Ho et al. [22] and is capable of handling multiple energy sources like PV, WECS and NIS. Also incorporated into RESCA is its ability of handling multi-constraint optimization of the HRES system.

The subsequent paper is organized as follows: Section II. describes the isolated HRES configuration with mathematical models of system components. Section III, briefly describes various optimization constraints and mathematical expression. Section IV, introduces the RESCA methodology and elucidates various optimization algorithm. Section V. presents the results obtained on implementation of the RESCA technique for the case study and also compares them with that obtained from HOMER. Finally, Section VI. provides important conclusion from the results.

II. ISOLATED HYBRID SYSTEM CONFIGURATION

The irregular power generation from a single renewable energy source can be reduced by combining more than one energy sources. The most commonly used combined energy sources are PV and wind systems as they use two different energy source for power generation, using them together can achieve synergy in the following ways [24]:

 i. Stabilize output power generation.
 ii. Seasonal variations are equalized.
 iii. Reduction in size of energy storage system.
 iv. Reduction in size of NIS if used.

The architecture of the renewable energy sources can be broadly classified into three categories AC bus, DC bus and hybrid architecture consisting of both AC and DC buses. The choice of AC or DC bus architecture can be made based on the comparison presented in Table I [25], [26]. The hybrid architecture which is adopted in this paper is also implemented by benchmark software like HOMER, HYBRID2, TRNSYS, etc. It incorporates the advantages of both AC bus and DC bus architecture by reducing the conversion stages thereby reducing the cost and increasing the reliability of the system.

The architecture of the HRES is shown in Fig. 1 [27], [28]. It consists of a PV system and BESS connected to a DC bus. The WECS, primary load, dummy load and NIS are connected to the AC bus. It is assumed that output voltages of system components are in synchronization with the buses they are connected to. The AC and DC bus are linked by a converter. The energy losses during power conversion and charging/discharging of the battery are taken into consideration during the analysis. The motive for adding NIS on the AC bus is to further reduce the system cost which is presented in later section of this paper. The advantage of adding a dummy load is that it can absorb the excess energy which can no longer be stored in the BESS. This dummy load can be water heating system, space cooling system, etc. Brief modelling of the main subsystems is shown in Fig. 1.

Table I Comparison of AC bus and DC bus HRES architecture

| Parameter	AC bus	DC bus
Topology	Complex with larger converter stages	Relatively simple
Controller complexity	Difficult as AC system transients are more complex	Easier as topology is relatively simpler
Power quality issues	Relatively complex as voltage, frequency power factor and phase angle have to be controlled	Only voltage issue is to be catered therefore higher power quality can be provided to the consumer
Efficiency	Less efficient (more conversion stages)	More efficient (less conversion stages)
Standardization	Better AC standards existing	Still under construction
Protection	Better protection techniques as existing AC protection systems can be employed	DC protection is difficult and still under research
Stability	Less stable as voltage and frequency synchronization is required for all the components	More robust as only voltage needs to be controlled
Reliability	Lower than DC, as more devices are used leading to higher probability of failure	Higher
Cost	Relatively lower cost if existing system devices are used.	Relatively less costly if a completely new system architecture is designed
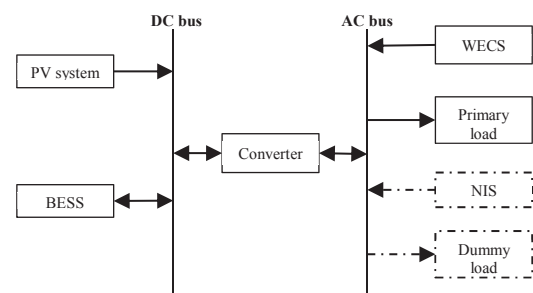
Fig. 1 Block diagram of hybrid energy system

A. *PV model*

The PV module performance is dependent on various factors like solar radiation, temperature and other weather variables. The hourly energy output from a PV module of area A_{PV} can be calculated by (1) [29]:

$$G_t^{PV} = N_{PV} * R_t * A_{PV} * \eta_{PV} \qquad (1)$$

Where, G_t^{PV} is the hourly energy generation in Wh from the PV generation system, N_{PV} is the number of PV units, R_t is the

hourly solar radiation in Wh/m^2 and η_{PV} is the efficiency of the PV conversion system.

B. *Wind energy conversion system model*

The power output from a wind turbine is strongly dependent on wind speed. The cut-in speed v_c is the wind speed above which the wind turbine generates electricity. The power output increases in accordance to Weibull shape parameter till the rated speed v_r is achieved. Between rated speed and cut-out speed v_f, the power output remains constant at the rated power, P_r. Beyond v_f, power generation reduces to zero to maintain the mechanical integrity of the WECS [30]. Therefore the hourly wind turbine generation can be written as (2) [31], [32]:

$$G_t^W = \begin{cases} P_r \dfrac{v^k - v_c^k}{v_r^k - v_c^k}, & v_c < v < v_r \\ P_r & , v_r < v < v_f \\ 0 & , otherwise \end{cases} \quad (2)$$

Where, G_t^W is the hourly energy generation of the WECS in Wh, k is the Weibull shape parameter which is assumed to be one, thereby making the increase in power from v_c to v_r linear [33].

The total hourly energy generation of the HRES at the AC bus can be calculated by (3):

$$G_t = (\eta_{conv.} \times G_t^{PV}) + G_t^W \quad (3)$$

Where, G_t is the net hourly energy generation at AC bus in Wh and η_{conv} is the converter efficiency. The WECS is connected directly to the AC bus where the load voltage and WECS output voltage is in synchronization with AC bus voltage, therefore no conversion loss is encountered by the WECS in furnishing primary load.

C. *Battery energy storage system model*

BESS is an essential part of the HRES as it increases the reliability of the system by providing power to the load, when energy sources are unable to cater the primary load. During excess energy generation from the PV and WECS the BESS is charged and during deficiency of energy generation BESS is discharged to carter to the primary load. The net hourly surplus energy is given by (4) which is used to simulate the BESS.

$$N_t = G_t - L_t \quad (4)$$

Where, L_t is the hourly load demand in Wh, and N_t the net hourly surplus generation in Wh.

The batteries are charged when N_t is positive as shown in (5) [34]:

$$C_t = \begin{cases} N_t * \eta_{char} * \eta_{conv.}, & N_t > 0 \\ 0 & , N_t \leq 0 \end{cases} \quad (5)$$

Where, C_t is the hourly energy by which BESS is charged in Wh, η_{char} is the charging efficiency.

The batteries are discharged when N_t is negative as shown in (6) [34]:

$$D_t = \begin{cases} N_t/(\eta_{disch} * \eta_{conv.}), & N_t < 0 \\ 0 & , N_t \geq 0 \end{cases} \quad (6)$$

Where, D_t is the hourly energy by which BESS is discharged in Wh, η_{disch} is the discharging efficiency. In both charging and discharging of the BESS the conversion losses have been considered.

The net cumulative energy of the BESS after the load has been catered, can be calculated by (7).

$$CE_t = CE_{t-1} + C_t + D_t \quad (7)$$

Where, CE_t is the cumulative energy in the current time interval in Wh and CE_{t-1} is the cumulative energy in the previous time interval in Wh.

The number of batteries required for the BESS can be calculated as shown in (8) [34]:

$$N_{bat} = \frac{NCE_t(max)}{I_{bat} * V_{bat} * DOD} \quad (8)$$

Where, N_{bat} is the number of batteries in the BESS, NCE_t is the net cumulative energy after pinch point adjustment in Wh, DOD is the depth of discharge of battery, V_{bat} is the output voltage of the battery and I_{bat} is the charge capacity of the battery in Ah. The BESS energy management strategy is shown in Fig. 2, where SOC is state of charge of battery.
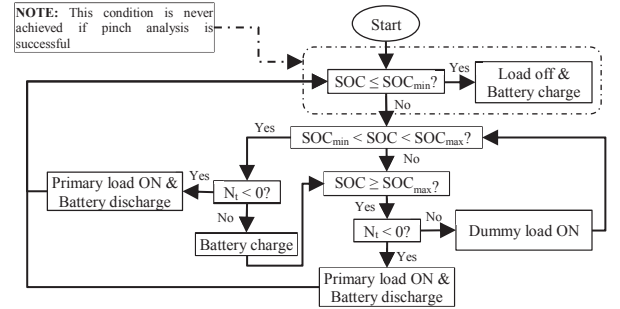

Fig. 2 Battery energy management strategy

D. *Converters*

The converter is an essential part of the system architecture as it helps in the flow of power between the AC and DC components. The converter capacity is given by (9) [23]:

$$P_{conv} = \frac{\max(G^{PV}L_t, G^W)}{\eta_{conv.}} \quad (9)$$

Where, P_{conv} is the rating of the converter in Watts.

The converter has three primary conversion, firstly the energy conversion of DC power from PV to AC bus, secondly conversion of AC power from WECS to DC bus to charge the BESS after load is furnished and thirdly, from DC to AC conversion of the energy when BESS is catering to the load. Therefore, the maximum load encountered during these conversion is used to find the converter rating.

III. OPTIMIZATION CONSTRAINTS

There are various constraints like cost of energy, annual system cost, net present cost, energy generation ratio, etc. on which the HRES can be optimized. The RESCA technique is implemented with few of these constraints as explained below.

A. *Final excess energy (FEE)*

FEE is a primary constraint which helps to find the most optimum size of the BESS for the HRES based on reliability of the system, hence for multi-constraint optimization evaluation of *FEE* is mandatory for isolated HRESs. FEE is net charge accumulated in the BESS at the end of time period of analysis and is expressed as the difference between the charge in BESS at the end and beginning of the analysis, which can be calculated by (10):

$$FEE = CE_{t=T} - CE_{t=0} \quad (10)$$

Where, T is the time period of the analysis. Reducing the FEE helps in optimizing the size of the BESS and thereby reducing the cost.

FEE also helps in estimating the reliability of the system by evaluation of Loss of Load (*LOL*), Loss of Power Supply

Probability (*LPSP*) [35] and System Average Interruption Duration Index (*SAIDI*), defined under IEEE Standard 1366-2003 as ratio of duration of interruption and duration of operation [36] . They can be evaluated using (11-14).

$$LOL = \begin{cases} 0, & FEE \geq 0 \\ FEE, & FEE < 0 \end{cases} \quad (11)$$

$$LPSP = \begin{cases} 0, & FEE \geq 0 \\ \dfrac{FEE}{\sum L_t * T}, & FEE < 0 \end{cases} \quad (12)$$

$$SAIDI = \frac{t_{intrupt}}{T} \quad (13)$$

$$where, t_{intrupt} = \sum_{t=1}^{T} t \quad \forall \; CE(t) < 0 \quad (14)$$

A positive *FEE* over-estimates the storage unit size which leads to excess charge accumulation in BESS with a reliability of unity. Whereas, a negative *FEE* under-estimates the BESS which leads to depletion of charge in the BESS during cyclic system operation leading to loss of supply and reliability < 1. During optimization ideally FEE = 0, but it is preferred to keep *FEE* slightly greater than zero, as it makes the system capable of handling slight variation in load demand. Also, the excess charge, if generated can be provided to dummy load making the system balanced at all times. This flexibility is not conceivable in case *FEE* is chosen slightly less than zero. For the scope of this paper all considered systems are optimized with zero loss of power.

B. *Cost of energy (COE)*

COE is an important constraint as it helps to estimate the cost of each energy unit generated by HRES. The main aim of choosing this constraint is to find the most optimum combination of number of PV and WECS which has the minimum cost of energy generation. *COE* of the system is calculated in (15) [35]:

$$COE = \frac{(CRF * C_{TSC})}{365 * \sum_{t=1}^{24} L_t} + LCE_{NIS} \quad (15)$$

Where, $C_{TSC} = N_a * \left(\sum_{a \in PV,W,bat} (C_{C,a} + C_{M\&O,a} + C_{I,a}) \right) + C_{BOS} \quad (16)$

and, $CRF = \frac{r*(1+r)^i}{(1+r)^i - 1} \quad (17)$

Where, *CRF* is the capital recovery factor determined by (13), *r* is the annual rate of interest, *i* is the lifetime of the system which is assumed to be 25 yrs., C_{TSC} is the total system cost, *LCE* is levelized cost of energy of *NIS* system used, C_C is the capital cost of components, $C_{M\&O}$ is the maintenance and operation cost of the components and C_I is the installation cost of the system, C_{BOS} is balance of system cost. As can be seen from (15-17) the total system cost is inclusive of all expenses, to get the most accurate *COE* value.

C. *Energy generation ratio (EGR)*

EGR is calculated for system with more than one energy generation source and a balance of power generation between the energy sources has to be maintained. The *EGR* for a system consisting of PV and WECS as energy sources is given by (18):

$$EGR = GF_W / GF_{PV} \quad (18)$$

$$where, GF_W = \frac{\sum_{t=1}^{T} G_t^W}{\sum_{t=1}^{T} G_t^W + \sum_{t=1}^{T} G_t^{PV}} \quad (19)$$

$$and \;\; GF_{PV} = \frac{\sum_{t=1}^{T} G_t^{PV}}{\sum_{t=1}^{T} G_t^W + \sum_{t=1}^{T} G_t^{PV}} \quad (20)$$

Where, GF_W and GF_{PV} is the generation fraction of WECS and PV respectively. *EGR* > 1 signify that the energy generated by WECS is more than energy generated by PV, *EGR* < 1 signify that the energy generated by PV is more and *EGR* of one signifies that the energy generated by WECS and PV are equal in the time period of analysis.

D. *Renewable energy fraction (REF)*

Unlike wind and PV, energy generation from *NIS* is continuous and is independent of the weather condition. *NIS* may be added to the hybrid system thereby reducing the size of PV, WECS and BESS required and also increasing the reliability of the system [37]. The drawback of *NIS* is that the maintenance and operation cost of such systems is higher in comparison to wind and PV, as a constant supply of fuel is required. The *REF* is calculated in (21) as mentioned [38], [39]:

$$REF = 1 - \frac{\sum_{t=1}^{T} G_t^{NIS}}{\sum_{t=1}^{T} L_t} \quad (21)$$

Where, G_t^{NIS} is the hourly energy generated by *NIS* in Wh. It is assumed that the *NIS* produces a constant power equal to its rating during the time interval of analysis. Due to the harmful impact of fossil fuel based *NIS* like diesel generators, renewable *NIS* like bio-mass generator, micro-hydro or even geothermal generation may be considered depending on the fuel availability and location of the site. For the scope of this paper bio-mass generator is chosen as the *NIS*. Due to the higher cost of the *NIS* the *REF* should be prudently chosen by the system planner.

IV. REFORMED ELECTRIC SYSTEM CASCADE ANALYSIS

Due to various components of the HRES, optimization of the size of each component is necessary for economic and reliability reasons. Thus, the RESCA technique incorporates different optimization constraints like *FEE*, *COE*, *NPC*, *EGR*, and *REF* for the optimization process. The conjectural basis of RESCA is power pinch analysis, a novel technique which is used to determine the size of the storage unit after the optimization of the energy source. All the algorithms of RESCA implementation require a common approach of extracting data and creation of a cascade table. The list of data required for the construction of cascade table are as follows: time period of analysis, hourly load demand, hourly solar radiation profile, hourly wind speed profile, PV module efficiency and rated power, wind turbine cut-in, cut-out, and rated speed, wind turbine rated power, converter efficiency and characteristics of battery. Hybrid cascade table (HCT) is unified in RESCA for optimization of the energy sources and to find the pinch point of the analysis (obtained after optimization constraints are met). When the data extraction is complete the HCT is generated, as presented in Section V.A, where each row represents one-time step and each column represents a system property which are calculated using (1-10). The novelty and flexibility of RESCA lies in its ability of handling the multi-source optimization irrespective of the initial assumption of energy sources. As shown in algorithms presented in Section IV. (A-C), the common approach is to create a HCT, but updating of energy units size vary depending on the constraints implemented.

A. Algorithm for FEE constraint

FEE is the base constraint for optimization, it is implemented as shown in Fig. 3. The tolerance of *FEE* is set at 100 Wh, if the condition is not met then the energy source size is optimized based on three scenarios.

Scenario 1: If *FEE* is greater than the net energy generated by one wind turbine (P_{w1}) and net energy generated by one PV (Pv_1), then, increase or decrease both N_{PV} and N_W, if *FEE* is negative or positive respectively.

Scenario 2: If *FEE* is less than the $P_{w1} + Pv_1$ and greater than Pw_1, then increase or decrease N_W, if *FEE* is negative or positive respectively.

Scenario 3: If *FEE* is less than the P_{w1}, then increase or decrease N_{PV}, if *FEE* is negative or positive respectively.

These scenario incorporates the inclusion of weather flexibility into optimization. If weather at the site is windier it will lead to higher value of P_{w1} leading to an optimized result which has higher wind generation contribution, if the site location is sunnier, leading to higher P_{v1} the optimized result tilts towards PV generation.
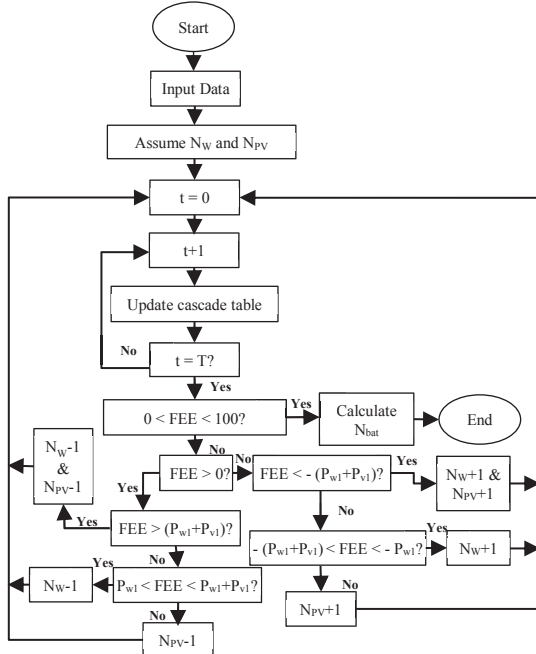
Fig. 3 Algorithm for RESCA implementation with FEE constraint only

B. Algorithm for EGR and FEE constraints

In this multi-criteria optimization, the system is optimized as shown in Fig. 4. The aim of this optimization is to maintain a balance between the energy generated between WECS and PV. The tolerance level of *FEE* is fixed at 100 W and the aim is to optimize the system for an *EGR* of 1 with 10% tolerance. The approach of optimization is as follows:

Scenario 1: For *EGR*>1.10, if *FEE* is negative then N_{PV} is increased and if *FEE* is positive N_W is reduced.

Scenario 2: For *EGR*<0.90, if *FEE* is negative the N_W is increased and if *FEE* is positive N_{PV} is reduced.

Scenario 3: For 0.90<*EGR*<1.10, if *FEE* is positive N_{PV} and N_W are reduced and if FEE is negative N_{PV} and N_W are increased.

C. Algorithm for COE and FEE constraints

In this multi-criteria optimization, the aim is to reduce the *COE* and is implemented as shown in Fig. 5. The approach for optimization is to fix the size of WECS and find the optimized size of PV source based on the *FEE* constraint.

WECS size is then incremented and new optimized size of PV is obtained. All the system configurations are tabulated until the optimized size of the PV obtained is less than 1. Once the tabulation is finished the *COE* for each combination is found, to obtain the best configuration of PV and WECS. It is to be noted that the reason of fixing WECS and not PV is the larger power capacity of each WECS in comparison to PV, which smoothen the approach to criteria realization. Once the tabulation of all optimized configuration is achieved, instead of *COE* any of the economic constraints like *TSC*, *NPC*, *ASC*, etc. can also be evaluated.
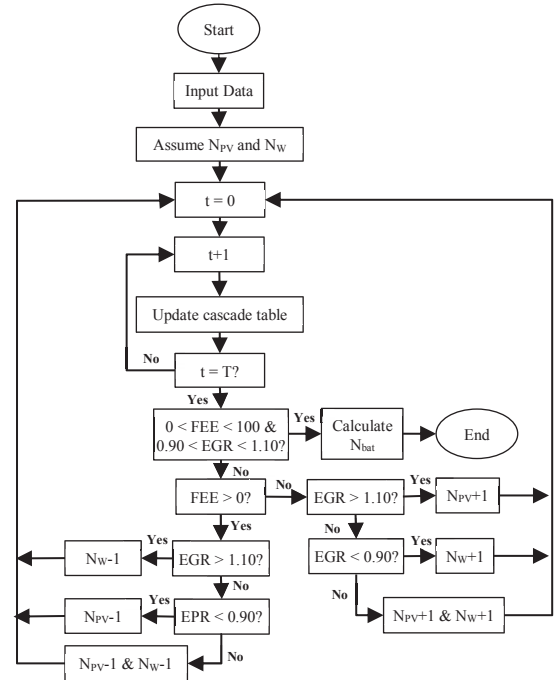

Fig. 4 Algorithm for RESCA implementation with EGR and FEE constraints
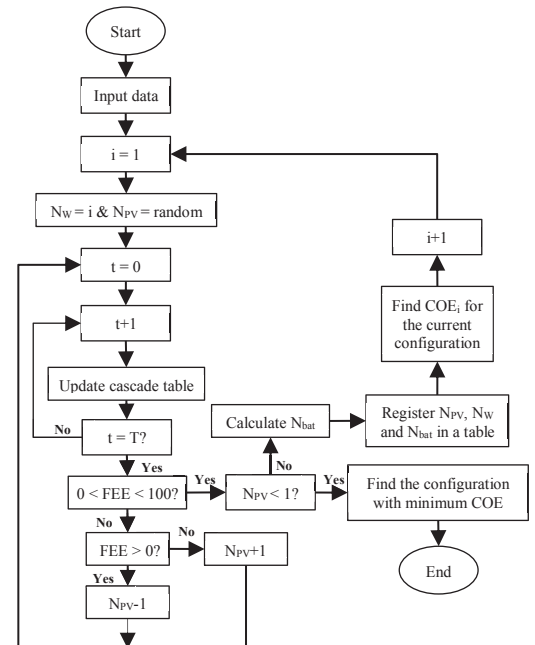

Fig. 5 Algorithm for RESCA implementation with COE and FEE constraints

V. RESULTS AND DISCUSSION

The developed RESCA methodology can be applied to any isolated HRES with PV, WECS, BESS and NIS irrespective

of the site location. For the scope of this paper RESCA is applied for optimization of HRES catering to 10 average households in Malaysia with load, solar radiation and wind speed profile as shown in Fig. 6 [22], [40]. MATLAB software environment is used to implement and programme the solution based on the proposed RESCA. The tolerance for *FEE* constraint is fixed at +100 Wh and *EGR* at 10%. The data required for the construction of the HCT is shown in Table II [29], [41], [42].
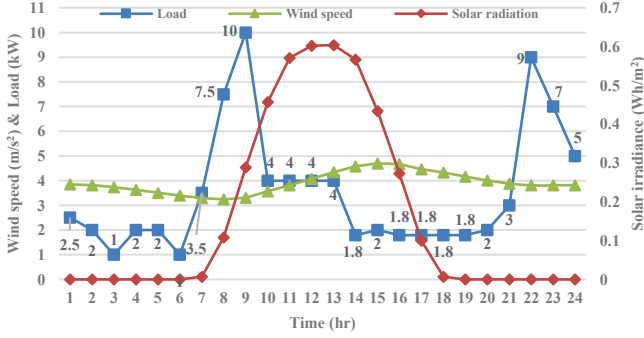

Fig. 6 Load, solar radiation and wind speed variation for the time period of analysis

Table II Data required for system modelling

General data	
Period of analysis	24 hr
Time step	1 hr
PV data	
Type	Mono-crystalline
Efficiency	15%
Area per unit	1.9 m^2
Cost per unit	$135
M&O cost per unit p.a.	$15
Installation cost per unit	$20
Balance of system	$600
Life span	25 yrs.
Wind energy conversion system data	
Type	3 blades, PMSG
Rated power	1000 W
Cut-in speed	2.5 m/s
Rated speed	10 m/s
Cut-out speed	25 m/s
Cost per unit	$1700
M&O cost per unit p.a.	$100
Installation cost per unit	$65
Balance of system	$2000
Life span	25 yrs.
Battery storage data	
Type	Li-ion
Battery capacity per unit	220Ah
Battery voltage	24V
Charging efficiency	88.3%
Discharging efficiency	88.3%
Depth of discharge	90%
SOC_{max}	95%
Cost per unit	$700
Replacement cost	$600
Life span	5 yrs.
Converter data	
Efficiency (dc/ac & ac/dc)	90%

Rating per unit	500 W
Cost per unit	$150
Life span	25 yrs.
NIS levelized cost (bio-mass gen.)	**0.15 $/kWh**

A. *Implementation of RESCA with FEE constraint only*

Implementation of RESCA methodology as shown in Fig. 3 is done with an initial estimate of $N_{PV} = 10$, $N_W = 5$ and zero initial charge in BESS. After 19 iterations, the optimized values of $N_{PV} = 27$ and $N_W = 18$ are obtained with *FEE* = +86 Wh. The HCT table obtained for the optimized size of PV and WECS is shown in Table III. The energy generated by WECS and PV sources and the net energy surplus is shown in Fig. 7. The variations in magnitude of *FEE* and total power generated by PV and WECS with each iteration is presented in Fig. 8. For the initial estimate of $N_{PV} = 10$ and $N_W = 5$, *FEE* is -84.63 kWh which progressively decreases after each iteration as the size of PV and WECS is optimized. As can be seen from Table III, the *CE* reaches a minimum value of -13274 Wh at t = 09:00 hrs, this point acts as the pinch point of the analysis. The energy deficiency at pinch point is the minimum charge required in BESS at the start of the analysis, on addition of this minimum charge a new cumulative energy (NCE_t) column is created. Since all the values of *NCE* are positive therefore no loss of load occurs making the *LOL* = *LPSP* = *SAIDI* = 0 and the pinch analysis is successful. The maximum value of *NCE* (29212 Wh at t = 20:00 hrs.) is put in (8) to obtain $N_{bat} = 6$ (32.12 kWh capacity). The plots of the CE_t, NCE_t and NCE_t with depth of discharge (*DOD*) adjustment are shown in Fig. 9
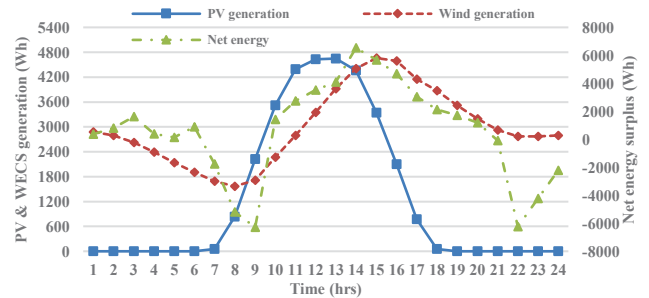

Fig. 7 Net energy required and energy generated by WECS and PV on RESCA implementation with FEE constraint
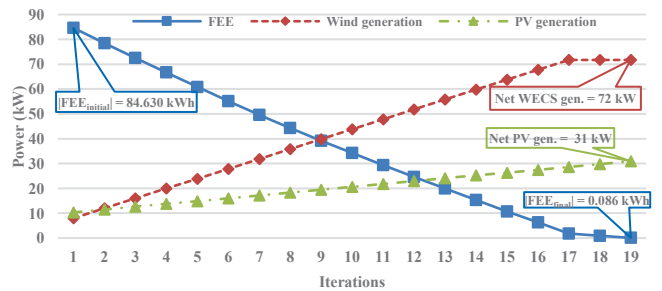

Fig. 8 Variation in magnitude of FEE and energy generated by WECS and PV on RESCA implementation with FEE constraint

Table III Cascade table obtained for RESCA implementation with only FEE constraint for HRES with $N_W = 18$, $N_{PV} = 27$ and $N_{bat} = 6$

T (hr)	L_t (Wh)	R_t (W/m²)	G^{PV}_t (Wh)	W_t (m/s²)	G^W_t (Wh)	N_t (Wh)	C_t (Wh)	D_t (Wh)	CE_t (Wh)	NCE_t (Wh)
1	2500	0	0	3.86	2880	380	302	0	302	**302+13274**
2	2000	0	0	3.82	2795	795	632	0	934	14208
3	1000	0	0	3.74	2626	1626	1292	0	2226	15500
4	2000	0	0	3.63	2393	393	312	0	2538	15812
5	2000	0	0	3.51	2139	139	110	0	2649	15922
6	1000	0	0	3.4	1906	906	720	0	3369	16642
7	3500	7	54	3.3	1694	-1757	0	-2211	1157	14431
8	7500	108	831	3.24	1567	-5185	0	-6524	-5367	7906
9	**10000**	**289**	**2224**	3.31	**1715**	**-6283**	**0**	**-7906**	**-13274**	**0**

| 10	4000	457	3517	3.57	2266	1431	1137	0	-12137	1137
11	4000	571	4394	3.82	2795	2750	2185	0	-9951	3322
12	4000	602	4632	4.08	3346	3515	2793	0	-7158	6116
13	4000	604	4648	4.35	3918	4101	3259	0	-3899	9374
14	1800	567	4363	4.58	4405	6531	5191	0	1291	14565
15	2000	434	3340	4.7	4659	5664	4502	0	5793	19067
16	1800	273	2101	4.67	4595	4686	3724	0	9517	22791
17	1800	100	770	4.46	4151	3043	2418	0	11935	25209
18	1800	7	54	4.33	3875	2124	1688	0	13623	26897
19	1800	0	0	4.16	3515	1715	1363	0	14986	28260
20	**2000**	**0**	**0**	**4.01**	**3198**	**1198**	**952**	**0**	**15938**	**29212**
21	3000	0	0	3.88	2922	-78	0	-98	15840	29114
22	9000	0	0	3.81	2774	-6226	0	-7834	8006	21280
23	7000	0	0	3.81	2774	-4226	0	-5318	2688	15962
24	5000	0	0	3.82	2795	-2205	0	-2774	-86	13188
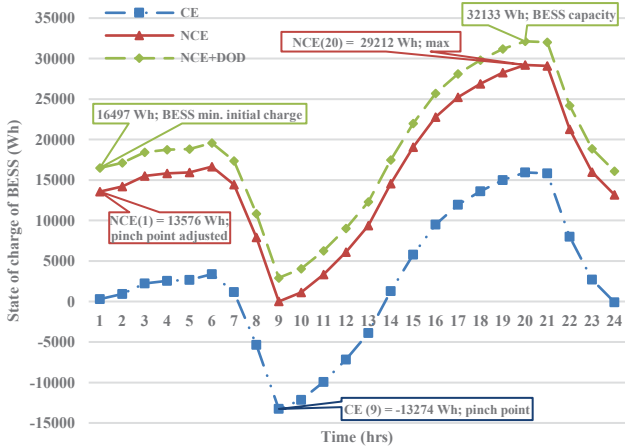
Fig. 9 State of charge of BESS with and without pinch point adjustment on RESCA implementation with FEE constraint

B. Implementation of RESCA with COE and FEE constraints

The application of RESCA with *COE* and *FEE* constraints requires implementation of methodology as shown in Fig. 5. The optimized size of PV with FEE constraint of +100 Wh is obtained as the size of N_W (larger rating energy source) is fixed and increased after PV optimization. N_W is incremented until the optimized size of PV (smaller rated energy source) obtained is less than 1. The different configurations of N_W, N_{PV}, N_{bat}, G_t^{PV} and G_t^W are tabulated and *COE* is found for each configuration using (15-17). The net power generated by WECS and PV and N_{bat} obtained for each configuration is shown in Fig. 10. As N_W is increased the power generated by PV decreases and also there is a sizeable decrease in N_{bat}. The *COE* calculated for each configuration and the energy cost of the PV system and WECS (excluding BESS cost) is presented in Fig. 11. The lowest value of *COE* obtained is 0.4041 \$/kWh for $N_W = 20$, $N_{PV} = 19$ and $N_{bat} = 6$.
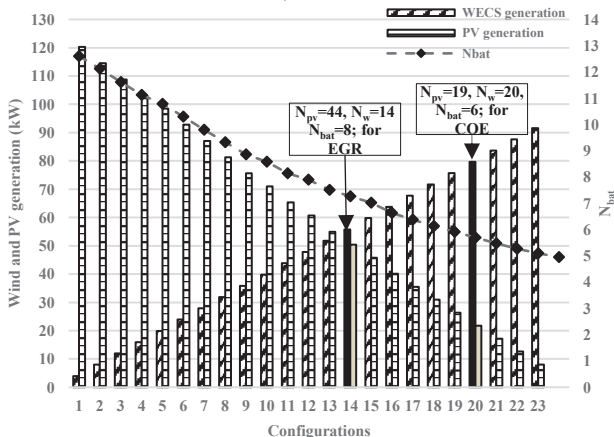

Fig. 10 Variation of energy produced by wind and PV on RESCA implementation with COE constraint

The *COE* of PV is high in comparison to WECS as seen from Fig. 11, therefore in the optimized result obtained the energy generation burden is higher for WECS. For the HRES COE the BESS cost is also included.
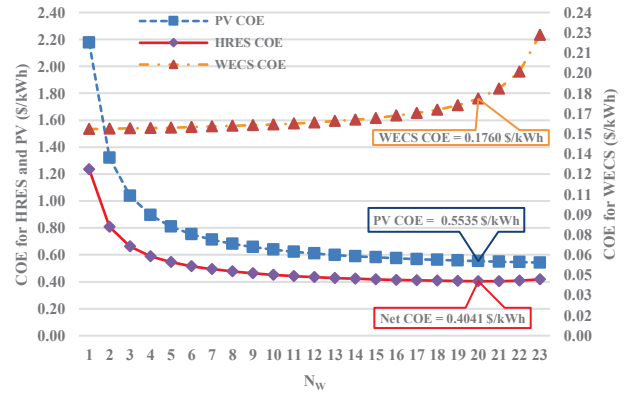
Fig. 11 Variation of COE and cost of energy of WECS and PV on RESCA implementation with COE constraint

C. Implementation of RESCA with EGR and FEE optimization constraints

RESCA methodology as shown in Fig. 4 is implemented for *EGR* and *FEE* constraints. Tolerance of +100 Wh is set for *FEE* and 10% for *EGR*, an initial estimate of $N_{PV} = 5$, $N_W = 5$ and zero initial charge in BESS is assumed. A total of 45 iterations are performed before the constraints are satisfied. The variations in GF_W, GF_{PV}, *EGR* and magnitude of *FEE* with each iteration are shown in Fig. 12.

Fig. 12 Variation of EGR, magnitude of FEE and energy fraction of wind and PV on RESCA implementation with EGR constraint

Initially *FEE* of -98.7 kWh and *EGR* of 3.56 is obtained, but as the iteration progresses the *FEE* decreases and *EGR* is optimized. After 45 iterations optimum values of $N_{PV} = 44$, $N_W = 14$ and $N_{bat} = 8$, are obtained for which the *FEE* = +42 Wh and *EGR* =1.0765.

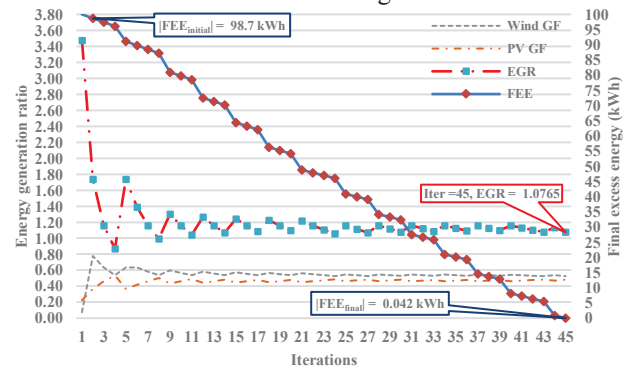### D. *Implementation of RESCA with REF and FEE optimization constraints*

Due to the constant supply of energy provided by the *NIS* (bio-mass generator in this case) the inconsistencies of the energy supply from PV and wind is reduced considerably. For HRES with NIS, the load is reduced by the rating of *NIS* and the optimized system size is found using *FEE* and *EGR* constraints. On the application of RESCA for the load considered the system configuration with increase in *REF* is shown in Fig. 13. As seen from the Fig. 13, as the *REF* increases the size of *NIS* decreases and the energy generation shifts to PV and WECS. Also increase in the storage unit size is observed as *REF* increases, due to irregularity in energy supplied by PV and WECS.
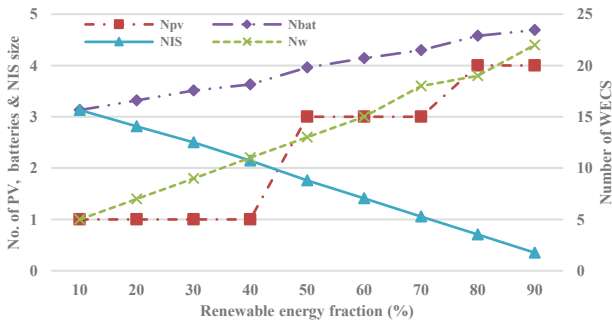

Fig. 13 Variation of number of wind turbines and PV on implementation of RESCA with REF and FEE constraints

E. *Comparison with HOMER and other optimization techniques*

For validating the results obtained from the RESCA methodology the optimization is also performed with HOMER considering an isolated HRES with the PV, WECS and BESS as system components. Since the data considered for analysis is of 24 hours the scaling factor of load and energy sources is set to unity. The sensitivity variable considered for system components are: numbers of WECS 10 to 25, PV system 20 to 50, batteries 4 to 9 and the maximum allowed capacity shortage parameter is set to zero (since RESCA is realized for no loss of power). The optimized results obtained from HOMER is $N_{PV} = 40$, $N_W = 15$ and $N_{bat} = 7$.

HOMER optimizes the system based on only NPC constraint. Therefore, the RESCA is also implemented with NPC and FEE constraint. The methodology adopted for NPC and FEE optimization is similar to that of COE as shown in Fig. 5. But instead of finding the COE of each optimized configuration NPC is found. The formulation of NPC can be found in [43]. A comparative study of the optimized system configurations obtained from RESCA and HOMER is presented in Table IV. The inferences drawn are as follows:

i. The optimized results obtained from RESCA and HOMER for NPC optimized constraint are comparable, which validates the proposed RESCA methodology.

ii. The optimized result obtained from HOMER and RESCA for NPC constraint has higher contribution of PV in comparison to wind.

iii. Since PV system has lower system cost in comparison to WECS, therefore for optimization with NPC constraint has higher contribution of PV in comparison to wind.

iv. The economic analysis in RESCA can also be done based on COE, which shows higher contribution of WECS,

because WECS has lower cost per unit of energy generated in comparison to PV as seen from Fig. 11.

v. The optimized results obtained from RESCA, for all optimization constraints except EGR has higher contribution of wind in comparison to PV.

vi. The BESS capacity increases with increase in the PV system rating because of sizeable irregularities in PV generation.

vii. The converter size rating is fixed by the maximum load.

viii. Reduction in rating of PV, WECS, BESS capacity and NPC is observed with inclusion of NIS.

It is to be noted that economic optimization in case of RESCA can be performed with any of the cost parameters like NPC, TSC, annualized system cost, etc. with change in formulation of the cost parameter (for e.g. COE is chosen for the scope of this paper). But this flexibility is not available in HOMER, which can only optimize based on NPC. To further emphasise the novelty and credibility of RESCA over other optimization techniques, a comparison is presented in Table V.

Table IV Comparison of optimized results obtained for various constraints

Parameter	RESCA						HOMER
	FEE	FEE, COE	FEE, EGR	REF, FEE	REF, EGR	FEE, NPC	NPC
N_w	18	20	14	15	13	15	15
N_{pv}	27	19	44	26	42	38	40
N_{Bat}	6	6	8	6	7	7	7
G_w (kW/day)	72	80	56	60	52	60	60
G_{pv} (kW/day)	31	22	53	30	48	42	45
NIS (kW)	0	0	0	5.28	5.28	0	0
REF (%)	100	100	100	85	85	100	100
NPC ($)	111,493	115,009	118,493	105,983	104,311	110,520	110,930
COE ($/kWh)	0.4064	0.4041	0.4280	0.4222	0.4290	0.4179	0.4182
EGR	2.3184	3.6613	1.0765	2.0064	1.0736	1.5384	1.3333
FEE (Wh)	+86	+29	+42	+32	+62	+98	+286

Table V Comparison of various optimization techniques with RESCA [17], [18], [35], [43]

Optimisation techniques	Demerits	RESCA improvements
Software based	Only considers a single objective function to minimize cost (e.g. NPC for HOMER).	Both reliability and cost can be analysed based on various constraints.
	Minimum time step of analysis cannot be less than one hour.	The time step of analysis can be less than one hour provided data is available.
	The code used for optimization is a "black box" and the user gets no information on why or how the results are obtained.	The user can understand how a particular result is obtained.
	In RETScreen, extraction of time series data is not possible.	It can be extracted.
	In iHOGA, system with maximum daily average load more than 10 kWh cannot be simulated.	No restriction is imposed here.
	In HYBRID2, not all performance parameters can be accessed.	All the system and optimization parameters can be accessed and represented in graphs and tables.
	The optimized results obtained are limited to the input range of the user, while the most optimum solution may lie beyond the predefined range.	Irrespective of the initial assumption, global optimum solution is obtained. However, rate of convergence may be affected.
Artificial Intelligence (AI)	For GA techniques there is guarantee to find the best solution.	Always global optimum solution is found.
	High probability of algorithm converging at a local minima if population generated is not sufficient.	Global optimum solution found is independent of initial assumption.
	For PSO, several modifications are required for AI techniques to be implemented for HRES.	Inherently built for hybrid energy systems.
	For SA, several initial assumptions are required	Only initial assumption of N_{PV}, N_W and BESS initial

	which strongly affect the final result.	charge is required which has no effect on the final result. Though the rate of convergence can be affected.
	For HS, complex optimization problem may lead to premature convergence.	Can handle HRES with different configurations and system components.
	For fuzzy logic approach it is difficult to formulate the membership function.	No such difficulty here.
	Analogues models have to be created thus making system modelling complex.	Inherently built for renewable energy system,
	For neural network technique, higher processing time for training and modelling the system is required.	Processing time and power is relatively less and independent of the system component modelling.

VI. CONCLUSION

This paper has presented the implementation of the RESCA technique for optimization of HRES consisting of PV, WECS and BESS. The versatility of this method lies in its ability of handling multi-criteria and multi-source optimization. The application of RESCA is shown for constraints like *FEE*, *COE*, *NPC*, *EGR* and *REF* for which the optimized configuration of the system components obtained vary depending on the chosen constraints. RESCA has shown its resourcefulness as it manages to provide the user with better insight of the influence of variation in wind speed and solar radiation on the PV and WECS power generation, charging/discharging trends of the BESS and identifying the optimal size of the BESS and energy sources through the cascade table. The results obtained are also compared with HOMER, which shows the flexibility of RESCA over HOMER in case of economic optimization constraints. The credibility of RESCA is bolstered by its capability to overcome drawbacks of other optimization techniques. The application of RESCA is limited for 24 hours time period which will be addressed in the future work for better real-world application of the technique, also the work is in progress for application of RESCA for grid connected HRES optimization.

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