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Multi-Objective Optimization of Hybrid Renewable Energy System Using Reformed Electric System Cascade Analysis for Islanding and Grid Connected Modes of Operation

RANJAY SINGH, RAMESH C. BANSAL, (Senior Member, IEEE), ARVIND R. SINGH, AND RAJ NAIDOO
Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0084, South Africa
Corresponding author: Ranjay Singh (ranjaysingh.c@gmail.com)

ABSTRACT This paper presents a new methodology of reformed electric system cascade analysis (RESCA) for the optimization of hybrid renewable energy system (HRES) with wind energy conversion system, PV system, battery energy storage system, non-intermittent source, and grid as system components. Four different configurations of HRES in islanding and grid-connected mode is considered for analysis. The four configurations of HRES is optimized using RESCA with constraints, such as final excess energy, renewable energy fraction, energy generation ratio, loss of power supply probability, and annual system cost (ASC). The optimization is realized for a residential load in Newark, USA consisting of 100 households with a daily consumption of 30 kWh for each house. The paper successfully presents the application of the RESCA methodology for the optimization of HRES based on reliability and economic constraints for both isolated and grid connected mode of applications.

INDEX TERMS Hybrid power systems, renewable energy sources, wind energy, solar energy, energy storage, optimization methods, iterative algorithm.

I. INTRODUCTION

There has been a constant increase in demand for electrical energy ever since the industrial age. This increase was catered by conventional fuel technologies, but due to the harmful environmental impact of fossil fuels, the focus has now shifted to renewable energy technologies. Renewable energy technologies not only provide clean energy but the input source like wind, solar irradiance, etc. are free of cost [1]. But due to economic and political barriers, the cost of energy from a renewable energy system is still high [2]. A major factor leading to increase in the cost of the renewable energy system is the addition of energy storage systems or multiple energy generating units to compensate for the irregularity in energy generation process [3]. A system consisting of multiple renewable energy sources and energy storage system is called as a HRES. There are two modes of operation of HRES, firstly in islanding mode and secondly, in grid-connected mode, both having its own merits and demerits [4]. Grid-connected mode of operation helps to shave off-peak power requirement from the conventional grid, reduces the spinning reserve of conventional energy generators and HRES in this mode, can also supply power to the grid in case of excess power generation having qualified certain pre-requisites [5]. This mode of operation is favourable for locations where transmission lines are already present and the reliability of supply is important, especially in cities and towns. The islanding mode of operation is favourable for a location which is still off the grid, it helps in the electrification of areas where construction of transmission line is difficult and an expensive affair [6].

The major barrier in the installation of these HRES is to optimize the size/rating of the components of HRES and to decide the mode of operation. Since the cost of renewable energy systems is high, optimum use of the system rating is necessary for the reduction in cost while balancing power supply reliability [7]. Several studies have been conducted in recent time for optimal sizing of Hybrid Energy Systems (HES) which have been summarized in TABLE 1.

The various software tools and optimization techniques can be found in [4], [8], and [9]. The major drawbacks of software tools like HOMER, RETScreen, HYBRID2, etc. are, that the user must input the size of the various components and the software provides results based on only the input range, whereas the most optimum solution might lie outside the input range of the user. HOMER considers only a single objective function to minimize the Net Present Cost (NPC) and it does not consider intra-hour variability. HYBRID2 has limited access to system parameters. RETScreen does not consider temperature variation on PV performance, time data series cannot be imported and lacks graphical representation of processed data. iHOGA can simulate load limited to average daily consumption of 10 kWh and sensitivity and probability analysis is not included [8]. These software basically provides the most feasible solution based on the economic aspect 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. Artificial Intelligence (AI) techniques prior knowledge of the working of these techniques is required. It is somewhat difficult to correlate and find analogues parameter and function for these techniques to optimize HRES.

NOMENCLATURE

ABBREVIATIONS

RESCA	Reformed Electric System Cascade Analysis
HRES	Hybrid Renewable Energy System
WECS	Wind Energy Conversion System
BESS	Battery Energy Storage System
NIS	Non-intermittent Source
FEE	Final Excess Energy
REF	Renewable Energy Fraction
EGR	Energy Generation Ratio
LPSP	Loss of Power Supply Probability
ASC	Annual System Cost
HES	Hybrid Energy System
TA	Tabu Search
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
SA	Simulated Annealing
PoPA	Power Pinch Analysis
LCE	Levelized Cost of Energy
TSC	Total System Cost
NPC	Net Present Cost
LOL	Loss of Load
LA	Level of Autonomy

SYMBOLS

E_{PV}	Hourly PV system generation (Wh)
N_{PV}	Number of PV modules
η_{PV}	PV module efficiency (%)
I(t)	Hourly calculated solar radiation (Wh/m^2)
η_r	Rated PV panel efficiency (%)
β_T	PV temperature coefficient of efficiency
T_c	Computed ambient temperature (°C)
T_r	Temperature at rated PV efficiency (°C)
NOCT	Normal operating cell temperature (°C)
T_a	Ambient temperature (°C)
I_{NOCT}	Solar radiation at NOCT (Wh/m^2)
A	Extra-terrestrial flux in (W/m^2)
k	Optical depth
m	Air mass ratio
n	Day number of the year
β	Altitude angle of the sun
I_n	Normal component of beam radiation (Wh/m^2)
I_d	Diffused component of beam radiation (Wh/m^2)
I_r	Reflected component of beam radiation (Wh/m^2)
ϕ	Azimuth angle in degrees
ρ	Ground reflectance coefficient
f	Ratio of deficient energy catered by the grid to the BESS for configuration II
ε	Tilt angle of the collector in degrees
Aw	Area swept by the wind turbine (W/m^2)
η_w	WECS efficiency
ρ	Air density (kg/m^3)
v	Wind speed at hub height (m/s)
MW	Molecular weight of gas (g/mol)
R	Ideal gas constant (m^3.atm.K^{-1}.mol^{-1})
P(h)	Atmospheric pressure (atm)
V_0	Wind speed at height H_0(m/s)
V	Wind speed at height H (m/s)
α	Friction coefficient
CE(t)	Cumulative energy in BESS (Wh)
C(t)	Charging energy of BESS (Wh)
D(t)	Discharging energy of BESS (Wh)
NCE(t)	Net cumulative energy after pinch point adjustment (Wh)
DOD	Depth of discharge of BESS
$grid_b$	Energy bought from the grid (kWh)
$grid_s$	Energy sold to the grid (kWh)
η_{gc}	Grid converter efficiency (%)
η_c	Converter efficiency (%)
$E_{NRC}(t)$	Energy generated from the non-renewable components (Wh)
L(t)	Primary load
T	Time period of analysis (hrs)
GF_W	Generation fraction of WECS
GF_{PV}	Generation fraction of PV
LPS(t)	Loss in power supply (Wh)
TSC	Total system cost ($)
$Cost_{comp}$	Cost of each component ($)
$Cost_{inst}$	Installation cost of each component ($)
$Cost_{M\&O}$	Maintenance and operation cost of each component ($)

k	Number of components
CRF	Capital recovery factor
r	Annual rate of interest (%)
L	Lifetime of the HRES
Ex_{gen}	Hourly excess energy (Wh)
t_{peak}	Peak time
EGR_{set}	Set value of EGR
REF_{set}	Set value of REF
P_{W1}	Sum of energy generated by one WT (Wh)
P_{V1}	Sum of energy generated one PV panel (Wh)
N_W	Number of wind turbines
η_{ch}	BESS charge efficiency (%)
η_{disch}	BESS discharge efficiency (%)
$\eta_{ac/dc}$ and $\eta_{dc/ac}$	Converter efficiencies (%)

For the GA approach, there is no guarantee of finding the best solution as it depends on the maximum generation set and the optimal solution may not be analysed. For neural network techniques the solution depends on the training process and after the system is trained introducing flexibilities in evaluation is difficult. For the fuzzy logic approach estimation of the membership function is a challenging and time consuming process. The drawbacks of AI techniques is that for a complex system with several system components the solution complexity, the convergence time and computation power requirement increases [10].

The prime aim of the paper is to provide a simple methodology for HRES optimization based on reliability, economic and performance constraints which overcomes the above mentioned weaknesses. For this RESCA methodology is proposed, which provides the user controllability of the analysis and feedback of why a solution is reached or cannot be reached using its cascade table and graphical representation of the processed data. The RESCA methodology proposed in this paper is based on the primitive cascade table methodology proposed by Ho *et al.* [11], [12]. There are several demerits to Ho's methodology, such as single source handling, single constraint optimization, only isolated mode of operation, simple power management strategy, and basic system component modelling. The proposed RESCA improves the above mentioned demerits and the case study presented on the application of RESCA shows simplicity and robustness of the optimization technique to overcome major flaws of the conventional optimization techniques in use.

The rest of the paper is organized as follows: Section II defines the proposed HRES configurations considered for analysis and Section III provides the system components modelling. Section IV gives the formulation of various optimization considered for HRES. Section V briefs about the RESCA methodology used for optimization and Section VI explains the power management of the considered configurations. Section VII explains the optimization strategy based on the optimization criteria set. Section VIII provides the details of the case study to which the RESCA optimization is applied and Section IX provides the result obtained from RESCA and discuss them. Finally, section X provides a brief conclusion on the successful application of the proposed RESCA methodology.

II. PROPOSED SYSTEM CONFIGURATION

To show the versatility of the RESCA methodology, four different configurations of HRES is chosen for the optimization process. The configurations include both islanding and grid connected mode of operations. The architecture of the configurations is shown in FIGURE 1.

A. CONFIGURATION I

The first configuration depicted in FIGURE 1 (a), consists of an isolated HRES comprising of PV system, WECS, BESS, bidirectional converter, AC load and dummy load, which are connected in a two bus architecture. The PV system and BESS are connected to DC bus whereas, the AC and dummy load along with WECS are connected to the AC bus. For simplicity of analysis, it is assumed that components connected to each bus are in synchronization with their respective bus voltages. The bi-directional flow of power between the AC and DC bus is achieved by the converter which can act as rectifier or inverter depending on the power management. For an isolated system use of dummy load is essential as it can absorb the excess energy generated by the system which cannot be stored in the BESS because of storage limitations [13]. The most common dummy loads used are resistive heating elements which can be used for heating water etc. depending on the site location.

B. CONFIGURATION II

The second configuration as shown in FIGURE 1 (b) consists of a grid-connected HRES, where instead of the dummy load the utility grid is connected through a separate bi-directional grid converter. The use of the dummy load is not required here as it is assumed that the excess power generated by the system can be fed back to the utility. The power management of this system is so designed that the HRES receives no power from the utility during peak power time.

C. CONFIGURATION III

The third configuration is shown in FIGURE 1 (c), consists of an isolated HRES system with no BESS. A NIS power generator is attached to the AC bus to compensate for the intermittent nature of the renewable power generation. The role of dummy load becomes very essential here as the excess energy left after catering the load can neither be stored nor sold back to the utility. The NIS system like diesel generators, biomass generators, etc. can be used but due to the harmful impact of conventional fuel generators, a renewable option like bio-mass generators should be selected.

D. CONFIGURATION IV

The fourth configuration is shown in FIGURE 1 (d), is a grid-connected HRES system similar to configuration II, but the

TABLE 1. Summary of studies conducted for HES optimization.

Optimization technique	System components	On/Off-grid	Optimization constraints	Findings	Ref.
ACO, ABC, GA	PV, WECS, BESS	Off-grid	TSC	Compared ACO with other AI techniques for economic optimization of HRES. Found ACO performs better in continuous domain analysis.	[15]
ABC, PSO	PV, WECS, BESS, BMG	Off-grid	TSC	Optimized the HRES to reduce TSC and found ABC gives smoother conversion in comparison to PSO. Validated the proposed technique with HOMER.	[16]
CS, PSO, GA	PV, WECS, BESS	Off-grid	TSC, Reliability	Performed economic analysis of HRES using CS algorithm. Results are compared with PSO and GA and found CS to be better.	[17]
PSO	PV, WECS, BESS	Off-grid	LCC	Applied PSO with adaptive weight adjustment for system optimization and found this technique better than other variants of PSO	[18]
BA, SA	PV, WECS, BESS	On-grid	TSC	Optimized the BESS using BA optimization technique for on grid and off grid operation. Results were also compared with SA	[19]
SA	PV, WECS	Off-grid	TSC, LPSP	Using SA optimal size of HRES is found for a rural village	[20]
ABS, PSO	PV, WECS, HESS	Off-grid	TSC, LPSP	Found that LPSP of 0%, 0.3% and 1% is most cost-effective for HRES with PV, WECS and HESS. Also found LPSP of 2% to be the most effective for HRES with WECS and HESS	[21]
PSO, TS, HS, SA	PV, WECS, BESS, HESS	Off-grid	ASC	Compared various AI techniques for HRES optimization and found PSO to be most effective.	[22]
HOMER	PV, WECS, BESS, DG	Off/on the grid	COE, REF	Compared the COE of for HES which is grid-connected and isolated. Found the COE of a grid-connected system to be less	[23]
HOMER	PV, WECS, BESS, DG	Off-grid	NPC,	Found the most economic configuration of HRES with 70% renewable fraction.	[24]
HOMER	PV, WECS, BESS	Off/ on the grid	COE	Compared the COE of for HES which is grid-connected and isolated. Found the COE of a grid-connected system to be less	[25]
iHOGA	PV, WECS, BESS, DG	Off-grid	COE, Emissions	Found PV to be the most economical generator for Spain	[26]
RETScreen	PV, BESS, DG	Off-grid	TSC	Found that the penetration of DG into the HRES reduced the TSC.	[27]

ACO – Ant Colony Optimization, GA – Genetic Algorithm, ABC – Artificial Bee colony, PSO – Particle Swarm Optimization, BA – Bat Algorithm, SA – Simulated Annealing, TS – Tabu Search, HS - Harmony Search, TSC – Total System Cost, LCC – Life Cycle Cost, NPC – Net Present Cost, LPSP – Loss of Power Supply Probability, COE – Cost of Energy, HESS – Hydrogen energy Storage System, BMG – Bio Mass Generator, DG – Diesel Generator.

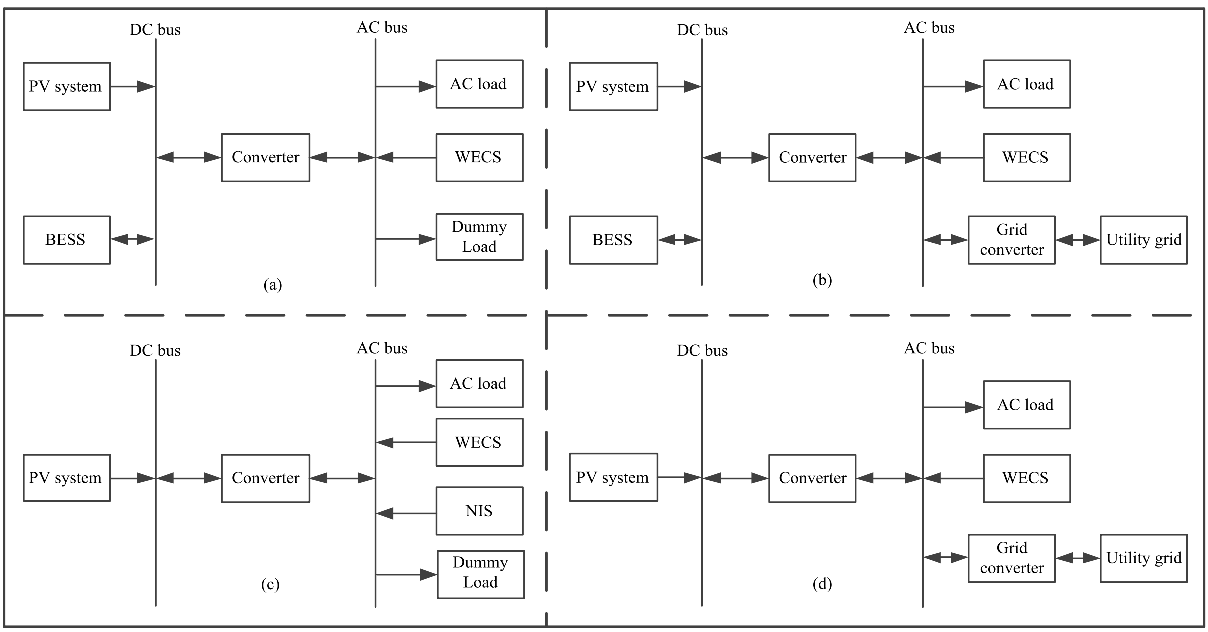


FIGURE 1. The architecture of various system configurations considered for analysis.

BESS is absent here. For this configuration, it is assumed that there is no restriction on buying and selling of power to the utility grid. Power can be bought from the grid irrespective of the hour of the day and all the excess power generated by the renewable energy sources is absorbed by the utility grid.

III. SYSTEM MODELLING

The various components of the HRES configurations mentioned above are modelled as follows:

A. PV MODEL

The hourly energy output for a mono-crystalline PV module can be expressed as shown in (1) [14]:

$$E_{PV}(t) = N_{PV} \times A_{PV} \times \eta_{PV} \times I(t) \quad (1)$$

Where, E_{PV} is the hourly energy generated by the PV system in Wh, N_{PV} is the number of PV modules, η_{PV} is the PV module efficiency and I (t) is the net hourly solar radiation reaching the PV modules in Wh/m^2. The efficiency of the PV modules is very low and varies with operating cell temperature which is also dependent on the ambient temperature. The variation of PV efficiency with temperature is modelled using (2-3) [14]:

$$\eta_{PV} = \eta_r[1 - \beta_T(T_c - T_r)] \quad (2)$$

$$T_c = T_a + \left(\frac{NOCT - T_{a,NOCT}}{I_{NOCT}}\right) \times I(t) \quad (3)$$

Where, η_r is the rated PV panel efficiency, β_T is the PV temperature coefficient of efficiency, T_c is the computed ambient temperature in °C, T_r is the temperature at rated efficiency in °C, NOCT is the normal operating cell temperature in °C, T_a is the ambient temperature in °C and I_{NOCT} is the solar radiation at NOCT in W/m^2.

1) SOLAR RADIATION ESTIMATION

The solar radiation reaching the PV modules depends on various factors like PV module tilt angle, latitude of the site, atmospheric attenuation, reflection from the surfaces etc. Therefore, it cannot be considered equal to the beam solar radiation available in the historical data sheets and other data source. The beam solar radiation I_B reaching the earth surface after attenuation is expressed by (4) [7]:

$$I_B = A \times e^{-km} \quad (4)$$

Where, A is the extra-terrestrial flux in W/m^2, k is the optical depth which is dimensionless and m is the air mass ratio as expressed in (5-7) [7]:

$$A = 1160 + 75 \times \sin\left[\frac{360}{365}(n - 275)\right] \quad (5)$$

$$k = 0.174 + 0.035 \times \sin\left[\frac{360}{365}(n - 100)\right] \quad (6)$$

$$m = \frac{1}{sin\beta} \quad (7)$$

Where n is the day number of the year, β is the altitude angle of the sun which is a function of hour angle (H), latitude (L) and solar declination angle (δ). The altitude angle is expressed by (8-10) [2], [7]:

$$sin\beta = (cosL \times cos\delta \times cos\delta) + (sinL \times sin\delta) \quad (8)$$

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(n - 81)\right] \quad (9)$$

$$H = 15^0 \times h \quad (10)$$

Where h is the number of hours before noon, it is considered negative afternoon and positive before noon. After reaching the earth surface the entire beam solar radiation does not reach the earth surface, instead goes through the process of diffusion and reflection. The net solar radiation reaching the PV module is expressed as (11) [7]:

$$I = I_n + I_d + I_r \quad (11)$$

Where I_n is the part of beam solar radiation reaching normally to the PV module surface, I_d is the part of beam solar radiation reaching after diffusion and I_r is the solar radiation reaching the PV module after reflection from the ground. They are expressed in (12-17) [2], [7]:

$$I_n = I_B \times \cos\theta \quad (12)$$

where,

$$cos\theta = (cos\beta \times cos\emptyset \times sin\varepsilon) + (sin\beta \times cos\varepsilon) \quad (13)$$

$$I_d = C \times I_b \quad (14)$$

where,

$$C = 0.095 + 0.04 \times \sin\left[\frac{360}{365}(n - 100)\right] \quad (15)$$

$$I_r = \rho \times I_b(sin\beta + C)\left(\frac{1 - cos\varepsilon}{2}\right) \quad (16)$$

Where ϕ is the azimuth angle in degrees, ρ is the ground reflectance coefficient and ε is the tilt angle of the collector in degrees. The ideal tilt angle for a PV module can be expressed as:

$$\varepsilon = 90 - \beta_N \quad (17)$$

Where β_N is the altitude angle at noon.

B. WECS MODELLING

The hourly energy generated by the WECS can be expressed as (18) [28]:

$$E_W = \frac{1}{2} \times \rho \times A_w \times \eta_w \times v^3 \quad (18)$$

Where A_w is the area swept by the wind turbine blades in m^2, η_w is the power conversion efficiency, ρ is the air density in kg/m^3 and v is the wind speed at hub height. The air density is not a constant parameter and varies with ambient temperature and height, therefore the variability of the air density is modelled by (19-20) [29]:

$$\rho = \frac{P(h) \times MW \times 10^{-3}}{R \times (273 + T_a)} \quad (19)$$

Where

$$P(h) = P_o e^{-(1.185 \times 10^{-4} \times H)} \quad (20)$$

Where, MW is the molecular weight of gas in (g/mol) usually considered 28.97 g/mol, R is the ideal gas constant = 8.2056 × 10^{-3} m^3.atm.K^{-1}.mol^{-1} and P(h) is the atmospheric pressure in atm which is a function of height (H) and varies as expressed in (20). The wind speed is usually recorded at a height of 10 m, but the wind speed varies with the increase in height. The wind speed at the hub height of the wind turbine can be expressed as (21) [30]:

$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha} \tag{21}$$

Where, v_0 is the wind speed in m/s recorded at height H_0, v is the wind speed in m/s at height H (hub height) and α is the friction coefficient. The friction coefficient for different terrains can vary from 0.1 for a smooth ground to 0.40 for cities with tall building [7].

1) WIND TURBINE SELECTION

The hourly energy output of the WECS as expressed in (18) is based on the concept of extraction/conversion of energy stored in the wind into electrical energy at the output of the WECS. The parameter η_w incorporates the efficiency in conversion of the wind energy to electrical energy. As the power curve of each wind turbine varies, the choice of wind turbine selection should be based on the efficiency of the conversion of wind energy to electrical. The efficiency parameter should incorporate both the mechanical conversion and electrical conversion efficiencies. One way to do that is to calculate the power generated by different turbines based on their power curve and the wind profile of the chosen site and calculate the net conversion efficiency by finding the ratio of the net power generated by the WECS for a particular wind speed profile and power stored in the wind. A total of thirteen different ratings/manufacturer of wind turbines have been considered for analysis which can work at a hub height of 40 m (considered for the presented work), their power curve is shown in Appendix I based on which a prudent choice of the wind turbine was made.

C. ENERGY STORAGE SYSTEM MODELLING

For a HRES, BESS plays an important role in providing the reliability of power and also in power quality improvement [31]. The battery is charged during surplus energy generation and discharges during deficiency of energy. The energy stored in the BESS and the net capacity of BESS can be expressed as (22-23) [12]:

$$CE(t) = CE(t-1) + C(t) + D(t) \tag{22}$$

$$BESS_{capacity} = \frac{NCE(t)_{max}}{DOD} \tag{23}$$

Where CE(t) is the cumulative energy in the BESS in Wh, C(t) is the charging energy of the BESS in Wh, D(t) is the discharging energy of the BESS in Wh, NCE(t) is the net cumulative energy after pinch point adjustment (explained in Section V.A) and DOD is the depth of discharge of battery. It is to be noted that the efficiency of the battery varies during the charge and discharge process, calculating the real-time efficiency of the BESS is very difficult. Therefore, manufacture provides an overall/roundtrip efficiency for the battery, which is considered constant throughout the process. This assumption is made here based on the work presented in [32]–[35].

D. GRID MODELLING

For the grid-connected configuration considered for analysis, the grid is assumed to provide and absorb all the power as required by the system. A separate converter is also used for grid/utility connection as shown in FIGURE 1 (b and d). The net energy bought from the grid ($grid_b$) and sold to the grid ($grid_s$) is expressed in (24-25).

$$grid_b = \left(\frac{Energydeficiency}{\eta_{gc}}\right) \tag{24}$$

$$grid_s = Energysurplus \times \eta_{gc} \tag{25}$$

Where η_{gc} is the grid converter efficiency.

E. CONVERTER MODELLING

The converter forms an essential part of the HRES as it aids the bidirectional flow of power between the AC and DC bus. It is assumed that the converter efficiency in rectification and inversion mode is the same and the net capacity of the converter is calculated using (26) [11]:

$$Converter_{rating} = \frac{(Maximum\ energy\ converted)}{\eta_c} \tag{26}$$

Where η_c is the converter efficiency. The rating of the converter is governed by the maximum energy converted by the converter during DC to AC conversion when PV and/or BESS are catering the load and AC to DC conversion when excess energy from WECS is used to charge BESS.

IV. OPTIMIZATION CONSTRAINTS

Due to the various components of the HRES, optimization of each component becomes very important. To do this, numerous constraints like Final Excess Energy (FEE), Renewable Energy Fraction (REF), Loss in Power Supply Probability (LPSP), Annual System Cost (ASC), etc. are available based on which the HRES can be optimized, these can be broadly classified as reliability constraints and cost/economic constraint. The prime aim of the reliability parameters is to optimize the HRES such that continuation of the power supply is maintained to the load. Whereas, the economic constraint tends to find the most economical system configuration. The types, merits and demerits of the optimization constraint can be found in [4]. For multi-constraint optimization, both reliability and economic constraints are selected simultaneously for optimization. Primary constraints are those constraints which are essential for the HRES optimization and secondary constraints are those constraints on which alone the HRES cannot be optimized and need to be clubbed with the primary constraints. For the constraints used in this study, their classification is presented in TABLE 2.

The choice of optimization constraint also depends on the system components and configuration. Therefore, the constraints on which each configuration presented in this work are optimized is presented in TABLE 3.

TABLE 2. Classification of optimization constraints.

Constraint	Type
FEE	Primary
REF	Primary
EGR	Secondary
LPSP	Secondary
ASC	Secondary

TABLE 3. System components and applicable constraint for various system configurations.

Configu -ration	System components	Constraints	Primary constraints
I	PV+WECS+ BESS	FEE, FEE+EGR, FEE+LPSP, FEE+ASC	FEE
II	PV+WECS+ GRID+ BESS	REF, REF+FEE, REF+FEE+EGR, FEE+REF+ASC	REF/FEE
III	PV+WECS+ NIS	REF, REF+EGR, REF+LPSP, REF+ASC	REF
IV	PV+WECS+ GRID	REF, REF+LPSP, REF+LPSP+EGR, REF+ASC	REF

A. FINAL EXCESS ENERGY

FEE is a primary constraint for HRESs consisting of energy storage system(s). FEE is the net charge accumulated in the BESS after the completion of the time period of analysis and is expressed as the difference between the charge in the BESS at the end and beginning of the analysis (27):

$$FEE = CE_{t=T} - CE_{t=0} \tag{27}$$

Where T is the time period of analysis. This constraint basically optimizes the size of the BESS. If FEE = 0, this implies that SOC of BESS will remain the same over repeated cycles of the load. If FEE < 0, this implies that the charge in BESS will keep diminishing over repeated cycles of load leading to failure of the system. If FEE > 0, this implies that the charge in the BESS will increase over repeated load cycles leading to an overestimation of BESS. The ideal value for FEE optimization should be zero but a small positive value of tolerance is set for FEE such that slight variations in load profile may not lead to diminishing margin in the BESS.

B. RENEWABLE ENERGY FRACTION

REF is another primary constraint for HRESs consisting of components like grid connection, diesel generators bio-mass generators, etc. REF is an indicator of the part of the load profile catered by renewable energy sources and the non-renewable energy sources, it is expressed as (28) [36]:

$$REF = 1 - \frac{\sum_{t=0}^{t=T} E_{NRC}(t)}{\sum_{t=0}^{t=T} L(t)} \tag{28}$$

Where, $E_{NRC}(t)$ is the energy generated from the non-renewable components, L(t) is the load component and T is the time period of analysis. If REF = 0, it implies that load is completely catered by non-renewable components of the system. If 0 < REF < 1, it implies that REF fraction of load is catered by renewable energy components and the rest by non-renewable components. If REF > 1 or REF < 0, implies that the size/rating of the system components is over or underestimated leading to failure of the optimization process.

C. ENERGY GENERATION RATIO

EGR is a secondary optimization constraint for the HRESs and can only be used in conjunction with REF and/or FEE. EGR gives the information of the fraction of energy generated by each renewable energy component (PV system and WECS in this case) and is expressed as (29-31):

$$EGR = \frac{GF_W}{GF_{PV}} \tag{29}$$

where,

$$GF_W = \frac{\sum_{t=0}^{t=T} E_W(t)}{\sum_{t=0}^{t=T} E_W(t) + \sum_{t=0}^{t=T} E_{PV}(t)} \tag{30}$$

where,

$$GF_{PV} = \frac{\sum_{t=0}^{t=T} E_{PV}(t)}{\sum_{t=0}^{t=T} E_W(t) + \sum_{t=0}^{t=T} E_{PV}(t)} \tag{31}$$

Where GF is the generation fraction of WECS or PV system. For the scope of this paper, EGR is considered as the ratio of energy generated by WECS to energy generated by the PV system. If EGF = 1, it implies that the load is catered equally by WECS and PV system. If EGR < 1, it implies that PV system is dominant in catering the load i.e. it generates more energy with respect to WECS and EGR > 1 implies the WECS is the more dominant energy generator.

D. LOSS OF POWER SUPPLY PROBABILITY

LPSP is another secondary constraint for the optimization of HRES. It may be considered as a primary constraint for isolated HRES with single renewable energy generator. But since the system configuration considered for analysis consists of multi-generator HRES, it is therefore considered a secondary constraint. LPSP is defined as the long-term fraction of the load not supplied by the generating system. It is a good indicator of the reliability of power supply to the load and is expressed as (32) [37]:

$$LPSP = \frac{\sum_{t=0}^{t=T} LPS(t)}{\sum_{t=0}^{t=T} L(t)} \tag{32}$$

where,

$$LPS(t) = \begin{cases} [L(t) - Supply(t)]\,\forall t, \\ when\ L(t) > Supply(t) \\ 0 \forall t, \quad when\ L(t) < Supply(t) \end{cases} \tag{33}$$

Where, LPS (t) is the loss in power supply and Supply (t) is the net energy of generators, BESS, NIS and grid (if applicable) at the AC bus. LPSP of zero implies that no loss of load occurs and the entire load is catered by the

HRES. LPSP of 1 implies that the load will never be satisfied. If $0 < LPSP < 1$ implies that part of the load is not catered by HRES.

E. ANNUAL SYSTEM COST

ASC is a secondary constraint for the optimization of the HRES and it indicates the annual cost of the HRES over its lifetime of use. Since a high initial investment requirement is one of the main drawbacks of a renewable energy system, therefore ASC becomes an important constraint for the system designer, it is evaluated as (34-36) [38]:

$$ASC = TSC \times CRF \tag{34}$$

where,

$$TSC = \sum_{i=1}^{i=k} Cost_{comp.}(i) + \sum_{i=1}^{i=k} Cost_{inst.}(i) + \sum_{i=1}^{i=k} Cost_{M\&O}(i) \tag{35}$$

and,

$$CRF = \frac{r \times (1+r)^L}{(1+r)^L - 1} \tag{36}$$

Where, TSC is the total system cost, $Cost_{comp.}$ is the capital cost of each component, $Cost_{inst.}$ is the installation cost of each component, $Cost_{M\&O}$ is the maintenance and operation cost of each component, k is the no. of components, CRF is the capital recovery factor, r is the annual rate of interest and L is the lifetime of the HRES.

V. REFORMED ELECTRIC SYSTEM CASCADE ANALYSIS

The RESA technique for HRES optimization takes into consideration the several factors like, mode of operation of HRES, types of energy generating unit, variability in weather condition, the effect of temperature on PV efficiency and power generated by the WECS and multi-criterion optimization of HRES which adds to the novelty of this technique. The flowchart of the implemented RESCA technique is shown in FIGURE 2 (a) and a brief explanation of the methodology is explained as follows [4], [36]:

Step 1: Data extraction: The time period of analysis, hourly load demand, Hourly wind, solar radiation and temperature profile, type and characteristic of energy generating components, rating and characteristics of BESS, converter(s) efficiency and system configurations need to be entered.

Step 2: Initial assumption of no. of WECS and PV system and initial charge in BESS is made (final solution is immune to the initial assumption).

Step 3: Initialization of power management depending on the configuration chosen.

Step 4: Construction of cascade table: a cascade table needs to be constructed with following columns

Column i: Time steps arranged in ascending order, a time interval of one hour is chosen here.

Column ii-v: Hourly load demand, wind speed, solar radiation and temperature

Column vi-vii: Hourly energy generation from PV system and WECS

Column viii: Hourly energy supplied by grid or NIS (if applicable)

Column ix-xi: Hourly excess energy (Ex_{gen}), $grid_b$ and $grid_s$ (if applicable)

Column xii-xiii: Battery charging and discharging energy (if applicable)

Column xiv: Hourly cumulative energy in the BESS

Column xv: Hourly net cumulative energy in the BESS after Power Pinch Analysis (PoPA).

Step 5: Selection of optimization constraint(s) and implementation of the optimization algorithm.

Step 6: If constraint(s) not satisfied, go back to step 3.

Step 7: Performing power pinch point analysis after constraint(s) satisfaction.

Step 8: Find the ratings of optimized HRES components.

Step 9: Graphical representation of the results (if required).

A. POWER PINCH ANALYSIS

PoPA is essential for HRES consisting of BESS. The final rating of the BESS in the RESCA technique is obtained using PoPA. It is inspired by the technique of process integration which has been in use to optimise various resources such as thermal energy, material production, etc. [39]. The steps involved in the implementation of PoPA are as follows [12], [40]:

Step 1: After successful criteria optimization, the minimum value of cumulative energy (CE) in BESS is found (which is the pinch point).

Step 2: The energy deficiency at the pinch point is added to CE (0) to form the new column of Net Cumulative Energy (NCE).

Step 3: The Depth of Discharge (DOD) adjustment is performed such that the SOC of BESS does not violate the DOD limit set.

Step 4: After pinch point and DOD adjustment, the maximum and initial value of NCE is found.

Step 5: The maximum value of NCE is the BESS capacity required and NCE (1) is the minimum initial charge required in BESS for the successful operation of the HRES.

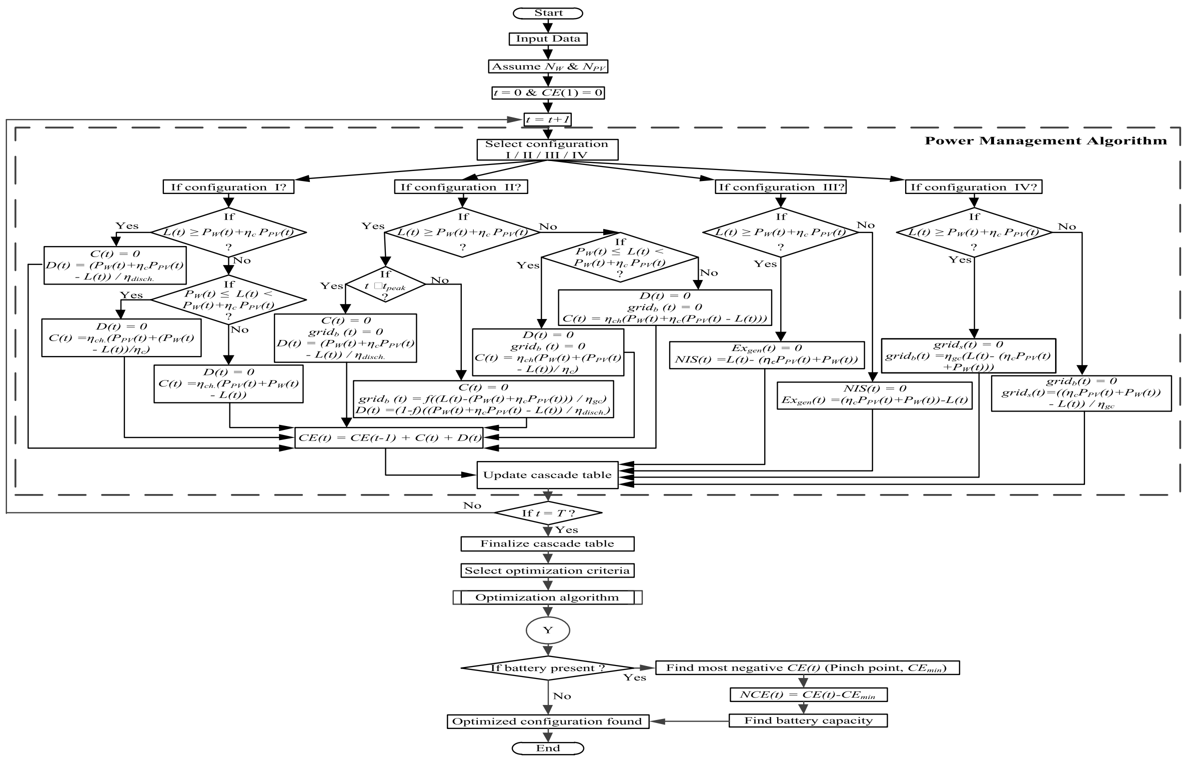
VI. POWER MANAGEMENT

The management of energy generated by system components is based on the configuration chosen for analysis. Based on the four configurations mentioned in Section II, the power management is explained as follows:

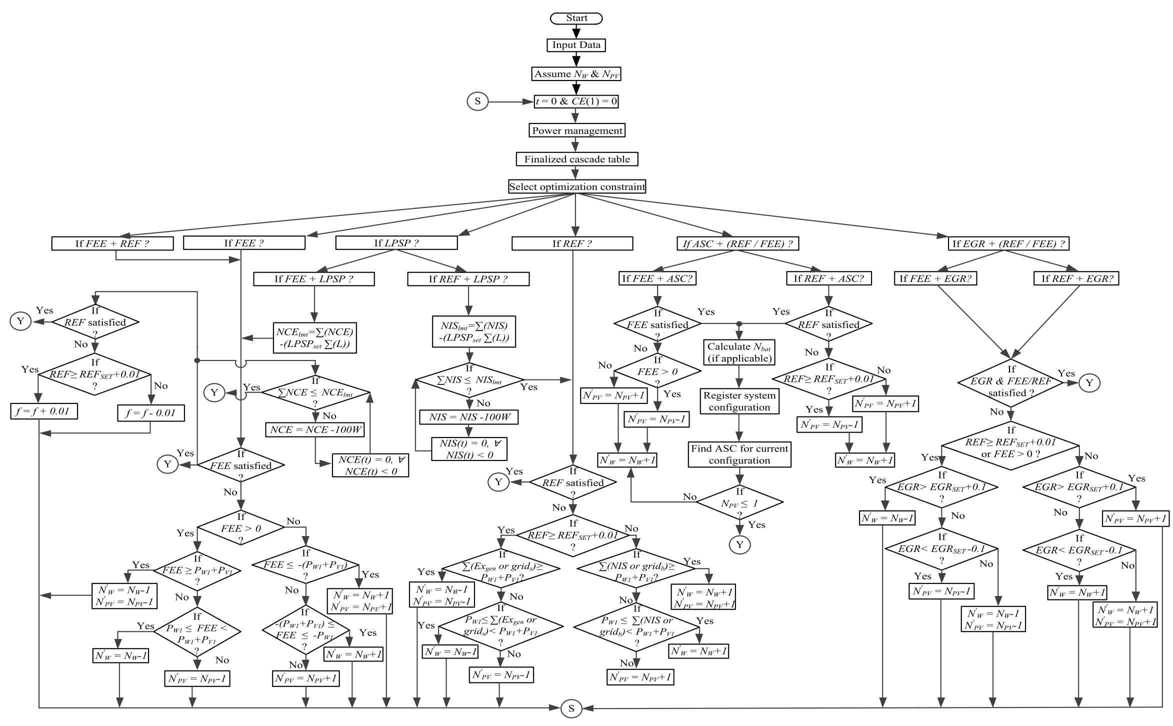
A. CONFIGURATION I (PV, WECS AND BESS)

As explained before the mode of operation of HRES is islanding. For this configuration power management strategy is as follows:

Senario 1: If the load is greater than the net energy generated by WECS and PV system at AC bus, then BESS discharges and provides the deficient energy.



(a)



(b)

FIGURE 2. (a) Algorithm for RESCA methodology with detailed power management, (b) Description of optimization algorithm of RESCA methodology.

Senario 2: If load greater than energy generated by WECS but less than the net energy generated by WECS and PV system at AC bus, then WECS provides all the energy generated to the load, PV system provides the deficient energy and remaining energy of the PV system is used to charge the BESS.

Senario 3: If the load is less than the energy generated by WECS, then WECS provides the required energy to the load, excess energy of WECS and the entire energy generated by PV system is used to charge the BESS.

The priority of energy supplied to the load is in the order of WECS, PV system and BESS. This helps in reducing the conversion loses encountered during PV energy conversion from DC to AC and charging/discharging of the BESS.

B. CONFIGURATION II (PV, WECS, GRID AND BESS)

For this grid-connected configuration, it is assumed that power from the grid can be extracted only during off-peak time and no restriction is imposed on selling of power. This conjecture can be adjusted by the system designer by defining the time interval of t_{peak} as shown in FIGURE 2 (a). If t_{peak} is set for the entire time period of analysis, then configuration II becomes similar to the configuration I and if t_{peak} is set to null then it becomes same as configuration IV. The priority of energy supplied to the load is in the order of WECS, PV system, BESS and GRID (if $t \notin t_{peak}$). The power management strategy for this configuration is as follows:

Senario 1: If $t \in t_{peak}$, then the system management follows scenario I-III of configuration I.

Senario 2: If $t \notin t_{peak}$and load is greater than the net energy generated by WECS and PV system at AC bus, then a fraction 'f' of the deficient energy is provided by the grid and the rest by BESS. Fraction $f \in [0,1]$, which is set randomly by the user initially for optimization of this configuration with REF constraint. If REF is not selected for the optimization of the system, then fraction 'f' is set to 1.

Senario 3: If $t \notin t_{peak}$and load is less than the net energy generated by WECS and PV system at AC bus, then the power management follows scenario II and III of configuration I.

It is to be noted that 'f' is defined as the ratio of energy supplied by the GRID ($grid_b$) to the net deficiency in energy when $t \notin t_{peak}$.

C. CONFIGURATION III (PV, WECS AND NIS)

For this islanding configuration of HRES, BESS is absent and the deficiency of the energy generation from WECS and PV system is catered from NIS. The power management strategy is as follows:

Senario 1: If the load is greater than the net energy generated by WECS and PV system at AC bus, then the load is catered by the energy generated by WECS and PV system at AC bus and remaining deficiency is catered by NIS and Ex_{gen} is zero.

Senario 2: If the load is less than the net energy generated by WECS and PV system at AC bus, then the load is catered by energy generated by WECS and PV system at AC bus and the excess energy Ex_{gen} (t), is fed to the dummy load.

D. CONFIGURATION IV (PV, WECS AND GRID)

For this grid-connected configuration since BESS is absent, therefore, no restriction is imposed on buying or selling power back to the utility. The power management strategy is as follows:

Senario 1: If the load is greater than the net energy generated by WECS and PV system at AC bus, then the load is catered by the energy generated by WECS and PV system at AC bus and remaining deficiency is catered by the grid ($grid_b$) and $grid_s$ is zero.

Senario 2: If the load is less than the net energy generated by WECS and PV system at AC bus, then the load is catered by energy generated by WECS and PV system at AC bus and the excess energy is fed back to the utility ($grid_s$).

VII. OPTIMIZATION ALGORITHM

The optimization of the system components depends on the choice(s) of optimization constraint. The optimization algorithm block of the RESCA methodology is elaborated in FIGURE 2 (b), the node 'Y' of the optimization algorithm is linked to the node 'Y' of RESCA methodology algorithm as shown in FIGURE 2 (a). A brief explanation is presented as follows:

A. FEE CRITERIA ONLY

This is a primary criterion for HRES configurations consisting of a BESS. The various scenarios of system updation if FEE criterion is not satisfied are listed as follows:

Senario 1: If FEE > 0 and greater than the sum of energy generated by one WT (P_{W1}) and one PV panel (P_{V1}). Then no. of wind turbines (N_W) and PV panels (N_{PV}) is reduced by 1, else if FEE lies between P_{W1} and $P_{W1} + P_{V1}$ then N_W is reduced by 1 else N_{PV} is reduced by 1.

Senario 2: If FEE < 0 and less than - (P_{W1} + P_{V1}). Then no. of wind turbines (N_W) and PV panels (N_{PV}) is incremented by 1, else if FEE lies between - (P_{W1}+P_{V1}) and - P_{W1} then N_W is incremented by 1 else N_{PV} is incremented by 1.

B. REF CRITERIA ONLY

This is another primary constraint which can be evaluated for a system consisting of NIS or having a grid connection. The system components are updated based on the following scenarios if REF is not satisfied.

Senario 1: If REF > REF_{set} (set value) and the sum of Ex_{gen} / $grid_s$ is greater than ($P_{W1} + P_{V1}$). Then N_W and N_{PV} are reduced by 1, else if the sum of Ex_{gen} / $grid_s$ lies between P_{W1} and ($P_{W1} + P_{V1}$) then N_W is reduced by 1 else N_{PV} is reduced by 1.

Senario 2: If REF < REF_{set} and sum of NIS / $grid_b$ is greater than ($P_{W1}+P_{V1}$). Then N_W and N_{PV} are incremented by 1, else if the sum of NIS / $grid_b$ lies between P_{W1} and (P_{W1} + P_{V1}) then N_W is incremented by 1 else N_{PV} is incremented by 1.

It is to be noted that parameter NIS and Ex_{gen} is used if system configuration is IV and $grid_b$ and $grid_s$ are used if the configuration is II. The parameter of NIS is analogues to $grid_b$ and Ex_{gen} is analogues to $grid_s$, but different notations are used for different configurations to make the algorithm more comprehensible.

C. FEE AND REF CRITERIAS

This multi-criteria optimization of HRES can only be performed for configuration II as it complies with the pre-requisite of their implementation. The various scenarios of updating the system components are as follows:

Senario 1: If FEE constraint is not satisfied, follow the scenario 1 and 2 of FEE only criteria, for system improvement.

Senario 2: Once FEE constraint is satisfied check for REF constraint fulfilment. If REF is not satisfied and is greater than the set value, then increment fraction 'f' by 0.01 else reduce 'f' by 0.01.

D. LPSP AND (FEE/REF) CRITERIAS

LPSP is a secondary constraint which can be used with any of the primary constraint (FEE and REF) for reliability optimization of HRES. The strategy for this optimization is not to increase the rating of NIS or BESS beyond a pre-set value (NCE_{lmt}/NIS_{lmt}). A brief explanation of this optimization strategy is as follows:

Senario 1: If LPSP and FEE criteria are chosen for HRES configuration I

Step 1: Set NCE_{lmt} using (37):

$$NCE_{lmt} = \sum_{t=0}^{t=T} NCE(t) - \left(LPSP_{set} \times \sum_{t=0}^{t=T} L(t) \right) \tag{37}$$

Step 2: Follow scenario 1 and 2 for FEE optimization of the HRES.

Step 3: If FEE constraint is met and net energy supplied by BESS (i.e. $\sum NCE(t)$) violates NCE_{lmt} then adjust the BESS capacity by 100W until NCE_{lmt} it met.

Senario 2: If LPSP and REF criteria were chosen for HRES configuration III

Step 1: Set NIS_{lmt} using (38):

$$NIS_{lmt} = \sum_{t=0}^{t=T} NIS(t) - \left(LPSP_{set} \times \sum_{t=0}^{t=T} L(t) \right) \tag{38}$$

Step 2: If net energy provided by NIS (i.e. $\sum NIS(t)$) satisfies the NIS_{lmt}, follow scenario 1 and 2 for REF optimization of HRES.

Step 3: Adjust the NIS rating by 100 W until NIS_{lmt} is met and Go to step 2.

It is to be noted that LPSP analysis is not considered for a grid connected system. This is due to the fact that if HRES is connected to the gird, continuity of power supply to the load is a prime feature for this mode of operation. However, if the system designer intends to perform this analysis it can easily be done following steps in scenario 2 and by setting a limit for power extracted by grid using (38). The main idea behind LPSP optimization is that initially system is optimized for no loss of power. Any loss of power if required by the system designer is provided by reducing the rating of BESS, NIS and GRID (if applicable). This is done so that in case the reliability of the system needs to be improved in future, the major infrastructure of PV and WECS is already present. Only reinvestment in the size/rating of BESS and NIS will be required which is less costly in comparison to increasing the rating of PV or WECS.

E. ASC AND (FEE/REF) CRITERIAS

ASC is an important optimization constraint for HRES which aims to find the most economical system configuration. The strategy for economic optimization for a multi-constraint multi-source HRES becomes a little complex as the cost of all system configurations satisfying the non-economic constraint(s) need to be evaluated. The strategy adopted here varies the $N_W$from unity to the maximum possible value for which the other constraints are satisfied. A brief explanation of the adopted strategy is as follows:

Step 1: Set the $N_W = 1$.

Step 2: Based on the other constraint (FEE/REF) chosen, update N_{PV} as shown in FIGURE 2 (b).

Step 3: If the optimized value of $N_{PV} \leq 1$ go to step 6 else proceed to step 4.

Step 4: Find the BESS capacity (if applicable) and register the rating of system components for the optimized HRES.

Step 5: Increment N_W by 1 and go to step 2.

Step 6: Find the ASC for all the obtained system configurations.

Step 7: Choose the system configuration with minimum ASC to obtain the optimized result.

It is to be noted that LPSP can also be chosen along with FEE/REF constraint. For this slight variation in step 2 is required where only N_{PV} is updated based on scenario 1 and 2 of LPSP criteria.

F. EGR AND (FEE/REF) CRITERIAS

EGR is neither an economic nor a reliability constraint, but it helps the system designer to obtain an optimized HRES which prioritizes the major energy generator in the system. The two energy generating units considered in this analysis are PV and WECS. EGR constraint helps in finding an optimized system which is more dependent on solar or wind based on the set value of EGR. This constraint is especially important for sites which show more inclination towards a particular energy source (wind/PV) during the pre-feasibility analysis of the site. The strategy for optimization is as follows:

Senario 1: If $EGR > (EGR_{set} + 0.1)$ and $FEE > 0$ or $REF > (REF_{set} + 0.01)$, then reduce N_W by 1.

Senario 2: If EGR < (EGR_{set} − 0.1) and FEE > 0 or REF > (REF_{set} + 0.01), then reduce N_{PV} by 1 else reduce both N_W and N_{PV} by 1.

Senario 3: If EGR > (EGR_{set} + 0.1) and FEE < 0 or REF < (REF_{set} + 0.01), then increase N_{PV} by 1.

Senario 4: If EGR < (EGR_{set} − 0.1) and FEE < 0 or REF < (REF_{set} + 0.01), then increment N_W by 1 else increment both N_W and N_{PV} by 1.

It is to be noted that N_W, N_{PV}, NIS, BESS ratings and fraction 'f' are updated by 1, 1, 100 W, 100 W and 0.01 respectively for each iteration. These values are set for the scope of this paper and can be altered by the user based on the rate of convergence and tolerance range set for optimization criteria. For example, if these values are reduced, the convergence rate increases but the tolerance range of each criterion can be narrowed. If these values are increased, convergence rate reduces but the tolerance range of the optimization criteria becomes wider. Therefore, a prudent decision should be made by the system designer for setting these values as well as the tolerance range of the constraints. Other reliability and economic constraint like Levelized Cost of Energy (LCE), Total System Cost (TSC), Net Present Cost (NPC), Loss of Load (LOL), Level of Autonomy (LA), etc. can also be used for RESCA optimization based on the above mentioned optimization strategies, with change in formulation of the optimization criteria which can be obtained from [4].

VIII. CASE STUDY

To show the application of RESCA for HRES optimization, the developed methodology is applied for 100 residential households in Newark, USA for 24 hour time period. The latitude and longitude of the location considered is 40.7°N and 74.17°W. MATLAB software environment is used for the implementation and programming of the proposed methodology. Four different configurations with different optimization constraints are considered for the load. The profile for the load, solar radiation (as calculated), wind speed (at 10 m) and temperature for the month of June is considered as shown in FIGURE 3 [41]–[43]. As the load is maximum during June therefore, 24 hours analysis for this month is chosen to show the implementation of the RESCA methodology. The technical specifications and cost information for various system components used are shown in TABLE 4 and the set values and the tolerance range of the optimization constraints are shown in TABLE 5.

TABLE 4. Technical and cost data required for system modelling and optimization [44]–[49].

General Data	
The time period of analysis (T)	24 hours
Time step	1 hour
Life of plant	25 yrs.
PV module data	
Type	Mono-crystalline
Peak power rating	250 Wp
Area per unit	1.1 m^2
Rated module efficiency (η_r)	15 %
Temperature coefficient of efficiency (β)	0.0045
Normal operating cell temperature (NOCT)	55^0C
Temperature at rated efficiency (T_r)	25^0C
Solar radiation at NOCT (I_{NOCT})	800 W/m^2
Capital cost per module	$ 135
Variable cost per module	$ 15
Balance of system	$ 600
Lifespan	25 yrs.
Wind Energy Conversion System	
Type	ENERCON 25
Rated power	25 kW
Cut in speed	4 m/s
Cut out speed	25 m/s
Rated speed	16 m/s
Hub Height	40 m
Rotor diameter	20 m
Hellman coefficient used (α)	0.35
Calculated WECS efficiency (η_w)	30 %
Capital cost per unit	1520 $/kW
M&O cost	5 % of capital cost
Lifespan	25 yrs.
Battery Energy Storage System	
Type	CellCube FB 200 kW
Battery capacity per unit	400/800/1600 kWh
Battery voltage	48 V (DC)
Battery charge efficiency ($\eta_{ch.}$)	80%
Battery discharge efficiency ($\eta_{disch.}$)	80%
Depth of discharge (DOD)	90% (after safe margin)
SOC_{max}	100%
Capital cost (stacks, pumps, tanks, etc.)	130 $/kWh
Vanadium Cost	140 $/kWh
The balance of system cost	95 $/kWh
Lifespan	15 yrs.
Converter data	
Converter efficiency ($\eta_{ac/dc}$ and $\eta_{dc/ac}$)	85%
Rating per unit	1000 VA
Cost per unit	$ 250
Lifespan	15 yrs.
NIS levelized cost (bio-mass generation)	0.18 $/kWh
GRID data	
Peak time	0800 to 1900 hrs.
Conversion efficiency (η_{gc})	90%
Cost per unit (peak time)	11.35 ¢/kWh
Cost per unit (off-peak time)	05.15 ¢/kWh
Cost per unit sold	02.50 ¢/kWh

IX. RESULTS AND DISCUSSION

The RESCA methodology is implemented for the above mentioned load for optimization of four different configurations of HRES. The HRES is optimized based on different single and multi-constraint criteria depending on the chosen system configuration. The results obtained are discussed as follows:

A. CONFIGURATION I

The first configuration considered for optimization consists of PV system, WECS and BESS connected in islanding mode of operation. Four different criteria were chosen for the optimization process namely, FEE (single constraint), FEE and EGR, FEE and ASC, FEE and LPSP (multi-constraints). For all the criteria's initial assumption of N_W = 1, N_{PV} = 1 and CE (0) = 0 (i.e. initial charge stored in BESS is zero) is considered.

1) OPTIMIZATION FOR ONLY FEE CONSTRAINT

For this optimization, the FEE constraint is set at 250 W and a tolerance range from zero to 250 W is set for the

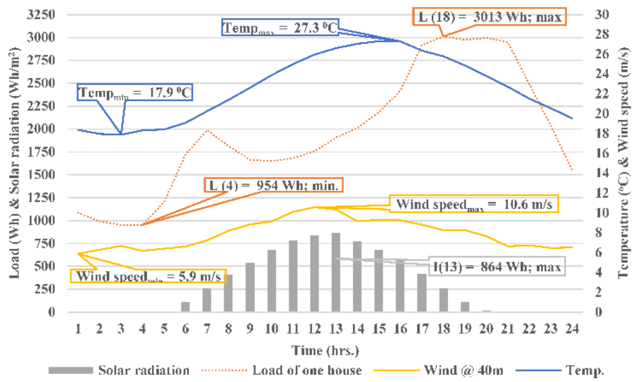


FIGURE 3. Load, solar radiation, wind speed and temperature profile of the chosen site.

TABLE 5. Set values and tolerance range of optimization constraints.

Constraint	Set value	Tolerance range
FEE	250 W	(0-250] W
REF	80 %	[80-81) %
LPSP	2 %	[1.95-2.00] %
ASC	Minimum	-
EGR	1	(0.9-1.1)
Time period (T)	24 hrs	-

convergence of the optimized result. On implementation of RESCA, the algorithm converges when FEE of 108 W is achieved. For the optimized HRES, the energy generated by the WECS, PV system and the charging/discharging profile of the BESS is shown in FIGURE 4 and the energy of BESS is shown in FIGURE 5. The pinch point of the analysis is obtained at t = 7 hrs, where maximum deficiency of energy is encountered by the system. After successful implementation of PoPA, the BESS capacity obtained is 1077 kWh with a minimum initial charge of 401 kWh. The optimized system configuration obtained is WECS of 853 kW, PV system of 213 kW and converter size of 189 kVA.

As seen in FIGURE 5, initially the majority energy profile of BESS lies in the negative region signifying that there is energy deficiency leading to a loss in power supply. After PoPA, the energy profile shifts in the positive region but the DOD limit of the BESS is violated, therefore, after DOD limit adjustment the SOC does not fall below 10 % (the set DOD limit) and the maximum value of this curve becomes the required BESS capacity. The cascade table obtained for the optimized system is shown in Appendix II.

2) OPTIMIZATION FOR FEE AND EGR CONSTRAINTS

Now configuration I of HRES is optimized using multi-constraints of FEE and EGR. The FEE constraint is set for 250 W and EGR for 1 with a tolerance of 0.9 to 1.1 for RESCA convergence. The aim for this optimization is to obtain a system configuration for which the energy generated by WECS and PV is same. The initial assumption for N_W, N_{PV} and BESS remains the same. After successful RESCA implementation, the optimized results are obtained

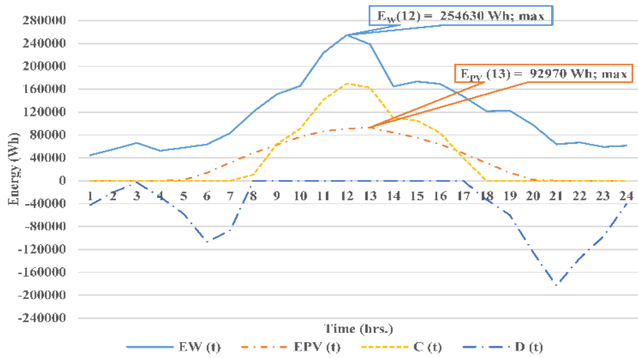


FIGURE 4. Energy generated and charge-discharge profile of BESS for optimized HRES in configuration I for only FEE constraint.

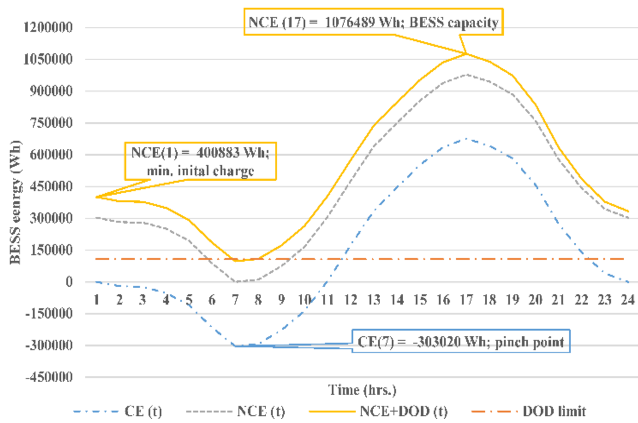


FIGURE 5. The energy of BESS for optimized HRES in configuration I for only FEE constraint.

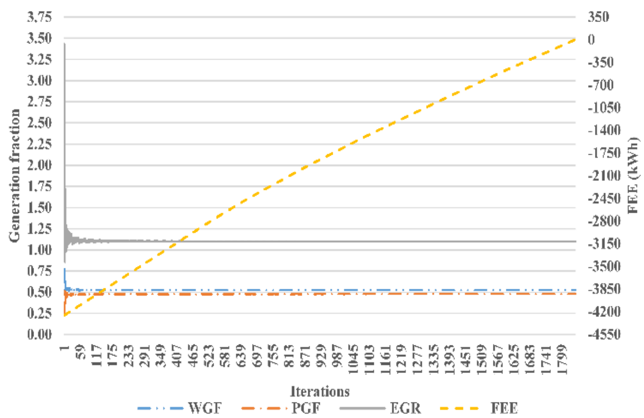


FIGURE 6. Variations in EGR, WGF and PVGF with each iteration for HRES in configuration I.

after an EGR of 1.089 and FEE of 148 W is achieved simultaneously. The change in EGR, wind generation fraction (WGF) and PV generation fraction (PVGF) are shown in FIGURE 6. The optimized system configuration obtained is WECS of 591 kW, PV system of 461 kW, BESS of 1403 kWh capacity with a minimum initial charge of 531 kWh and converter rating of 211 kVA.

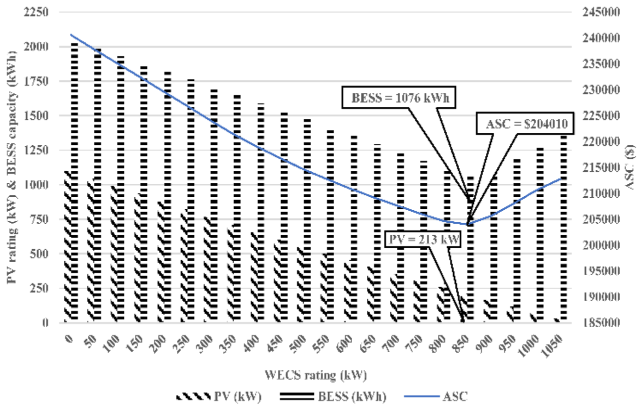


FIGURE 7. PV rating, BESS capacity and ASC variations with the change in WECS rating for HRES in configuration I.

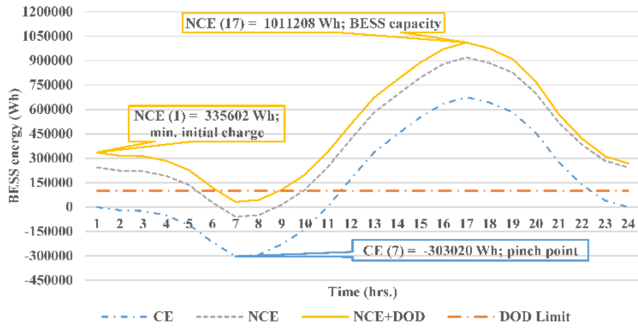


FIGURE 8. The energy of BESS for optimized HRES in configuration I with FEE and LPSP constraint.

3) OPTIMIZATION FOR FEE AND ASC CONSTRAINTS

To optimize HRES based on economics RESCA is implemented with FEE and ASC constraints. The aim of this optimization is to obtain the system with minimum annual system cost that satisfies the FEE constraint. For this, initial assumption of WECS equal to zero is made which is incremented by 50 kW (i.e. two N_W) at each step while obtaining the system configuration satisfying FEE constraint. WECS is incremented till 1050 kW after which it stops as N_{PV} obtained after this becomes zero violating the system configuration. On successful implementation of RESCA, the system configuration with minimum ASC consists of WECS of 850 kW, PV system of 213 kW, BESS capacity of 1076 kWh with a minimum initial charge of 303 kWh and converter rating of 189 kVA. The variations of PV system rating, BESS capacity and ASC as WECS rating is increased is shown in FIGURE 7.

It can be observed from FIGURE 7, that as WECS rating is increased, the PV system and BESS size reduces. This is because the PV system only generates energy during daytime and depends on the energy storage system at night. Therefore, for HRES with high PV rating requires higher BESS capacity. A change in trend is observed when WECS is increased beyond 850 kW due to the rise in BESS capacity. This rise in BESS is due to the large output generated by the overrated WECS. This implies that the HRES overcompensated the load and produces excess energy.

4) OPTIMIZATION FOR FEE AND LPSP CONSTRAINTS

The reliability optimization of HRES is performed by implementing RESCA with FEE and LPSP. The constraint is to optimize HRES such that LPSP does not exceed 2%. On successful implementation of RESCA, HRES configuration obtained is WECS of 853 kW, PV system of 213 kW, BESS capacity of 1011 kWh with a minimum initial charge of 336 kWh and converter rating of 189 kVA. The charge of the BESS is shown in FIGURE 8.

As stated earlier, the optimised WECS and PV system ratings remain the same as that obtained for only FEE criteria. But the BESS capacity reduces due to flexibility in the reliability of power. As seen from FIGURE 8 the energy of BESS is negative after PoPA analysis and violates the DOD limit after DOD adjustment. This leads to a reduced size of BESS and a loss of load during the time DOD limit is violated.

TABLE 6. Details of HRES with different optimization constraints in configuration I.

Parameter	Optimization constraints			
	FEE	FEE+ EGR	FEE+ASC	FEE+LPSP
WECS (kW)	853	591	850	853
PV system (kW)	213	461	213	213
BESS (kWh)	1077	1403	1076	1011
BESS initial (kWh)	401	531	303	336
Converter (kVA)	189	211	189	189
Pinch point (hrs.)	7	8	7	7
FEE (W)	108	148	174	118
LPSP	0.0000	0.0000	0.0000	1.9860
ASC ($)	204018	212211	204010	202327
EGR	3.4282	1.0890	3.4232	3.4282
REF (%)	100	100	100	100

The system parameters for various constraints implemented by RESCA is shown in TABLE 6. Inferences drawn from the comparison are as follows:

i. Optimized system rating of HRES is comparable for all optimization constraint except for EGR.
ii. Since EGR is 1 therefore, the rating of the PV system increases in case of EGR criteria.
iii. ASC for system obtained with EGR criteria is maximum because of the increased capacity of the PV system and BESS.
iv. The optimized system obtained with minimum ASC is very close to that obtained with only FEE constraint. This signifies that the RESCA inherently incorporates cost parameter even if the economic constraint is not chosen.
v. The energy generation profile of WECS and PV system and the charge/discharge profile of BESS remains the same as that shown in FIGURE 4 with a difference in the magnitude.

B. CONFIGURATION II

This HRES configuration consists of WECS, PV system, BESS in grid-connected mode. The RESCA methodology is

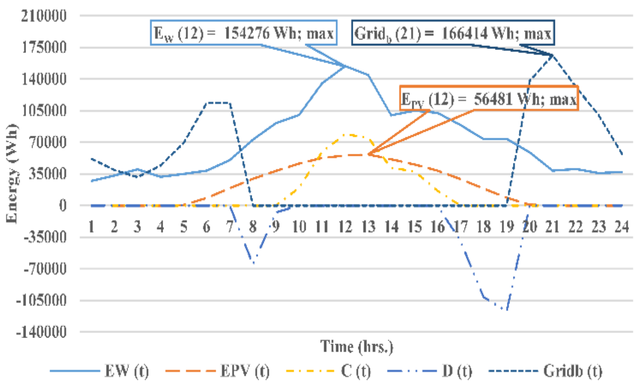


FIGURE 9. Energy profile of system components for HRES in configuration II for only FEE constraint.

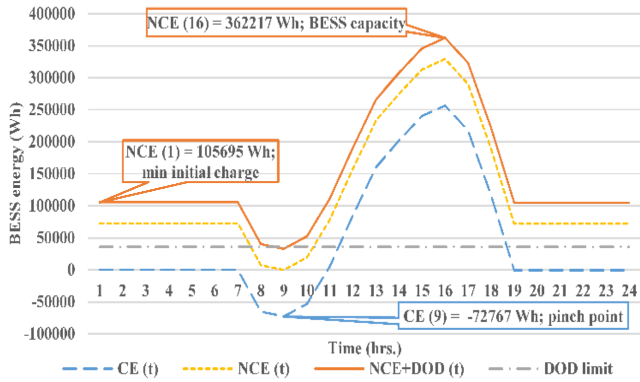


FIGURE 10. The energy of BESS for optimized HRES in configuration II for only FEE constraint.

implemented for different optimization criteria. For all criteria, it is assumed that the initial value of $N_W = 1$, $N_{PV} = 1$ and CE $(0) = 0$ and that no power is bought from the grid during peak hours (0800 to 1900 hrs.).

1) OPTIMIZATION FOR ONLY FEE CONSTRAINT

When RESCA is implemented for configuration II with only FEE constraint, the algorithm converges once FEE of 221 W is obtained. The optimized HRES configuration is obtained for HRES after successful RESCA implementation is WECS of 515 kW, PV system of 129 kW, BESS capacity of 363 kWh with a minimum initial charge of 106 kWh, converter rating of 188 kVA and grid converter rating of 166 kVA with 1057 units of electricity bought. The energy generation profiles of WECS and PV system, charging/discharging profile of BESS and grid energy requirement is shown in FIGURE 9.

As seen in FIGURE 9, no energy is bought from the grid during the peak hours. During peak hours the excess energy generated is used to charge the BESS and deficiency of energy is provided by BESS. After peak hours the deficiency is catered by the grid only, as fraction 'f' for FEE criteria is set to unity, and no REF constraint is imposed. Hence the optimized HRES constraint has lower BESS capacity with REF of 68 %. The charge of BESS is shown in FIGURE 10, which shows that the pinch point occurs at t = 9 hrs. After successful PoPA and DOD adjustment, the maximum capacity of BESS obtained is 363 kWh with minimum initial BESS capacity of 106 kWh. The SOC of BESS does not violate the DOD limit. Therefore, no loss of power occurs and the profile remains flat outside peak hours as neither charging nor discharging of BESS takes place since deficiency of energy during this period is catered by the grid. The cascade table obtained for this configuration is shown in Appendix II.

2) OPTIMIZATION FOR FEE AND REF CONSTRAINTS

When REF constraint is also imposed along with FEE, variation in energy profile of system components is seen in FIGURE 11. Here the parameter 'f' is also altered after

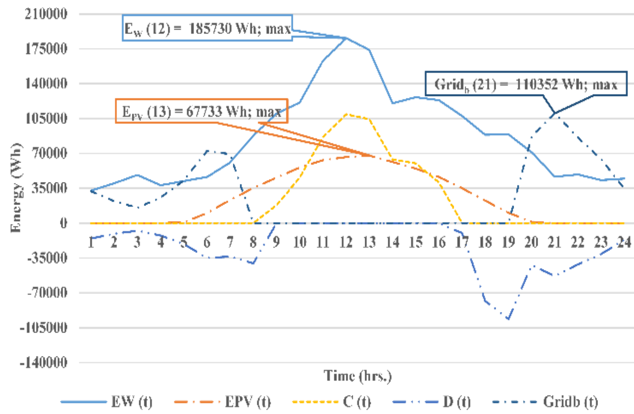


FIGURE 11. Energy profile of system components of HRES in configuration II for FEE and REF constraints.

every iteration to achieve REF of 80% (set value). Initially, the 'f' is set as unity and the RESCA algorithm converges when FEE of 213 W and REF of 80% is achieved at f = 0.70. The optimized system configuration obtained is: WECS of 620 kW, PV system 155 kW, BESS capacity of 581 kWh grid converter rating 111 kVA with 662 kWh of energy bought. The energy generation profiles of system components are shown in FIGURE 11.

As seen in FIGURE 11, no energy transaction takes place during peak hours. But since REF constraint is imposed, during off-peak time deficiency in load is catered partially by grid and BESS simultaneously. This leads to an increase in capacity of BESS, WECS and PV system but reduces the load on the grid in comparison to the optimized system configuration obtained for only FEE criteria. The charge of BESS is shown in FIGURE 12, which clearly shows the variation in energy profile of BESS even during off-peak hours because of BESS discharging (off-peak hour profile was flat in the previous case). A comparative chart of variation in system components rating and REF with the change in fraction 'f' is shown in FIGURE 13 to emphasise on the impact of parameter 'f'. It shows that as 'f' reduces the REF achieved increases and the contribution on grid reduces.

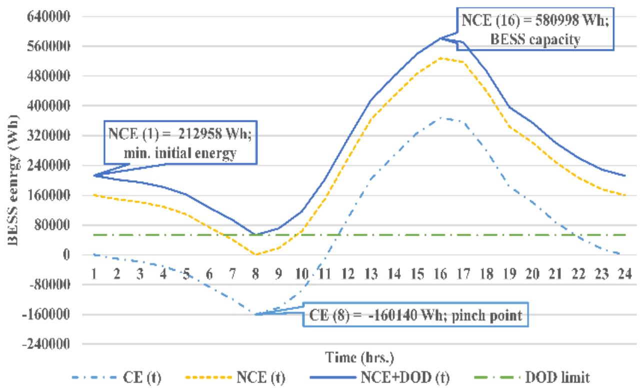


FIGURE 12. The energy of BESS for optimized HRES in configuration II for FEE and REF constraints.

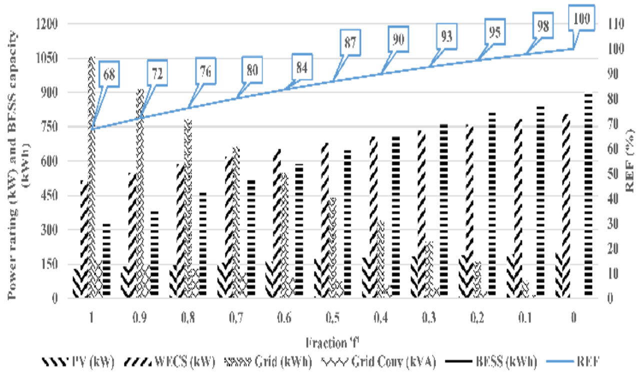


FIGURE 13. Variation in system components rating of HRES in configuration II with the change in fraction 'f'.

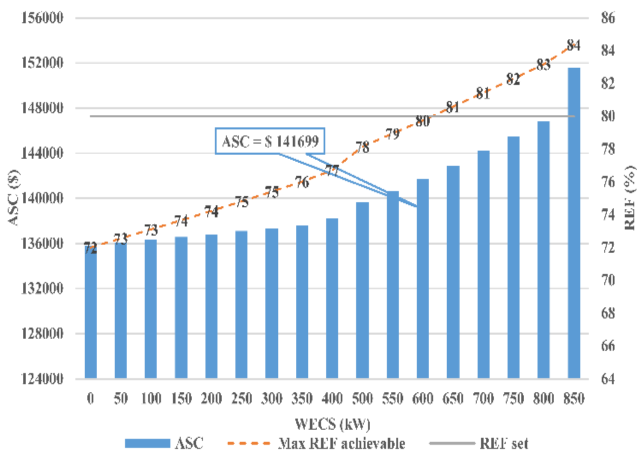


FIGURE 14. Maximum REF achievable and ASC variation with change WECS rating of HRES in configuration II.

3) OPTIMIZATION FOR FEE, REF AND ASC CONSTRAINTS

When RESCA is implemented with FEE, REF and ASC constraints, as WECS rating is increased the optimized system obtained does not satisfy the REF constraint. A plot showing the ASC obtained for various optimized HRES with maximum REF achievable is shown in FIGURE 14. It is seen that the ASC increases with the increase in WECS rating because

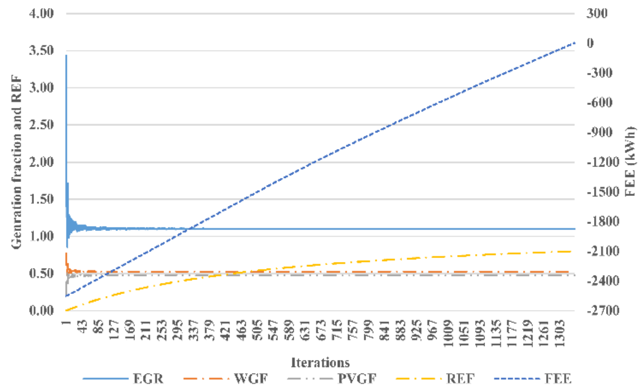


FIGURE 15. Variation in EGR, WGF, PVGF, FEE and REF with each iteration for HRES in configuration II.

of increase in PV and BESS rating and reduction grid burden (comparatively cheaper), but the maximum REF achievable is not always 80%. The acceptable optimized results are obtained when the WECS rating is 600 kW, at this point REF constraint is satisfied. The optimized HRES with minimum ASC comprises of WECS of 600 kW, PV system of 170 kW, BESS capacity of 538 kWh, grid converter rating of 113 kVA with 674 units of electricity bought.

4) OPTIMIZATION FOR FEE, REF AND EGR CONSTRAINTS

When EGR is also considered for system optimization of HRES the variation in EGR, WGF, PVGF, FEE and REF with each iteration is shown in FIGURE 15. The RESCA methodology converges when EGR of 1.08 is obtained along with FEE of 130 W and REF of 80 % at f = 0.62. The optimized system configuration thus obtained is, WECS of 429 kW, PV system of 335 kW, BESS capacity of 686 kWh, grid converter rating of 108 kVA with 682 units bought from the grid.

Summary of the optimized result obtained for HRES in configuration II is shown in TABLE 7. The inferences drawn from the comparison of results obtained are as follows:

i. Energy bought from the grid doesn't violate the t_{peak} constraint set.
ii. EGR constraint increases the PV system rating and units bought from grid thereby increasing the system cost.
iii. Most economical system configuration obtained is for FEE criteria which compromises on the renewable fraction (68 %).
iv. Cost of the system is greatly reduced by penetration of utility signifying that COE from renewable energy sources is high.
v. The nature of energy generation profiles is strongly affected by t_{peak} and REF constraint as depicted in FIGURE 9 and 12.

C. CONFIGURATION III

This configuration of HRES consists of WECS, PV system and a NIS generator and no BESS. Any deficiency encountered by the load is catered by the NIS generator in use. Due to

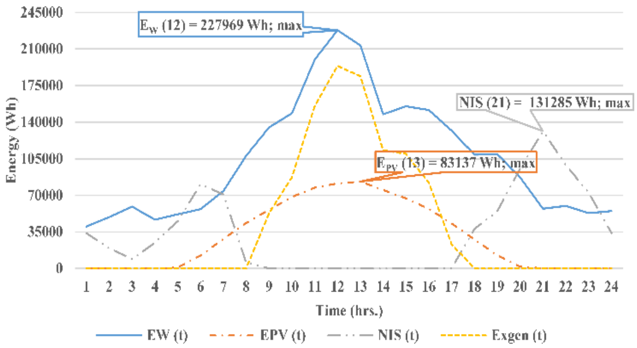


FIGURE 16. Energy generation profile of system components for HRES in configuration III with only REF constraint.

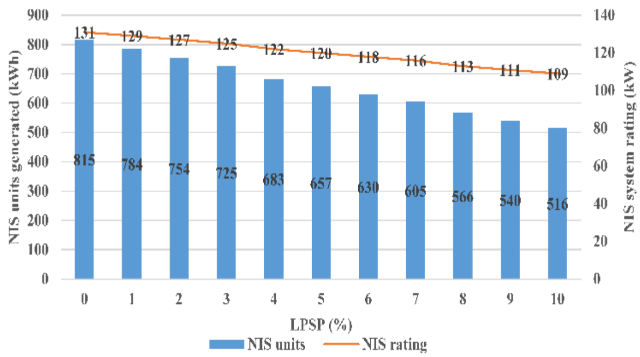


FIGURE 17. Variation of NIS rating and energy generated with a change in LPSP for HRES in configuration III.

TABLE 7. Details of HRES with different optimization constraints in configuration II.

Parameter	Optimization constraints			
	FEE	FEE+ REF	FEE+REF+ ASC	FEE+REF+ EGR
WECS (kW)	515	620	600	429
PV system (kW)	129	155	170	335
BESS (kWh)	363	581	538	686
BESS initial (kWh)	106	213	162	206
Pinch point (hrs)	9	8	8	8
Converter (kVA)	188	188	188	188
Grid conv. (kVA)	167	111	113	108
$Grid_b$ (kWh)	1057	662	674	682
REF (%)	68	80	80	80
ASC ($)	115316	143499	141699	145689
FEE (W)	221	213	113	130
f	1.00	0.70	0.70	0.62
EGR	3.4189	3.4322	3.5242	1.0801
LPSP (%)	0	0	0	0

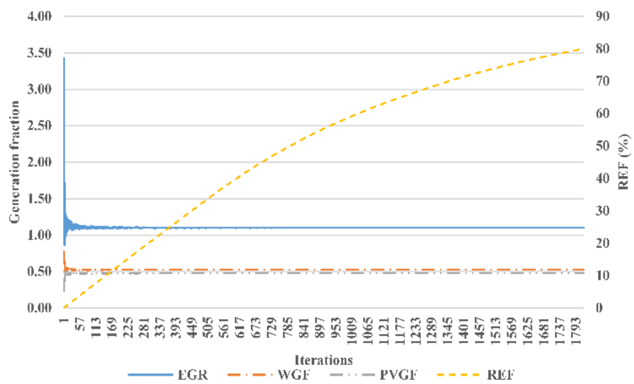


FIGURE 18. Variation in EGR, WGF, PVGF and REF with each iteration for HRES in configuration III with REF and EGR constraint.

the environmental impact of the conventional fuel generators bio-mass generator is assumed as the NIS source, but the optimization methodology remains same irrespective of the type of NIS.

1) OPTIMIZATION FOR ONLY REF CONSTRAINT

Since no BESS is used here, only one primary constraint can be considered for this configuration which is REF. The aim is to achieve a REF of 80 % between the WECS, PV system and NIS. Since the NIS considered is also renewable in nature, an exception is considered to make the analysis generalized with any type of source. After successful implementation of RESCA, the optimized system configuration obtained is WECS of 761 kW, PV system of 190 kW and NIS of 132 kW rating requiring to generate 815 kWh of energy. The energy generation curve is shown in FIGURE 16.

It can be seen from FIGURE 16, the deficiency in energy generation is catered by NIS, while the excess energy generated by the renewable sources is fed to the dummy load since no BESS is provided. It is to be noted that if BESS is also considered in this system configuration then the optimization methodology becomes similar to that of configuration II.

2) OPTIMIZATION FOR REF AND LPSP CONSTRAINTS

On successful implementation of RESCA, LPSP constraint of 2 % is achieved for the optimized system configuration of WECS of 761 kW, PV system of 190 kW and NIS of 127 kW rating requiring to generate 755 kWh of energy. It is observed that the WECS and PV system rating remains unaltered by introducing LPSP constraint, only the rating of NIS and units generated by NIS vary with change in LPSP as shown in FIGURE 17.

3) OPTIMIZATION FOR REF AND EGR CONSTRAINTS

For RESCA implementation with EGR and REF constraints the optimized system configuration obtained is WECS of 583 kW, PV system 455 kW and NIS rating of 144 kW generating 922 kWh of energy after EGR of 1.0995 and REF of 80.04 is obtained. The variation of EGR, WGF and PVGF in each iteration is shown in FIGURE 18.

4) OPTIMIZATION FOR REF AND ASC CONSTRAINTS

For ASC optimization of HRES the various optimized configuration obtained with REF set to 80 % is shown in FIGURE 19. As WECS rating increases reduction in ASC is observed due to the reduction in PV system and NIS rating. After a WECS rating of 750 kW, a change in the trend is

TABLE 8. Details of HRES with different optimization constraints in configuration III.

Parameter	Optimization criteria			
	REF	REF+ LPSP	REF+EGR	REF+ASC
WECS (kW)	761	761	583	750
PV system (kW)	190	190	455	205
NIS units (kWh)	815	754	922	821
NIS (kW)	132	127	144	132
Converter (kVA)	188	188	188	188
REF (%)	80.03	80.03	80.04	80.04
LPSP (%)	0	1.9170	0	0
ASC ($)	157627	157612	173453	156328
EGR	3.4322	3.4323	1.0995	3.1431

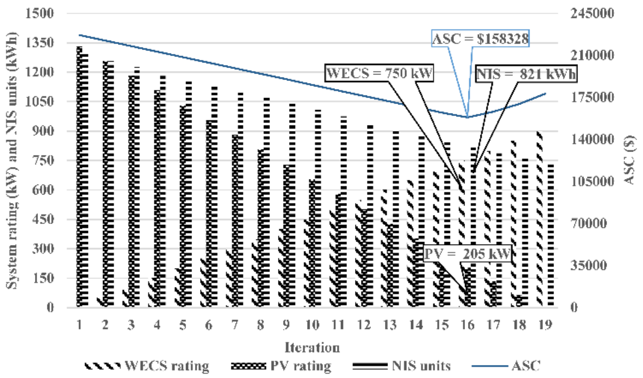


FIGURE 19. Change in ASC, PV rating and NIS unit with variation in WECS rating for HRES in configuration III.

observed due to excess energy generation. The final optimized system configuration is WECS of 750 kW, PV rating of 205 kW and NIS rating of 132 kW generating 820 units of energy.

Summary of the optimized result obtained for HRES in configuration III is shown in TABLE 8. The inferences drawn from the comparison of results obtained are as follows:

i. Annual system cost obtained for various optimization criteria is higher in comparison to those obtained for configuration II since the cost of energy of each unit from NIS is expensive in comparison to units bought from the utility.
ii. This configuration should be preferred over configuration II only if the site location is isolated having no provision of the grid.
iii. Comparing the results of configurations, I and III which work in islanding mode, Configuration III turns out to be a more economical solution, provided constant supply of fuel to the NIS can be maintained.
iv. The nature of energy generation profile as shown in FIGURE 16 remains the same with a difference in the magnitude.

D. CONFIGURATION IV

This configuration consists of a WECS and PV system in a grid-connected mode with no BESS. Optimization is similar to that of configuration III, with the difference in excess energy handling management. Unlike configuration III deficiency of energy is provided by the grid and excess energy generated by WECS and PV system is fed back to the grid and not to the dummy load (absent here). If there is no arrangement of selling energy back to the grid, then a dummy load needs to be added and the system optimization becomes similar to that of configuration III.

TABLE 9. Comparative details of HRES with different optimization constraints in configuration III.

Parameter	Optimization constraints			
	REF	REF + LPSP	REF + LPSP + EGR	REF + ASC
WECS (kW)	761	761	583	750
PV system (kW)	190	190	455	205
$Grid_b$ (kWh)	814	754	781	821
$Grid_s$ (kWh)	1001	1001	1389	1019
Converter (kVA)	188	188	188	188
Grid conv. (kVA)	195	195	238	197
REF (%)	80.02	80.02	80.04	80
LPSP (%)	0	1.8940	1.8440	0
ASC ($)	157622	157620	173445	156323
EGR	3.4323	3.4323	1.0995	3.1431

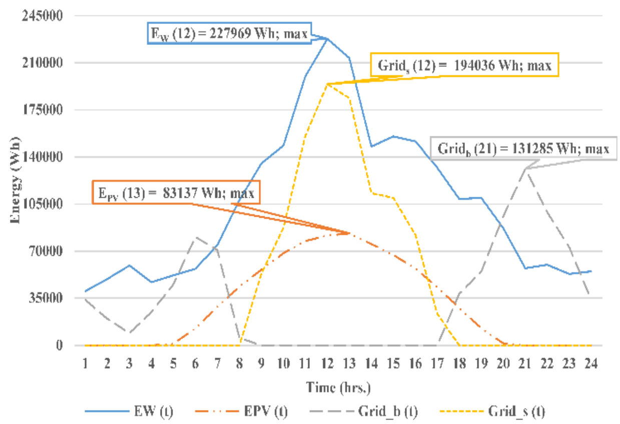


FIGURE 20. Energy generation profile of WECS, PV system and Grid for HRES in configuration IV with only REF constraint.

1) OPTIMIZATION FOR ONLY REF CONSTRAINT

On successful implementation of RESCA, REF of 80.02 % is achieved for system configuration: WECS of 761 kW, PV system of 190 kW with 814 units bought and 1001 units sold to the grid. The energy generation profile of the system components is shown in FIGURE 20.

2) OPTIMIZATION FOR REF AND LPSP CONSTRAINTS

For HRES optimization with LPSP constraint the optimized system configuration obtained is WECS of 761 kW,

TABLE 10. Comparison of various optimization techniques with RESCA [4], [8], [10], [50].

Optimisation technique	Demerits	RESCA improvements
HOMER	It only considers a single objective function to minimize cost.	It considers both cost and reliability analysis.
	HOMER does not consider DOD of BESS.	DOD is considered for BESS sizing
	The time step cannot be reduced below 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 of why or how the results are obtained.	The user can see and understand why and how a particular result is obtained.
RETScreen	Does not consider the effect of PV or WT performance variations with temperature.	It is considered here
	Time series data cannot be extracted.	It can be extracted.
	Limited option of visualization of obtained data.	The optimized data can be easily represented in graphs and tables.
iHOGA	Can simulate a system with a maximum daily average load of 10 kWh.	No restriction is imposed here.
HYBRID 2	It has limited access to performance parameters.	All the system and optimization parameters can be accessed and represented in graphs and tables.
Software (generalized)	The optimized result obtained is restricted to the predefined user input range, the most optimal solution may lie outside the predefined range.	The universal optimal solution is obtained irrespective of the initial assumption made.
Genetic algorithm	No guarantee to find the best solution and it might be difficult to obtain the global optimum solution.	The optimal solution is independent of the initial assumption.
	High probability of algorithm converging at a local minima if population generated is not sufficient.	The global optimum solution is found.
Particle Swarm Optimization (PSO)	Several modifications are required for it to be implemented for HRES.	Inherently built for hybrid energy systems.
Simulated Annealing (SA)	Several initial assumptions are required which strongly affect the final results.	Only initial assumptions of NPV, NW and BESS initial charge are required which have no effect on the final results. Although the rate of convergence can be affected.
Harmony Search (HS)	Complex optimization problem may lead to premature convergence.	Can handle HRES with different configurations and system components.
Fuzzy logic	Difficult to formulate membership function.	No such difficulty here.
	System modelling is difficult, as analogues system needs to be created.	Inherently built for renewable energy system, no analogues comparison is required.
Neural network	Needs high processing time for training and system modelling and training is complex for a larger system.	The processing power required is less and is independent of the system component modelling.

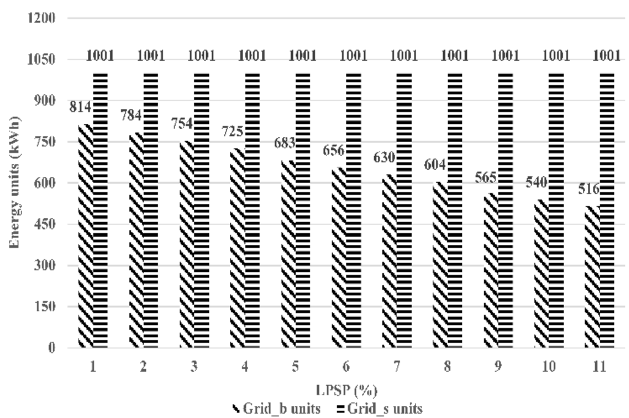


FIGURE 21. **Variation in units bought and sold to the grid with a change in LPSP for HRES in configuration IV.**

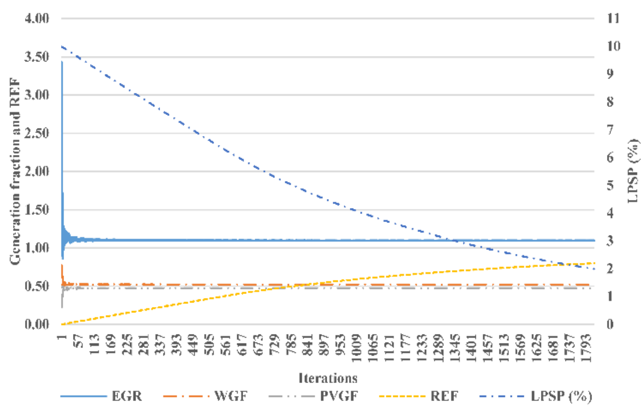


FIGURE 22. **Variation in EGR, WGF, PVGF, LPSP and REF with each iteration for HRES in configuration IV with REF, LPSP and EGR constraint.**

PV system 190 kW, with 754 units bought and 1001 units sold to the grid for LPSP of 1.8940 %. As LPSP increases the units bought from grid reduce but the units fed back to the grid remains unchanged as shown in FIGURE 21. This is because the WECS and PV system rating remains unchanged with the variations in LPSP.

3) OPTIMIZATION FOR REF, LPSP AND EGR CONSTRAINTS

On successful implementation of multi-constraint optimization, the algorithm converges when REF of 80.04, LPSP of 1.8440 and EGR of 1.0995 is achieved. The optimized system configuration obtained is: WECS of 583 kW, PV system of 455 kW with 781 units bought and 1389 units sold to

TABLE 11. Power curves of various wind turbines evaluated [41], [46], [51]–[53].

Wind speed @40m	ENERCON 25 kW	FUL AG 30 kW	ENERGIE PGE 35 kW	ENTEGRITY 50 kW	AOC WIND 65 kW	FUL AG 100 kW	FUL AG 250 kW	WES 250 kW	Wind World 250 kW	Bonus 300 kW	ENERCON 330 kW	Vestas 600 kW	NEG Micon 1000 kW
0	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0
1	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0
2	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0
3	0.00	0.50	0.00	0.00	0.00	1	1	0	0	4	5	0	0
4	3.40	1.60	1.20	0.00	0.00	2	7	0	0	15	14	0	10
5	8.00	3.50	1.60	1.42	1.84	8	25	4	12	32	30	22	51
6	13.30	7.00	4.10	6.02	7.82	17	35	15	33	53	55	65	104
7	18.40	12.00	7.80	12.25	15.93	30	59	29	60	87	92	120	186
8	22.10	17.00	11.70	18.46	24.00	45	91	56	92	129	138	188	291
9	24.80	22.00	16.30	24.92	32.40	63	127	77	124	172	196	268	412
10	25.90	26.00	21.00	31.77	41.30	79	160	116	153	212	250	356	529
11	26.30	28.00	25.80	37.00	48.10	94	190	145	180	251	293	440	655
12	26.40	30.00	30.00	41.38	53.80	108	218	179	205	281	320	510	794
13	26.00	30.50	33.80	45.31	58.90	119	228	222	224	297	335	556	911
14	25.40	31.00	36.50	47.77	62.10	125	238	241	238	305	335	582	986
15	24.30	32.00	36.50	49.31	64.10	122	249	257	247	300	335	594	1000
16	22.90	33.00	36.00	49.62	64.50	120	255	259	253	281	335	598	998
17	22.90	33.00	35.50	50.08	65.10	112	268	258	258	271	335	600	984
18	22.90	32.00	35.50	49.54	64.40	107	275	257	260	259	335	600	971
19	22.90	28.00	35.50	49.15	63.90	101	290	259	259	255	335	600	960
20	22.90	26.00	35.50	48.92	63.60	97	299	260	256	253	335	600	962
21	22.90	25.00	35.50	48.23	62.70	96	300	260	250	254	335	600	967
22	22.90	24.40	35.50	47.54	61.80	95	291	0	243	255	335	600	974
23	22.90	25.00	35.50	46.85	60.90	94	284	0	236	256	335	600	980
24	22.90	0.00	35.50	46.15	60.00	97	278	0	230	257	335	600	985
25	22.90	0.00	35.50	45.46	59.10	101	272	0	224	258	335	600	991
26	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0	0	0

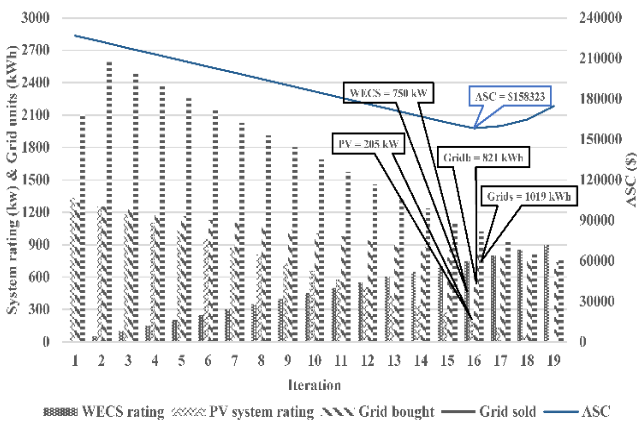


FIGURE 23. Variation of ASC and system rating with the change in WECS rating for HRES in configuration IV.

the grid. The variations of EGR, WGF, PVGF, REF and LPSP with each iteration are shown in FIGURE 22.

4) OPTIMIZATION FOR REF AND ASC CONSTRAINTS

On successful RESCA implementation with REF and ASC constraints the optimized system configuration obtained is WECS of 750 kW, PV system 205 kW with 821 units bought and 1019 units sold to the grid. The variation in ASC and system rating with an increase in WECS rating are shown in FIGURE 23.

Summary of the optimized result for HRES in configuration IV is shown in TABLE 9. The inferences drawn from the comparison of results are as follows:

i. Even though configuration IV has fewer components in comparison to configuration II, but the ASC is slightly more, due to the higher WECS and PV system rating.
ii. The increased cost is also due to the poor cost recovery by selling energy back to the grid (expected to change in the near future).
iii. The excess charge, in this case, can only be fed back to the grid unlike configuration II where it is used to charge the BESS.
iv. In this case deficiency of energy is only catered by buying expensive energy from the grid, while in case of configuration II the deficiency is also contributed by BESS which reduces the units bought from the grid and overall system cost.

To highlight the credibility of proposed RESCA methodology, a comparison with other common optimization techniques is presented in TABLE 10.

X. CONCLUSION

This paper has successfully demonstrated the application of the proposed RESCA methodology for HRES optimization. The extensive case study shown in the paper bolsters the robustness and versatility of the RESCA by showing its implementation for various HRES configurations. The RESCA is immune to the drawbacks of other optimization techniques such as poor conversion rate, non-surety of a definitive solution, localise optimal solution depending on the input range set, etc. RESCA has overcome the drawbacks of the primitive methodology of ESCA, by incorporating multi-constraint optimization criteria for both on and off the grid mode of operation. RESCA has included the variations in PV and WECS performance based on the temperature and system modelling. The variations in solar radiation profile reaching the PV module depending on the day of the year, latitude of the site, etc. have also been incorporated, which are mostly omitted in other analysis as seen in the literature review. The prime aim of this research is, to show the

TABLE 12. Cascade table for optimized system configuration I for only FEE constraint.

Time	Wind (m/s)	Solar (Wh/m^2)	Temp. (^{0}C)	Load (Wh)	E_W (Wh)	E_{PV} (Wh)	C (Wh)	D (Wh)	CE (Wh)	NCE (Wh)	NCE+DOD (Wh)
1	5.9	0	18.4	73865	44952	0	0	-42518	0	303020	**400883**
2	6.3	0	18.0	68705	55005	0	0	-20146	-20146	282873	380736
3	6.7	0	17.9	68336	66164	0	0	-3194	-23340	279680	377542
4	6.2	0	18.3	71424	52266	0	0	-28172	-51512	251508	349370
5	6.4	9	18.4	98161	58017	1227	0	-57501	-109014	194006	291869
6	6.6	98	19.1	148001	63553	13942	0	-106761	-215774	87246	185108
7	**7.2**	**230**	**20.3**	**169420**	**83076**	**31784**	**0**	**-87246**	**-303020**	**0**	**97863**
8	8.2	363	21.4	150479	120608	48688	10837	0	-292183	10837	108700
9	8.9	482	22.6	129797	150818	62875	63753	0	-228430	74590	172453
10	9.1	603	23.9	119146	165694	76443	90945	0	-137485	165535	263398
11	10.1	700	25.0	110178	223319	86625	141711	0	4226	307246	405109
12	10.6	746	26.0	103189	254630	91114	169814	0	174040	477060	574922
13	10.4	767	26.6	100363	238484	92970	162773	0	336813	639833	737695
14	9.2	684	27.1	98596	164912	84097	109720	0	446533	749553	847415
15	9.3	602	27.3	102632	173373	75061	105323	0	551856	854876	952738
16	9.2	502	27.3	118037	169361	63803	83889	0	635745	938765	1036628
17	**8.8**	**369**	**26.4**	**145379**	**147373**	**48232**	**39861**	**0**	**675606**	**978626**	**1076489**
18	8.3	231	25.8	170438	121489	31029	0	-33198	642408	945428	1039971
19	8.3	102	24.9	175015	122273	14112	0	-59923	582486	885506	974056
20	7.7	13	23.8	184162	97316	1761	0	-125514	456972	759992	835991
21	6.6	0	22.7	188475	63878	0	0	-183231	273741	576761	634437
22	6.7	0	21.5	158869	66894	0	0	-135257	138484	441504	485654
23	6.5	0	20.6	125696	59194	0	0	-97798	40687	343706	378077
24	6.5	0	19.5	88929	61404	0	0	-40478	208	303228	333551

TABLE 13. Cascade table for optimized system configuration II for only FEE constraint.

Time	Wind (m/s)	Solar (Wh/m^2)	Temp. (^{0}C)	Load (Wh)	E_W (Wh)	E_{PV} (Wh)	C (Wh)	D (Wh)	CE (Wh)	NCE (Wh)	NCE+DOD (Wh)
1	5.9	0	18.4	73865	44952	0	0	-42518	0	303020	**400883**
2	6.3	0	18.0	68705	55005	0	0	-20146	-20146	282873	380736
3	6.7	0	17.9	68336	66164	0	0	-3194	-23340	279680	377542
4	6.2	0	18.3	71424	52266	0	0	-28172	-51512	251508	349370
5	6.4	9	18.4	98161	58017	1227	0	-57501	-109014	194006	291869
6	6.6	98	19.1	148001	63553	13942	0	-106761	-215774	87246	185108
7	**7.2**	**230**	**20.3**	**169420**	**83076**	**31784**	**0**	**-87246**	**-303020**	**0**	**97863**
8	8.2	363	21.4	150479	120608	48688	10837	0	-292183	10837	108700
9	8.9	482	22.6	129797	150818	62875	63753	0	-228430	74590	172453
10	9.1	603	23.9	119146	165694	76443	90945	0	-137485	165535	263398
11	10.1	700	25.0	110178	223319	86625	141711	0	4226	307246	405109
12	10.6	746	26.0	103189	254630	91114	169814	0	174040	477060	574922
13	10.4	767	26.6	100363	238484	92970	162773	0	336813	639833	737695
14	9.2	684	27.1	98596	164912	84097	109720	0	446533	749553	847415
15	9.3	602	27.3	102632	173373	75061	105323	0	551856	854876	952738
16	9.2	502	27.3	118037	169361	63803	83889	0	635745	938765	1036628
17	**8.8**	**369**	**26.4**	**145379**	**147373**	**48232**	**39861**	**0**	**675606**	**978626**	**1076489**
18	8.3	231	25.8	170438	121489	31029	0	-33198	642408	945428	1039971
19	8.3	102	24.9	175015	122273	14112	0	-59923	582486	885506	974056
20	7.7	13	23.8	184162	97316	1761	0	-125514	456972	759992	835991
21	6.6	0	22.7	188475	63878	0	0	-183231	273741	576761	634437
22	6.7	0	21.5	158869	66894	0	0	-135257	138484	441504	485654
23	6.5	0	20.6	125696	59194	0	0	-97798	40687	343706	378077
24	6.5	0	19.5	88929	61404	0	0	-40478	208	303228	333551

successful implementation of RESCA for which the time period of analysis was set to 24 hours and performed for a month. In future scope, the implementation of the RESCA can be done for a time period of one year with reduced time step to achieve more realistic results.

APPENDIX I

See Table 11.

APPENDIX II

See Table 12.

APPENDIX III

See Table 13.

REFERENCES

[1] R. C. Bansal, *Handbook of Distributed Generation: Electric Power Technologies, Economics and Environmental Impacts*. Cham: Switzerland: Springer, 2017.

[2] A. F. Zobaa and R. C. Bansal, *Handbook of Renewable Energy Technology*. Singapore: World Scientific, 2011.

[3] Y. Kalinci, A. Hepbasli, and I. Dincer, "Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options," *Int. J. Hydrogen Energy*, vol. 40, no. 24, pp. 7652–7664, Jun. 2015.

[4] R. Singh and R. C. Bansal, "Review of HRESs based on storage options, system architecture and optimisation criteria and methodologies," *IET Renew. Power Gener.*, vol. 12, no. 7, pp. 747–760, May 2018.

[5] N. K. S. Naidu and B. Singh, "Grid-interfaced DFIG-based variable speed wind energy conversion system with power smoothening," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 51–58, Jan. 2017.

[6] A. Kumar and R. C. Bansal, "A review of multi criteria decision making (MCDM) towards sustainable renewable energy development," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 596–609, Mar. 2017.

[7] G. M. Masters, *Renewable and Efficient Electric Power Systems*. Hoboken, NJ, USA: Wiley, 2013.

[8] S. Sinha and S. S. Chandel, "Review of software tools for hybrid renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 192–205, Apr. 2014.

[9] M. D. A. Al-Falahi, S. D. G. Jayasinghe, and H. Enshaei, "A review on recent size optimization methodologies for standalone solar and wind hybrid renewable energy system," *Energy Convers. Manage.*, vol. 143, pp. 252–274, Jul. 2017.

[10] A. Ansari and A. A. Bakar, "A comparative study of three artificial intelligence techniques: Genetic algorithm, neural network, and fuzzy logic, on scheduling problem," in *Proc. 4th Int. Conf. Artif. Intell. Appl. Eng. Technol.*, Washington, DC, USA, 2014, pp. 31–36.

[11] W. S. Ho, H. Hashim, M. H. Hassim, Z. A. Muis, and N. L. M. Shamsuddin, "Design of distributed energy system through electric system cascade analysis (ESCA)," *Appl. Energy*, vol. 99, pp. 309–315, Nov. 2012.

[12] W. S. Ho, M. Z. W. M. Tohid, H. Hashim, and Z. A. Muis, "Electric system cascade analysis (ESCA): Solar PV system," *Int. J. Elect. Power Energy Syst.*, vol. 54, pp. 481–486, Jan. 2014.

[13] A. Gazarian, *Energy Storage for Power Systems*, vol. 1, 2nd ed. Edison, NJ, USA: IET, 2011.

[14] H. Belmili, M. Haddadi, S. Bacha, M. F. Almi, and B. Bendib, "Sizing stand-alone photovoltaic-wind hybrid system: Techno-economic analysis and optimization," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 821–832, Feb. 2014.

[15] A. Fetanat and E. Khorasaninejad, "Size optimization for hybrid photovoltaic-wind energy system using ant colony optimization for continuous domains based integer programming," *Appl. Soft Comput.*, vol. 31, pp. 196–209, Jun. 2015.

[16] S. Singh, M. Singh, and S. C. Kaushik, "Feasibility study of an islanded microgrid in rural area consisting of PV, wind, biomass and battery energy storage system," *Energy Convers. Manage.*, vol. 128, pp. 178–190, Nov. 2016.

[17] S. Sanajaoba and E. Fernandez, "Maiden application of cuckoo search algorithm for optimal sizing of a remote hybrid renewable energy System," *Renew. Energy*, vol. 96, pp. 1–10, Oct. 2016.

[18] A. Askarzadeh and L. dos Santos Coelho, "A novel framework for optimization of a grid independent hybrid renewable energy system: A case study of Iran," *Sol. Energy*, vol. 112, pp. 383–396, Feb. 2015.

[19] B. Bahmani-Firouzi and R. Azizipanah-Abarghooee, "Optimal sizing of battery energy storage for micro-grid operation management using a new improved bat algorithm," *Int. J. Elect. Power Energy Syst.*, vol. 56, pp. 42–54, Mar. 2014.

[20] M. Fadaeenejad, M. A. M. Radzi, M. Z. A. AbKadir, and H. Hizam, "Assessment of hybrid renewable power sources for rural electrification in Malaysia," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 299–305, Feb. 2014.

[21] A. Maleki and A. Askarzadeh, "Artificial bee swarm optimization for optimum sizing of a stand-alone PV/WT/FC hybrid system considering LPSP concept," *Sol. Energy*, vol. 107, pp. 227–235, Sep. 2014.

[22] A. Maleki and A. Askarzadeh, "Comparative study of artificial intelligence techniques for sizing of a hydrogen-based stand-alone photovoltaic/wind hybrid system," *Int. J. Hydrogen Energy*, vol. 39, no. 19, pp. 9973–9984, Jun. 2014.

[23] M. Baneshi and F. Hadianfard, "Techno-economic feasibility of hybrid diesel/PV/wind/battery electricity generation systems for non-residential large electricity consumers under southern Iran climate conditions," *Energy Convers. Manage.*, vol. 127, pp. 233–244, Nov. 2016.

[24] F. Baghdadi, K. Mohammedi, S. Diaf, and O. Behar, "Feasibility study and energy conversion analysis of stand-alone hybrid renewable energy system," *Energy Convers. Manage.*, vol. 105, pp. 471–479, Nov. 2015.

[25] R. Singh, S. Awasthi, and G. Khanduri, "A case study on economic viability of a stand-alone and grid connected generation system for Mumbai," in *Proc. Int. Conf. Ind. Electron. Elect. Eng.*, Bengaluru, India, vol. 4, 2016, pp. 14–19.

[26] R. Dufo-López *et al.*, "Multi-objective optimization minimizing cost and life cycle emissions of stand-alone PV–wind–diesel systems with batteries storage," *Appl. Energy*, vol. 88, no. 11, pp. 4033–4041, Nov. 2011.

[27] T. Hove and H. Tazvinga, "A techno-economic model for optimising component sizing and energy dispatch strategy for PV-diesel-battery hybrid power systems," *J. Energy Southern Africa*, vol. 23, no. 4, pp. 18–28, 2012.

[28] R. Hosseinalizadeh, H. G. Shakouri, M. S. Amalnick, and P. Taghipour, "Economic sizing of a hybrid (PV-WT-FC) renewable energy system (HRES) for stand-alone usages by an optimization-simulation model: Case study of Iran," *Renew. Sustain. Energy Rev.*, vol. 54, pp. 139–150, Feb. 2016.

[29] O. Anaya-Lara, *Wind Energy Generation: Modelling and Control*. Chichester, U.K: Wiley, 2009.

[30] D. B. Nelson, M. H. Nehrir, and C. Wang, "Unit sizing of stand-alone hybrid wind/PV/fuel cell power generation systems," in *Proc. IEEE Power Eng. Soc. General Meeting*, vol. 3, Jun. 2005, pp. 2116–2122.

[31] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, and R. Villafáfila-Robles, "A review of energy storage technologies for wind power applications," *Renew. Sustain. Energy Rev.*, vol. 16, no. 4, pp. 2154–2171, May 2012.

[32] K. Anoune, M. Bouya, A. Astito, and A. B. Abdellah, "Sizing methods and optimization techniques for PV-wind based hybrid renewable energy system: A review," *Renew. Sustain. Energy Rev.*, vol. 93, pp. 652–673, Oct. 2018.

[33] S. Yilmaz and F. Dincer, "Optimal design of hybrid PV-diesel-battery systems for isolated lands: A case study for Kilis, Turkey," *Renew. Sustain. Energy Rev.*, vol. 77, pp. 344–352, Sep. 2017.

[34] C. Scheubel, T. Zipperle, and P. Tzscheutschler, "Modeling of industrial-scale hybrid renewable energy systems (HRES)—The profitability of decentralized supply for industry," *Renew. Energy*, vol. 108, pp. 52–63, Aug. 2017.

[35] L. Park, Y. Jang, S. Cho, and J. Kim, "Residential demand response for renewable energy resources in smart grid systems," *IEEE Trans. Ind. Inform.*, vol. 13, no. 6, pp. 3165–3173, Dec. 2017.

[36] R. Singh, R. C. Bansal, and N. Tiwari, "Optimization and comparison of autonomous renewable energy system based on ESCA technique," presented at the IEEE Int. WIE Conf. Elect. Comput. Eng., Dehradun, India, 2017, pp. 1–5.

[37] A. Kumar, A. R. Singh, Y. Deng, X. He, P. Kumar, and R. C. Bansal, "A novel methodological framework for the design of sustainable rural microgrid for developing nations," *IEEE Access*, vol. 6, pp. 24925–24951, 2018.

[38] M. K. Deshmukh and S. S. Deshmukh, "Modeling of hybrid renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 12, no. 1, pp. 235–249, Jan. 2008.

[39] S. R. W. Alwi, N. E. M. Rozali, Z. Abdul-Manan, and J. J. Klemeí, "A process integration targeting method for hybrid power systems," *Energy*, vol. 44, no. 1, pp. 6–10, Aug. 2012.

[40] S. Bandyopadhyay, "Design and optimization of isolated energy systems through pinch analysis," *Asia–Pacific J. Chem. Eng.*, vol. 6, no. 3, pp. 518–526, May 2011.

[41] *Wind Energy Factsheet | Center for Sustainable Systems*. Accessed: Feb. 15, 2018. [Online]. Available: http://css.umich.edu/factsheets/wind-energy-factsheet

[42] *Daily Weather Records | Data Tools | Climate Data Online (CDO) | National Climatic Data Center (NCDC)*. Accessed: Jun. 29, 2018. [Online]. Available: https://www.ncdc.noaa.gov/cdo-web/datatools/records

[43] *Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States—OpenEI DOE Open Data*. Accessed: Jun. 29, 2018. [Online]. Available: https://openei.org/doe-opendata/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states.

[44] *Home*. Accessed: Jun. 29, 2018. [Online]. Available: https://www.enercon.de/en/home/

[45] *New Jersey Residential Electric Rates*. Accessed: Mar. 22, 2018. [Online]. Available: http://www.electricrate.com/residential-rates/new-jersey/

[46] J. N. Libii, ''Comparing the calculated coefficients of performance of a class of wind turbines that produce power between 330 kW and 7,500 kW,'' *World Trans. Eng. Technol. Educ.*, vol. 11, no. 1, pp. 36–40, 2013.

[47] M. Moore, R. Counce, J. Watson, and T. Zawodzinski, ''A comparison of the capital costs of a Vanadium redox-flow battery and a regenerative hydrogen-Vanadium fuel cell,'' *J. Adv. Chem. Eng.*, vol. 5, no. 4, pp. 1–3, Nov. 2015.

[48] *CellCube*. Accessed: Jun. 29, 2018. [Online]. Available: https://www.cellcube.com/

[49] AZoCleantech.com. (Jul. 1, 2016). *Solar (PV) Panel Comparison for Efficiency, Material, Voltage*. Accessed: Feb. 16, 2018. [Online]. Available: https://www.azocleantech.com/article.aspx?ArticleID=603

[50] R. Siddaiah and R. P. Saini, ''A review on planning, configurations, modeling and optimization techniques of hybrid renewable energy systems for off grid applications,'' *Renew. Sustain. Energy Rev.*, vol. 58, pp. 376–396, May 2016.

[51] A. W. Manyonge, R. M. Ochieng, F. N. Onyango, and J. M. Shichikha, ''Mathematical modelling of wind turbine in a wind energy conversion system: Power coefficient analysis,'' *Appl. Math. Sci.*, vol. 6, no. 91, pp. 4527–4536, 2012.

[52] F. D. Bianchi, R. J. Mantz, and H. De Battista, ''The wind and wind turbines,'' in *Wind Turbine Control Systems: Principles, Modelling and Gain Scheduling Design*, 1 ed. London, U.K.: Springer, 2007, pp 7–28.

[53] P. Denholm, M. Hand, M. Jackson, and S. Ong, ''Land use requirements of modern wind power plants in the United States,'' Nat. Renew. Energy Lab, Golden, CO, USA, Tech. Rep. NREL/TP-6A2-45834, 2009.

RANJAY SINGH received the B.E. degree in electrical engineering from Panjab University, Chandigarh, India, in 2011, and the M.Tech. degree in power electronics from the Motilal Nehru National Institute of Technology, Allahabad, India, in 2014. He is currently pursuing the Ph.D. degree in optimization of hybrid renewable energy systems with the Department of Electrical Engineering, University of Pretoria, Pretoria, South Africa. He was an Assistant Professor with the Department of Electrical Engineering, DIT University, Dehradun, India, from 2014 to 2016. His research interests include renewable energy system optimization, power system, smart grid, and microgrids.

RAMESH C. BANSAL (SM'03) has more than 25 years' experience in teaching, research, and industry. He is currently a Professor and the Group Head (Power) of the Department of Electrical, Electronic and Computer Engineering, University of Pretoria (UP). Prior to his appointment at UP, he was employed by The University of Queensland, Australia, the University of the South Pacific, Fiji, the Birla Institute of Technology and Science, Pilani, India, and the Civil Construction Wing of All-India Radio. He was with Powerlink, an Australian government-owned corporation responsible for Queensland's high-voltage electricity transmission network. He has significant industrial experience working with power utilities, includes NTPC (A 40 GW Indian Power Generation Company) and ESKOM (Generation, Transmission & Distribution Company, Africa). He has authored or co-authored over 275 journal articles, presented papers at conferences, and has contributed to books and chapters in books. He has supervised 16 Ph.D. students and currently supervising 10 Ph.D. students. His diversified research interests in the areas of renewable energy and conventional power systems include wind, photovoltaics, hybrid power systems, distributed generation, grid integration of renewable energy, power systems analysis, smart grid, flexible ac transmission systems (FACTS), and power quality. He is a fellow and a Chartered Engineer with the Institution of Engineering and Technology, U.K., a fellow of Engineers Australia, and a fellow of the Institution of Engineers (India). He is an Editor of the highly regarded journals, *IET-Renewable Power Generation* (regional editor for Africa) and *Electric Power Components and Systems*.

ARVIND R. SINGH received the B.E. degree in electrical engineering from the Walchand College of Engineering, Government Autonomous Institute, Sangli, India, in 2009, the M.Tech. degree in electrical power system from the College of Engineering, Government Autonomous Institute, Pune, India, in 2011, and the Ph.D. degree in electrical engineering from the Visvesvaraya National Institute of Technology, Nagpur, India, in 2017. He is currently a Post-Doctoral Research Fellow with the University of Pretoria, Pretoria, South Africa. His area of research includes power system protection, power system compensation, smart grid, microgrid and renewable energy generation, optimization & integration, and soft computing applications.

RAJ NAIDOO received the Ph.D. degree in electrical engineering from the University of Cape Town. He serves as the Director of Smart Grids Research in Collaboration, South African National Energy Development Institute. He is currently a Faculty Member with the Department of Electrical, Electronic and Computer Engineering, University of Pretoria, South Africa. He has authored or co-authored a number of research papers in national and international journals and is continuously engaged in guiding research activities at undergraduate and post-graduate levels. His research interests are in the areas of smart grids, power systems, and energy systems.