Review of HRESs based on storage options, system architecture and optimisation criteria and methodologies

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Abstract: The fast-growing awareness of depleting fossil fuel and adverse impact of conventional energy generation methods on environment has brought passionate attention to renewable energy sources (RES). Due to stochastic nature of energy production from RES, two or more sources are combined to form hybrid renewable energy system (HRES). Optimization of size, cost and reliability of power production of HRES are important factors in planning of HRES. This paper presents a review of optimization tools and constraints on which HRES system is optimized. The types of storage/backup system available for HRES are also presented in this study.

Keywords- Hybrid Renewable Energy System, Optimization techniques, Optimization constraints, Energy storage system (ESS).

1. Introduction

The energy demand of the world is ever increasing and it is estimated to increase up to 55% by 2035 from 2013 [1]. This energy growth cannot be sustained on conventional energy production which depends on depleting fossil fuels. Further, the Paris climate change conference of 2015 has laid emphasis on all the countries for reducing carbon emission [2]. Since fossil fuel burning is a major cause to greenhouse gases, renewable energy production seems to be a viable solution. The renewable energy resources like solar, wind, tidal, geothermal, etc. not only have the potential to cater to the current energy demand but also sustain the increase in energy demand [3].

The intermittent nature of renewable energy resource makes the energy production from a single RES unreliable [4]. Therefore, HRES is growing more in popularity which incorporates more than one energy production system [5]. The most commonly used RES are wind and solar which are dependent on the climate and topology of the area and therefore the site for installation of HRES has to be chosen prudently [6]. The reliability of HRES can be increased by incorporating energy storage units like battery bank, fuel cell, etc. to cater to the load demand at times when power production from renewable resources are not sufficient. HRES may or may not be connected to the grid from the point of common coupling (PCC) [7]. HRES not connected to the grid is in islanding mode where reliability of power becomes the prime constraint for the system planners. There is an increase in reliability of power for HRES with storage units, in which renewable energy system produce power for limited period of time. Therefore HRES with storage units can be successfully used for rural areas isolated from the utility grid. This is more cost-effective in contrast to actually installing the grid to the remote areas [8]. HRES not only have the advantage of clean energy production but also the cost of production and maintenance of the system is less in comparison to conventional energy systems for isolated areas not yet connected to the power grid [9]. To efficiently utilize the resources for renewable energy system economic and reliability optimization is required, which can be done using various available techniques like genetic algorithm (GA), particle swarm optimization (PSO), electric system cascade analysis (ESCA), etc. [10]. The energy planning involves optimal location of the plant, system architecture, economic and reliability constraints [11], [12].

The paper aims to present the latest study in the field of optimization of renewable energy systems based on the economic and reliability constraints. The paper is structured as follows: Section 2 shows the different components of the HRES system and the present scenario of renewable energy generation of the world. Section 3 presents the different type of storage units available along with their comparative analysis. Section 4 presents various architectures in which HRES can be designed and their merits and demerits. Section 5 presents different constraints on which HRES system is optimized. Section 6 shows the various techniques in use for the optimization of the system and finally the conclusion of the comprehensive literature review of the HRES is presented in Section 7.

2. Hybrid renewable energy system components

Our planet has enough renewable energy resources to sustain the current and future electricity demand. But the power generated from most of these resources is intermittent in nature. Therefore, solely depending on a single source is not sustainable for isolated system. Hence a hybrid system consisting of more than one power producing source is widely used. It overcomes the economic and physical barriers of a single power producing system [5]. The most common generating sources for hybrid system are wind, solar, hydrogen, geothermal, biogas, micro-hydro and fossil fuels. Due to the environmental impact of conventional sources like coal, diesel and nuclear emphasis is given to renewable resources as depicted in Fig. 1.

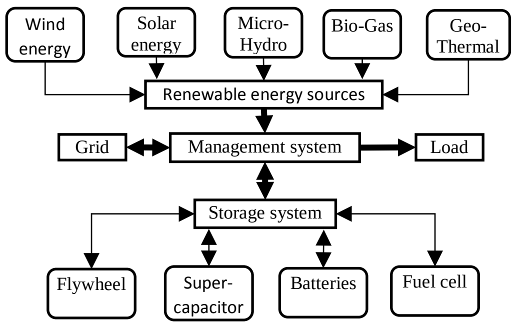

Fig. 1 *Hybrid renewable energy system*

The hardship of laying down transmission lines to remote areas makes HRES most attractive option. Integrating more than one resource preferably with storage unit overcomes the issue of unreliable power production [13]. In order to promote green and clean energy production, research is in progress for optimization and control tools for the HRES [14]. Out of the various sources mentioned above hydro and bio-gas are among the first-generation resources which have been in use since the 19th century. Further advancement in power electronic technology has led to solar and wind resources which comprise the second generation. Further research has led to the third generation which include bio-mass, geothermal, tidal and ocean energies [15]. Their development is aided by advancement in nanotechnology [16]–[18]. The total renewable energy installed capacity of the world presented in Table 1 [19], shows that photo-voltaic (PV) and wind energy conversion system (WECS) are the most popular and significantly increasing renewable energy sources in the world. The aim of the paper is to present optimization tools for a HRES with sources like solar and wind with ESS. Zhou et al. in [20], [21] and Bajpai et al. in [22] present modelling and size estimation of such HRES, which signify increasing popularity of the use of PV and WECS [23]–[29].

Table 1 Renewable energy installed capacity of the world

Types	Capacity (GW)		Increase (%)	Capacity (GW) in 2020 [1]	Capacity (GW) in 2030 [1]
	2015	2016			
Wind	370	433	17.03	800	2000
PV	177	227	28.24	489	1760
Bio power	101	106	4.95	112	210
Geo-thermal	12.9	13.2	2.32	22	32
Total	661.9	779.2	17.9	1423	4002

There are many factors on which the power production from PV depends like solar irradiance, temperature, tilt angle of the solar panel, location of the site and season. How to extract maximum power considering these conditions can be accessed from [7], [30]. PV cells are mainly made of three type of materials namely mono-crystalline, ploy-crystalline and thin film each having their own merits and demerits [31]. Research is also going on a new titanium oxide coted PV cells as well [25]. Currently, China (44 GW) has the largest installed capacity of PV power followed by Germany (38 GW) and Japan (35 GW) [19]. Wind energy is the fastest growing green energy. China with 150 GW leads the highest installed capacity of wind farms in the world followed by USA (80 GW) and Germany (48 GW) [19]. Power production from WECS is strongly dependent on the velocity of wind along with other factors like air density, height of tower and location of site. Due to mechanical and electrical integrity there are also limitations on the power production with respect to wind speed [7], [30]. The most commonly used turbine system available for the WECS are doubly fed induction motor (DFIG) and permanent magnet synchronous motor (PMSG) and their design and applications are explained in [30], [32]. Elma et al. [33] have modelled and designed a WECS with optimal energy management control while Zaho et al. [34] have designed the system with reactive power control of the distributed network. The modelling and optimization of WECS has been discussed in [26]–[28], [35].

3. Energy storage systems

The drawback of RES is that power generation is completely dependent on the climatic condition and topography of the plant site and not on the load demand unlike other conventional power generation systems [36]. Therefore, there can arise a problem of power mismatch. Hence storage system forms an important part of HRES in order to aid its reliability with a trade-off with system cost. Also, the power generated by the RES is irregular as it depends on the natural resources thereby increasing the irregularities in power system and depreciating its power quality. Therefore storage system is essential to provide backup to ancillaries which help in power quality improvement [37], [38]. In order to eliminate uncertainties which strongly affect the production from a RES a Bayesian network can be created to get a probabilistic idea of the size of storage system as well as the operation time of the storage/back-up system. Arseniev et al. [6] have created such a network for a UK home to solve uncertainties relating to variety of cause-and-effect relations for considered area with random and uncertain factors. The storage system not only provides interim power to the load at times when RES is unable to cater to the load demand but also provides reactive power compensation to the system in case of islanding mode of operation of HRES [39], [40]. Diaz et al. [41] have reviewed various types and applications of storage system. The main application listed are as follows:

- Power Quality Improvement (PQI)
- Ancillary Power Supply (APS)
- Short Term Power Supply (STPS)
- Peak Time Load Sharing (PTLS) (for grid connected system)

Following subsection briefly discusses the various storage technologies available:

3.1 Compressed air energy storage (CAES)

In this system when HRES power production is more than the load demand, excess power is used to compress air and store in caverns under high pressure. This pressurized air is combusted with natural gas which on expansion releases energy that drives a turbine to generate electricity. Very large storages are required because of the low energy density of the compressed air. Preferable locations are in artificially constructed salt caverns in deep salt formations. Salt caverns are characterised by several positive properties like high flexibility, no pressure losses within the storage, no reaction with the oxygen in the air and the salt host rock. If no suitable salt formations are present, it is also possible to use natural aquifers, however tests have to be carried out first to determine whether the oxygen reacts with the rock and with any microorganisms in the aquifer rock formation, which could lead to oxygen depletion or the blockage of the pore spaces in the reservoir. Depleted natural gas fields are also being investigated for compressed air storage [42]. Research is in progress in Germany so as to extract maximum amount of power from the compressed gas by utilizing minimum amount of natural gas [43].

3.2 Battery energy storage system (BESS)

This is most commonly used electric storage system. The excess energy from the HRES is stored in the form of chemical energy which can be converted to electricity when required. The most commonly used batteries are of four types, each having their own advantages and disadvantages. Na-S gives the highest energy density, Ni-Cd has the longest life, Lead-acid are the cheapest and Li-ion is the most commonly used of all with the best trade-off of all properties [37]. Since batteries are the most commonly used storage system in HRES, following are certain constraints which should be satisfied for modelling of the battery source [10], [44], [45]:

$$SOC_{t+1} = \begin{cases} (SOC_t \times \sigma) + \dfrac{I_{bat}(t) \times \Delta t \times \eta_{ch}\left(I_{bat}(t)\right)}{Q_n}, Charging \\ (SOC_t \times \sigma) + \dfrac{I_{bat}(t) \times \Delta t}{Q_n \times \eta_{disch}\left(I_{bat}(t)\right)}, \quad Discharging \end{cases} \quad (1)$$

$$SOC_{min} \leq SOC_t \leq SOC_{max} \quad (2)$$

$$P_{max-char} \leq P_{bat} \leq P_{max-dischar} \quad (3)$$

where, SOC_t is the state of charge of battery which should always lie between manufacture defined max and min limits, σ is the self-discharging rate of the battery, I_{bat} (t) is the current, which is positive during charging and negative during discharging of the battery, Δt is the period of sample and $\eta_{ch}(I_{bat}(t))$ is the charging efficiency and $\eta_{disch}(I_{bat}(t))$ discharging efficiency of the battery, Q_n is the nominal capacity of the battery in Ah. P_{bat} is power extracted from battery, which should lie between maximum allowed charging power and discharging power of the battery as shown in (3), for which P_{bat} is considered positive during discharging and negative during charging of the battery [46].

3.3 Hydrogen-based energy storage system (HESS)

This is a highly advanced and emission free technology for energy storage that converts chemical energy directly into DC electrical energy. The basic structure of a fuel cell comprises of an electrolyte layer and two porous electrodes. The electrolyte can be liquid as in case of molten carbonate fuel cells (MCFC) or solid as in case of polymer electrolyte membrane fuel cell (PEMFC) and solid oxide fuel cells (SOFC), the electrolyte has the property of conducting the ions but not the electron. A fuel cell is continuously fed hydrogen (fuel) at the anode and air or oxygen (oxidant) at the cathode, electrochemical reaction at the electrodes converts the chemical energy into electricity [47]. The prime advantage of this system is that it is completely pollutant free with water as the only by-product. The disadvantages are its poor efficiency , slow response time, low voltage of less than 1 V produced by each cell (stacking of RFC required) and safety issue of hydrogen storage which is a highly flammable gas [48]. Due to its slow response time it is used as a backup/secondary storage in HRES especially in case of an isolated system [10].

3.4 Supercapacitor energy storage system (SESS)

Supercapacitors are also known as ultra-capacitors. Advancement in dielectric technology has led to the development of supercapacitors which store energy in electrostatic form between the capacitor plates [49]. This is the most advanced technology for storage system which has zero maintenance and very high efficiency. Currently research is in progress to further increase its energy density [37], [39].

3.5 Flywheel energy storage system (FESS)

Flywheel stores energy in the form of kinetic energy of a rotating flywheel. Excess energy is used to rotate a flywheel to store energy and when electricity is to be produced brakes are applied to retrain flywheel by a motor and electricity is produced regeneratively [50].

The merits and demerits of various ESS have been presented in Table 2. All the storage systems have different cost, life span, power density and efficiency based on which they are selected for various applications as shown in Table 3 [51], [52]. These tables help the system planner make a judicious decision in choosing the right type of ESS for the HRES.

Table 2 Merit and demerits of energy storage systems

ESS	Merits	Demerits
CAES	Low cost, low self-discharging, longer life	High initial cost, very large scale, geographical restriction for installation
Ni-Cd Battery	Low maintenance, high energy density, high reliability	High cost, suffers from battery memory
Lead-Acid Battery	Average power density, low initial investment, widely available, no requirement of cell management system	Low life cycle, low efficiency ventilation required, requires proper disposal of used batteries
Li-ion Battery	High efficiency, high energy density, long life cycle, relatively compact in size, scope of rapid technological advancements	High initial capital cost due to special packing, risk of rupturing battery body
HESS	Almost pollution free, wide power range	Low efficiency, slow response time, high cost, installation restriction because of hydrogen storage tank
SESS	High efficiency, long life cycle, high power capacity	Low energy density, relatively high cost
FESS	High energy density, long lifetime, fast charge capability	High cost as a separate vacuum chamber is required, safety issues, high self-discharging, high cost

Table 3 Comparison of various storage devices and their applications

ESS	Lifetime	Applications

	Cost ($/kWh)		Efficiency (%)	Power Range	Specific Energy (Wh/kg)	STPS	PTLS	PQI	APS
CAES	150-350	40 yrs.	70	5-300 MW	30-60	✓	✓	-	✓
Na-S Battery	450	2000+ cycles	85	15 kW-40 MW	60-80	✓	✓	✓	-
Ni-Cd Battery	150-1000	3800+ cycles	80	10 kW-40 MW	50-75	✓	✓	✓	-
Lead-Acid Battery	150-1300	5-10 yrs.	75-85	10 kW-20 MW	30-50	✓	✓	✓	-
Li-ion Battery	150-1000	3500+ cycles	85-98	1-100 kW	75-200	✓	✓	✓	-
HESS	800-1200	20 yrs.	45	1500-3000 kW	150-450	-	-	✓	✓
SESS	250-350	100000+ cycles	95	1-300 kW	2.5-15	-	-	✓	-
FESS	400-2500	20000+ cycles	85	1-250 kW	10-30	✓	-	✓	-

4. Hybrid renewable energy system architecture

It has been established that having more than one RES makes the system more reliable. The architecture of the connection of various renewable energy resources, converters and buses can be different, each having their own complexity, as shown in Fig. 4 of Appendix. The prime aim in the architecture of the HRES is to minimize the number of conversion stages so as to reduce the conversion losses and complexity of control system while making system reliable and cost efficient [53]. The HRES system may consist of energy storage units which are connected through a bidirectional converter that can store energy during excess power production and can supply power to the load or system during power deficit state. The HRES can be isolated or connected to the grid [54], different architecture of HRES are as follows:

4.1 DC coupled isolated system

This architecture consists of a single DC bus line where coupling of different components of the system takes place as shown in Fig. 4a. In this architecture, the RES producing DC power can be connected directly or through a DC/DC converter depending on the DC bus voltage. No synchronization requirement of the bus to the power frequency (AC load) makes the control system simple [53], [55], [56].

4.2 AC coupled isolated system

Here we only have single AC bus line which acts as the point of coupling. Renewable energy system can be directly connected to the AC bus or via AC/AC converter depending on the AC bus voltage and frequency. It is to be noted that in such a system synchronisation of AC system is an essential part [57]. This system is suitable for small system usually rural with predominant AC load [53], [55], [56], [58]. The schematic of this architecture is shown in Fig. 4b.

4.3 Hybrid coupled isolated system

This system as shown in Fig. 4c consists of AC and DC bus. It has the advantages of fewer number of conversion stages, thereby increasing the efficiency of the system. On the other hand, having two buses increases the control complexity of the system and makes the energy management control difficult in comparison to other architectures. A dummy load can also be connected for large isolated HRES which can absorb excess power generated and also help in optimizing the size of energy storage system [55], [59]. The storage system should be designed in such a way such that after every cycle of the load profile (e.g. a month or a year) the initial stored energy or the final excess energy increases slightly, in order to incorporate future increase in load without compromising the system reliability [60].

4.4 Hybrid coupled grid connected system

Another architecture of the hybrid system is to have utility grid connected to the system as shown in Fig. 4d. The advantage of grid connected system is that size of the storage unit can be reduced or omitted as power can be extracted from the grid if power production from RES are not sufficient to cater to the load demand. Also during excess power production from the RES power can be fed back to the grid thereby making the operation of converter connected to the grid bidirectional. The financial savings by reduction in size of the storage unit, lower rating of the power generating units and cost recovered by selling power back to the grid makes this architecture an attractive alternative [56], [58], [61].

A summary of HRES architecture based on its merits and demerits is provided in Table 4. Table 5 [10], [62] shows various studies in the literature review based on real world applications of HRES, which show that majority studies of HRES are for isolated systems with target population of around 500.

Table 4 Summary of HRES architectures

Type	RES	Converters		Storage	Merits	Demerits
		Min	Max			
DC-Isolated	DC or AC	2	4	✓	Simple and less complex	If DC bus fails the entire system collapses

AC-Isolated	AC or DC	2	4	✓	Best suited for small scale real world applications having AC load	All the AC components have to be synchronised with the frequency of the AC bus
Hybrid-Isolated	AC or DC	2	6	✓	High system efficiency and reliability	System control and management is more complex
Hybrid-Grid connected	AC or DC	3	7	✓ (can be omitted)	Best suited for semi-urban location having grid accessibility	Power quality management is important concern for grid connection

Table 5 Studies based on load sector, target population and planning

Region/ Country	Energy Sources	Applications				Target Population	Planning	Technique/ Software	Ref.
		Domestic	Commercial	Agriculture	Other				
Rajasthan, India	PV-WECS-BGS	-	-	✓	-	Above 500	ST	Artificial Intelligence	[63]
Community in Australia	PV-BESS-DG	✓	-	-	-	Above 500	ST	Artificial Intelligence	[64]
Villages in Brazil	PV-BESS-DG	✓	-	-	-	200-500	LT	Software Based (self-made)	[65]
Chennai, India	PV-WECS-BESS	✓	-	-	-	Above 500	ST	HOMER	[66]
Abu Dhabi	PV-WECS	✓	-	-	-	Above 500	ST	HOMER	[67]
Nicosia, France	PV-W ECS-BESS	✓	-	-	-	Above 500	ST	TRNSYS	[68]
Cameroon, South Africa	PV-DG-SHP	✓	-	-	-	Up to 200	ST	HOMER	[69]
Canada	PV-WECS-RFC	-	-	-	✓	200-500	ST	MATLAB/ Simulink	[70]
Indonesia	PV-BESS-SHP	✓	-	-	-	Above 500	ST	Levelled cost of energy model	[71]
Madhya Pradesh, India	PV-WECS-BESS	✓	-	-	-	Up to 200	MT	Power Pinch analysis	[60]
Oujda, Morocco	PV-BESS	-	✓	-	-	200-500	MT	ESCA	[72]
Oujda, Morocco	PV-WECS-BESS	-	✓	-	-	200-500	MT	ESCA, HOMER	[73]

PV- Photo Voltaic, WECS-Wind Energy Conversion System, BESS-Battery Energy Storage System, BGS-Biogas Generating System, DG-Diesel Generator, SHP-Small Hydro Power Plant, ST-Short Term, MT-Medium Term, LT-Long Term

5. Optimization criteria

Criteria on which a HRES is optimized is basically divided into two categories, economic and reliability [62]. It is up to the discretion of the designer of the system, which criteria has to be given priority and to select a tolerance level for each criteria. The economic criteria basically deal with the cost of the system or in some cases the size of the system whereas reliability criteria give priority to the continuation of power to the load. Even though the prospects of having HRES as a clean and green source of energy having very low maintenance and operation cost, the initial investment required for installation of HRES is very high making the cost of energy and cost recovery time very high [74]. Therefore, optimization of its cost becomes a prime criteria for the system planner, especially for developing nation. Installing large rating of the renewable generating units for the peak load demand (may be for a short duration) incurs a heavy increase in the cost of the system, as the rating of the generating units increases, so does the storage system capacity. Therefore in accordance with the load demand, location and type, a trade-off can be done between the economic and reliability criterias chosen. The optimization criterias are cited in Table 6 along with certain limitations that pertain to each system criteria [10], [75]. Also shown in Table 7 is a brief description of the criteria and the context under which a criteria should be evaluated and optimized.

Table 6 Optimization criteria and limitations for HRES

Criteria	Type	Mathematical Function	Description	Limitations	Ref.

Annualized cost of system (ACS)	Economic	$ACS = TSC * CRF$ $where, TSC = \sum C_{install\_k} + \sum C_{M\&O\_k}$ $and\ CRF = \frac{i*(1+i)^L}{(1+i)^L - 1}$	TSC is the total system cost including maintenance and installation, $C_{install\_k}$ is the installation cost of all the components of the system, $C_{M\&O\_k}$ is the cost of maintenance and operation of the components, i is the discount rate and L is the total life time of the system.	Variation in interest rate and inflation is not integrated in the cost estimation.	[73], [76]
Levelled cost of energy (LCE)	Economic	$LCE = \frac{ACS}{E_{tot}}$	ACS is total annualized cost of the system which includes cost of equipment and their installation and maintenance cost, E_{tot} is the total expected energy generated.	Moderate number of power producing units are considered and the salvage cost of the system after its life time is not included.	[77], [78]
Net present cost (NPC)	Economic	$NPC = \sum NPC_{sale\_k} + \sum NPC_{end\_k} - C_{invest} - \sum NPC_{replace\_k} - \sum NPC_{M\&O\_k}$	NPC_{sale_k} is the income obtained by selling of the components to be replaced (for a grid connected system it also includes the income from energy sold to the grid), NPC_{end_k} is the income obtained by selling of HRES components of the HRES at the end of the lifetime of the system, C_{invest} is the total investment cost, $NPC_{replace\_k}$ is the cost of replacement of components during the lifetime of the plant and $NPC_{M\&O\_k}$ is the cost of maintenance and operation of all the components.	Cannot incorporate the change in fuel cost (if conventional sources are included) and uncertainties in lifetime of system components like batteries.	[79]–[82]
Cost of energy (COE) per unit	Economic	$COE = \left[\left(\frac{i*(1+i)^L}{(1+i)^L - 1}\right) * \left(\frac{P}{8760}\right)\right] + (M\&O)$	P is total installed capacity and M&O is maintenance and operation cost of the system.	Cost recovered by salvaging system components after system life span not included.	[83]
Life loss cost of battery (LLCB)	Economic	$LLCB = \frac{A_c}{A_{tot}} C_{ini-bat}$	A_c is the effective cumulative Ah, A_{tot} is the total cumulative Ah throughout life cycle, $C_{ini\text{-}bat}$ is initial investment cost of batteries.	Derating of battery performance during its lifetime is not considered.	[13]
Loss of power supply probability (LPSP)	Reliability	$LPSP = \frac{\sum_{t=1}^{T} DE(t)}{\sum_{t=1}^{T} P_{load}(t)\Delta t}$	DE is deficiency in energy, P_{load} is power demand of the load and T is the time period for which LPSP needs to be calculated.	It can be defined for a given load profile and deviation in the load profile are not considered.	[84]–[87]
Expected energy not supplied (EENS)	Reliability	$EENS(L, P_h) = \begin{cases} L - \int_{P_{h\_min}}^{P_{h\_max}} P_h \cdot f_{P_h}(P_h) dP_h & L > P_{h\_max} \\ \int_{P_{h\_min}}^{L} (L - P_h) \cdot f_{P_h}(P_h) dP_h & P_{h\_min} \le L \le P_{h\_max} \\ 0 & L \le P_{h\_min} \end{cases}$	L is the load demand at a time instant, P_h is the power generated by HRES, P_{h_max} is the maximum power generated by the HRES, P_{h_min} is the minimum energy generated by the HRES (assumed zero) and $f_{ph}(P_h)$ is the probability function of the power output from the HRES.	Probability in the variation in load demand is not considered.	[88]–[90]
Loss of load (LOL)	Reliability	$LOL = \sum_{t=1}^{T} DE(t)$	-	Normalized with total annual energy demand.	[91], [92]
Level of autonomy (LA)	Reliability	$LA = 1 - \frac{T_{LOL}}{T_{Opt}}$	T_{LOL} is the duration of loss of load and T_{Opt} is the total duration of operation of the system.	-	[93]
Deficiency of power supply probability (DPSP)	Reliability	$DPSP = \frac{\sum_{t=1}^{T} EPG}{\sum_{t=1}^{T} E_L}$	EPG is the excess power generated and E_L is the electric load.	For $EPG < E_L$, it is same as LPSP.	[94]
Loss of loads probability (LLP)	Reliability	$LLP = \frac{\sum_{t=1}^{T} DE(t)}{\sum_{t=1}^{T} P_{load}(t)}$	-	The limitation of the constraint is that load considered is fixed and variations in the load are omitted.	[95]

Table 7 Context of selecting optimization criteria

Optimization Criteria	Optimization Variable	Application

ACS	Cost	It indicates the cost of the system annually considering its maintenance, installation cost and life span of the HRES. It is best suited for large scale HRES where the initial investment is high and majority of it is financed.
LCE/COE	Cost	It shows the cost of each energy unit (kWh) generated by the HRES. It is best suited for medium to small scale grid connected HRES, to evaluate the amount of energy to be borrowed from the utility in order to reduce the ratings of HRES system components thereby reducing cost of the system and cost of energy.
NPC	Cost	It indicates the net cost of the HRES once it has passed its due life span, which includes the maintenance and operation cost, cost salvaged by selling the system components and also the replacement cost of the system components during the life span. This criteria can be evaluated for HRES of any size. It helps the system planner to identify if the system cost for a particular load can be recovered, if not what would be the final cost of the system post the sale of system components after the system life span.
LLCB	Cost	It evaluates the cost of BESS inclusive of initial investment and replacement costs of batteries during the life span of the system. It is best suited for medium to large scale HRES, as the size and rating of storage units is high. It also helps in comparison of cost of having BESS to other storage options like SESS, CAES, FESS, etc. and making a judicious decision on choosing the correct type of storage unit for the HRES.
LPSP/LLP	PSC	It indicates the probability of HRES not catering to the load demand. It is important to evaluate these criteria for HRES in islanding mode of operation, especially large scale HRES catering to a wider load where priority of PSC increases.
EENS	PSC	It gives the estimated energy not supplied by the HRES to the load. It is a good indicator to evaluate if the HRES should be grid connected or not. By evaluating the units of energy demanded by load from utility, prudent decision can be made on the mode of operation of the HRES.
LOL	PSC	It gives an exact amount of energy not supplied by the HRES to the load based on the assumption that the load profile and RES generation profiles remain constant. It is best suited for small scale HRES catering to a rural area. It is simple to implement and gives a rough estimation of the system reliability.
LA	PSC	It indicates the time duration for which the loss of power occurs. It is also based on the same assumptions as that of LOL and is best suited for small scale HRES for rural areas.
DPSP	PSC	It is expressed as the ratio of the power generated by HRES to the load demand. DPSP<1 if power generated is less than demand, DPSP>1 in case the power generated is more than demand. It is evaluated for grid connected HRES where load may decrease for a long duration of time during which DPSP>1 and power can be sold back to the utility. It also helps in projecting the increase in load that can be sustained by the HRES during its life time, as probability in variation in load demand is considered.

PSC- Power supply continuity

6. Optimization methods

The various methods available for the optimization of HRES can be broadly categorized as artificial intelligence methods, iterative methods and software methods [96]–[98]. The artificial intelligence methods comprise of methods like genetic algorithm (GA), particle swarm optimization (PSO), tabu search (TS), simulated annealing (SA), harmony search (HS), etc., while iterative methods may include electric system cascade analysis (ESCA), hill climbing algorithm power pinch analysis (PoPA) etc. The software tools available for optimization are HOMER, Hybrid2, etc., each having their own underlying optimization technique. The following section briefly explains these techniques.

6.1 Artificial intelligence methods

6.1.1 Particle swarm optimization

It is one of the most commonly used optimization technique because of its simplicity. It was invented by Kennedy and Eberhart in 1995 [99]. It is based on the social behaviour of animals such as swarm or fishes and how they move in a group. Each feasible solution forms a particle and each particle has memory to store two data which are best experiences found by the particle (pbest) and found in the group (gbest). The position and velocity of each particle is updated after each iteration as follows [99].

$$v_k(iter+1) = w(iter) \times v_k(iter) + c_{1k} \times r_{1k}\big(pbest_k(iter) - x_k(iter)\big) + c_{2k} \times r_{2k}\big(gbest_k(iter) - x_k(iter)\big) \quad (4)$$

$$x_k(iter+1) = v_k(iter+1) + x_k(iter) \quad (5)$$

$$w(iter+1) = \beta \times w(iter) \quad (6)$$

Where v_k and x_k are the velocity and position of each particle and k=1, 2, 3….., N_p is the particle's index, N_p is the population size, r_{1k} and r_{2k} are random numbers between 0 and 1 which are different for each particle in each update and

c_{1k} and c_{2k} are the learning factors which control the importance of the best solution found for the kth particle and the best solution found by the swarm and w is the weight which is initialised as w_o (positive value) and changes after each iteration as shown in Eq. (6) to get closer to the final solution where β is a predefined deceleration parameter. The steps of PSO algorithm are briefly expressed as follows [100]–[102]:

Step 1. Search space is filled with a randomly generated population or particles.
Step 2. Each particle is randomly assigned an initial velocity, usually 10% of the particle position [102].
Step 3. Objective function value is calculated for each particle.
Step 4. The initial position of each particle is selected as pbest and gbest.
Step 5. New particle positions and weights are calculated using Eqs. (5-6).
Step 6. If particles violate the predefined constraint a new positon and velocity is assigned to the particle.
Step 7. Objective function is recalculated and pbest and gbest are updated.
Step 8. If the predefined constraints are met then iteration is terminated and gbest is selected as the optimal solution else process steps 5 to 8 are repeated.

A multi criterion approach to optimise the reliability cost and emission from a hybrid system is proposed in [99], [103]. Kanwar et al. [104] have used PSO for optimized distribution of energy from different sources in a smart grid. Kennedy and Eberhart [105] also proposed a binary particle swarm optimization (BPSO) algorithm to implement PSO concept for binary implementation.

6.1.2 *Tabu search*

Tabu search developed by Glover in 1986 [106] is a metaheuristic algorithm which finds the best solution comparing with neighbouring solution. A random solution is initially chosen as the best solution and is compared with specific numbers of neighbouring/trial solutions to find the best solutions. The improved solution is shifted from x (current solution) to x' (new improved solution) following a predefined set of criterion [107]. All the solutions obtained are kept in a tabu list which comprise the improved solution, the entire search space is travelled in this manner to find the best solution of the search space and the iteration is terminated. The tabu list also comprises of a given set of rules and banned solution that filters out from the memory structures for a faster conversion of solution [108].

6.1.3 *Simulated annealing optimization*

It was introduced for optimization problems by Kirkpatric, Gelatt and Vecchi in 1983 [109]. This algorithm is inspired by annealing of metals where metal is heated/melted at high temperature and then cooled in a controlled manner so that the size of the metal crystal increases while its defects are diminished [110]. In SA a new random state is selected at temperature T and its energy E is compared with the previous state. If $\Delta E \leq 0$, then the new state is accepted else it is accepted with a degree of probability. After reaching an equilibrium temperature the process can be repeated for lower temperatures. This algorithm can be implemented in HRES optimization by replacing energy with cost function and temperature with constraints [105]. Askarzadeh et al. [106] have implemented SA for cost optimization of a PV-WECS using the following logic mentioned in Eqs. (7-9) [111], [112].

$$x(iter+1) = \begin{cases} x_{new}\ , & if\ e^{(\frac{-\Delta f}{T})} > r \\ x(iter)\ , & other\ wise \end{cases} \tag{7}$$

$$x_{new} = x(iter) + WF \tag{8}$$

$$T(iter+1) = s \times T(iter) \tag{9}$$

Where, x (iter) is the current state, x (iter+1) is the next state, WF is the vector with randomly distributed elements between [-wf,wf] , s is the step size and r is a random number between [0,1]. The range of WF and the values of r and s are set by the user depending on the application of the SA technique. The probability of the next solution x (iter +1) being at x_{new} (random solution close to x (iter)) is given by Δf, where $\Delta f = f(x_{new}) - f(x\ (iter))$ is difference between corresponding fitness values. If $\Delta f \leq 0$, x_{new} is always accepted otherwise probability is found of selecting x (iter+1) as a new solution even if it is inferior solution to x (iter). This probability depends on the difference in objective function values Δf and temperature T. The process of finding new solution of x and T is continued by means of Eqs. (8-9) until a predefined $iter_{max}$ is achieved [113], [114].

6.1.4 *Harmony search*

It is metaheuristic algorithm which is inspired by the improvisation of the Jazz musicians. It was introduced by Geem, Kim, and Loganathan in 2001 [115]. In this each musician (decision variable) plays (generates) a note (a value) for finding a best harmony (global optimum) all together [116]. The important point for the convergence of the HS algorithm are harmony memory conversion rate (HMCR), pitch adjusting rate (PAR) and bandwidth of generation (BW). HMCR varies between 0 and 1 and is the rate at which a value is chosen from the harmony memory (HM). PAR and BW are defined as follows:

$$PAR(t) = PAR_{min} + \frac{PAR_{max} - PAR_{min}}{iter_{max}} \times iter \tag{10}$$

$$BW(t) = BW_{max} e^{c \times iter} \tag{11}$$

$$C = \frac{\ln(\frac{BW_{min}}{BW_{max}})}{iter_{max}} \tag{12}$$

In order to implement HS for cost optimization (discrete application) of a HRES consisting of PV and WECS Askarzadeh [117] have adopted the following steps:

Step 1. A feasible solution is generated which consists of number of PV panels and wind turbines that are named as harmony and saved in the HM.
Step 2. For each value ACS is calculated.
Step 3. Algorithm parameters are set.
Step 4. A new harmony is produced using pseudocode as shown in [75], [118].
Step 5. The improvised harmony is saved to HM if it has better quality than the worst solution in the HM.
Step 6. Steps 3-5 are repeated until critical criteria is achieved.

Step 7. The best values of the harmony from the HM space are returned as the optimized solution.

6.1.5 *Genetic algorithms*

It is stochastic algorithm inspired by Darwin's theory of survival of the fittest. GA consists of five basic processes namely: generation of the population, generation of fitness function and the optimization process which includes selection, crossover and mutation of the population. In the selection process a set of feasible solutions are selected from the population generated. Crossover operation finds the fittest solution among them. Mutation operation helps the GA to come out from a local minima trough, which may result in false termination of the algorithm [119]. This algorithm can be easily adopted to optimize HRES as performed by Kaldellis et al. [120] for which the main aim of the study was to minimize the cost of the system with zero loss of load. A flowchart showing optimization of HRES as adopted by Kaldellis et al. [120] is shown in Fig. 2, the figure has been further modified to show the five processes of the genetic algorithm.

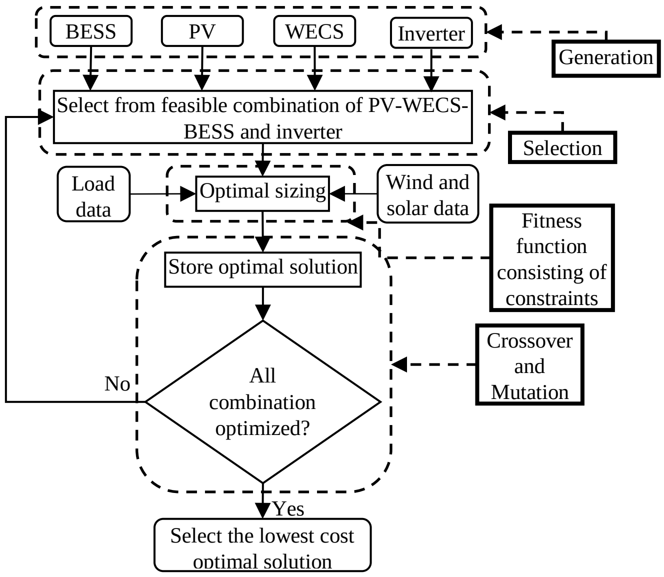

Fig. 2 *Optimization of HRES with GA [120]*

6.2 *Iterative methods*

6.2.1 *Power pinch analysis*

Pinch analysis (PA) involves the technique of process integration which have been in use to optimize various resources such as thermal energy, material production, etc. [121]. This concept can also be applied for energy systems where energy represents the flow variable and time represents the directional quantity. As in heat exchange networks (HEN) the heat flows from hot stream to cold stream in the same way energy goes from generator (hot stream) to load (cold stream). PoPA provides a designer with graphical representation for easier decision making. This method is most commonly used for storage system optimization for a HRES. The steps involved for optimization of HRES are as follows [60], [122]:

Step 1. Input load, generation and storage data

Step 2. Plot generation and load data verses time (grand composite curve obtained) [60]

Step 3. Selection of minimum generating unit based on energy balance and non-negative storage energy

Step 4. Determination of storage unit based on the power generated and load demand

Step 5. Generation of sizing curve

Step 6. Operational cost evaluation for various configurations on the sizing curve

Step 7. Selecting the most optimal solution from the design space

6.2.2 *Electric system cascade analysis*

Ho et al. [123] have proposed this method based on PoPA for optimization of non-intermittent generators like natural gas, diesel, biogas, etc. Later they also applied ESCA optimization for single source PV power generation. Zahboune et al. [72], [73] have further exhibited that it can be applied to PV-WECS-BESS as well. The basic premise of this method is to find out the accumulated energy and according to fixed constraints recalculate the number of energy sources and energy storage elements. The flowchart showing the working of ESCA for PV-BESS is shown in Fig. 3.

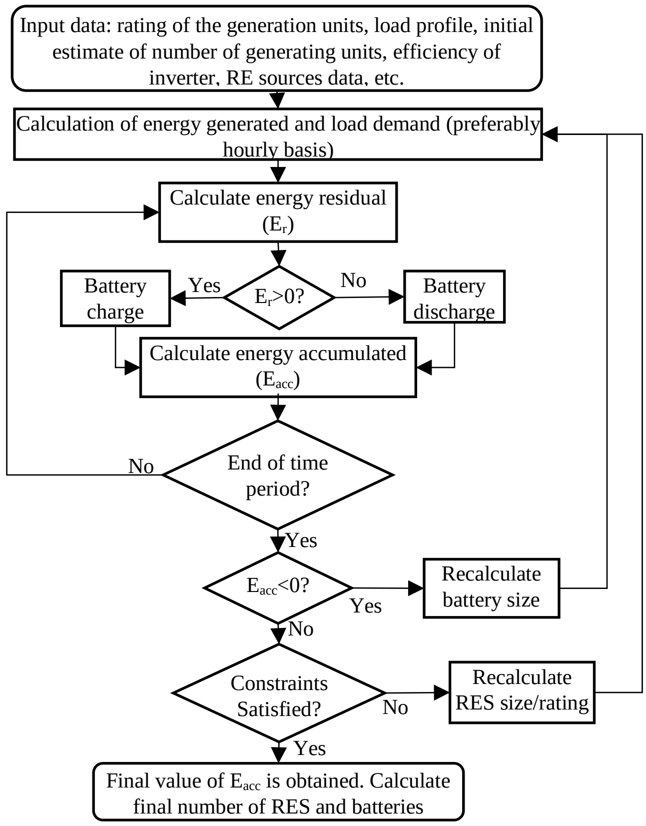

Fig. 3 *Flowchart of sizing algorithm for ESCA*

6.3 *Software tools for optimization*

6.3.1 *HOMER*

HOMER stands for Hybrid Optimization Model for Electric Renewable and is developed by National Renewable Energy Laboratory (NREL) in USA. The software can simulate various types of hybrid systems including renewable and conventional resources. The optimization constraints like cost, emissions, renewable fraction and others can be set for the simulation. The software simulates the different combinations of generating units and gives the most cost effective optimal solution. The prime advantage of HOMER is the graphical representation of various aspects of the system, which makes it user friendly and gives more control to the designer for planning. The drawback is long iteration time as all the possible combinations, even the non-feasible are also evaluated. But the simplicity of use of the software makes it an attractive choice for energy planners. Many different versions of the software are available online with HOMER Pro being the latest and can be installed and used free of cost for a period of three months [124].

6.3.2 HYBRID2

RERL (Renewable Energy Research Laboratory) of University of Massachusetts has developed this software. Hybrid2 was designed to study wide varieties of hybrid power systems. The hybrid systems can include three types of electrical loads, multiple wind turbines of different types, photovoltaics, multiple diesel generators, battery storage, and four types of power conversion devices. Systems can be modelled on AC, DC, or both buses. A variety of different control strategies/options can be implemented which incorporate detailed diesel dispatch as well as interactions between diesel gensets and batteries. An economic analysis tool is also included that calculates the economic worth of the project using many economic and performance parameters [125] . There are other software optimisation tools available in the market like GAMS (General Algebraic Modelling System), RETscreen, INSEL (Integrated Simulation Environment Language), TRNSYS (Transient Energy System Simulation), SOMES (Simulation and Optimization Model for Energy System), RAPSIM (Remote Area Power Simulator), iHOGA (Improved Hybrid Optimization by Genetic Algorithm), etc. which can be used for planning and optimization purposes [125].

Each of these techniques have their own merits and demerits which have been presented in Table 8. The applications of these optimization techniques in the literature review are presented in Table 9.

Table 8 Merits and demerits of optimization techniques

Optimization Techniques	Merits	Demerits	Ref.
PSO	Derivative free technique Less sensitive to nature of objective function Less dependent on the set of initial points Has good efficiency rate	Lacks a solid mathematical foundation Is a variant of stochastic optimization techniques requiring larger computational time	[126], [127]
TS	Easy to integrate with other methods Devotes larger time in region where solution is good Uses deterministic moves which reduce the variability due to initial solution	Uses more number of iterations Slower conversion rate	[128]
SA	Can deal with non-linear models Statistically guarantees finding an optimal solution Easy to code for complex system	A lot of initial constraints required Initial assumption strongly affects the final solution	[110]
HS	Easy implementation Less adjustment of parameters Quick convergence	Complex optimization problems leads to premature convergence	[129], [130]
GA	Solves problems with multiple solutions GA are easily transferred to existing simulations and models	May stuck in local minima if the initial population generated is not sufficient	[131]
PoPA	Graphical interface makes it easy to understand and implement the constraint problems	Can be implemented for a single generating unit system	[132]
ESCA	Inspired from PoPA and can handle multi-generation system	Multi-constraint optimization makes the technique implementation complex	
HOMER	Easy to implement complex system Graphical representation of data makes it easy to understand Gives the best cost-effective system combination	Reliability analysis cannot be performed	[133]

Table 9 Optimization techniques applications in literature review

Energy Sources	Techniques	Constraints	Outcomes	Ref.
PV-WECS-BESS	PSO	LCE	Levelled cost of the system was obtained considering financing insurance and various depreciating factors	[134]
PV-SHP-BGS-WECS-DG	PSO	NPC, EENS	Proposed 12 different combinations for the HRES of which 10th combination had minimum cost and maximum renewable energy fraction. Also found that fuel consumption cost of DG system was the minimum for 10th iteration	[135]
PV-WECS-BESS	PSO	TSC	Proposed a cost-effective solution for both on grid and off grid operation	[136]
PV-WECS-DG	PSO	LCE, LOL	Performed two case studies, one to find the best cost-effective combination and second to check the robustness of the system with uncertainties	[137]
Distributed Generation	PSO		Found the optimal location of the RES for reduction in power loss	[138]
PV-WECS-BESS	PSO, TS, SA, HS	Comparison	Different optimization techniques were compared and PSO is found to be the most promising and robust. Also, system was compared to HRES	[75]
PV-WECS-BESS	SA	ACS	Found the optimum number of the BESS, PV and WECS thereby minimising the cost of the system	[112]
PV-WECS-BESS-DG-HESS	SA, TS	COE	Found the optimum generator scheduling, charging and discharging of the batteries was found to reduce the cost of energy (COE) per unit	[139]
PV-WECS-BESS	HS	ACS, EENS	Found the optimum number of the battery storage system, PV and WECS thereby minimising the cost of the system	[112]
PV-WECS-BESS	GA	LOL, ACS	Found the lowest system cost combination with no loss of load	[120]
PV-WECS-BESS	GA	LPSP	The system is optimized to increase the reliability of the system by reducing the loss of load probability	[140]
PV-WECS-BESS/HESS	GA	COE, Emissions	Found a solution for a small hybrid system with economic and environmental constraints	[141]
PV-WECS-BESS-DG	GA	COE, Battery Life	Reduced the power generation cost with consideration to lifetime of lead acid battery	[13]
PV-WECS-BESS-DG	GA	LCE	Reduced the energy cost by including RES to an existing DG unit for small isolated system	[142]
PV-WECS-BESS	GA	LPSP	The cost of HRES system was reduced with minimum loss of power	[24]
PV-WECS-BESS	GA	NPC, Maintenance Cost	Optimum number of RES was found to minimise the cost of system and maintenance cost	[143], [144]
PV-WECS-BESS	GA	ASC, Power quality	Designed a system with minimum cost and optimal power quality from RES	[145]
PV-WECS-DG-BESS	GA	LCE	Minimized the cost of battery storage system by introducing a DG unit	[146]
PV-WECS-BESS	GA	LLCB	Optimal number of generating units were found for a house in Massachusetts	[147]
PV-WECS-DG-BESS	GA	LCE	The cost of energy and system reduced by evaluating different combinations of the hybrid system	[148]
PV-WECS-BESS	GA	LPSP	Determined the optimal size of PV and wind with reliability constraint	[84]
PV-DG-BESS	GA	LLP	Found the most optimal solution for generating unit to serve the load with specified LLP	[95]
PV-BESS	ESCA	LPSP	Applied ESCA to find the optimal number of PV panels for a load in Oujda	[72]
PV-BESS	ESCA	ACS, LPSP	Implemented ESCA to find the optimal number of PV panels for rural house with energy consumption of 5.575 kWh	[149]
PV-WECS-BESS	ESCA	ACS, LPSP	Applied ESCA to find the optimal number of PV panels and WECS for a load.	[150]
PV-WECS-BESS	ESCA/HOMER	ACS, LPSP	Applied modified ESCA to find the optimal number of PV panels and WECS for a load in Oujda and results were compared with HOMER. Modified ESCA was found to be faster	[73]
PV-WECS-BESS-FESS	HOMER	NPC	Compared nine different scenarios and found the most optimum with respect to cost	[151]
PV-BESS-Grid	HOMER	NPC	Found the reduction in utility cost by using a roof top PV system.	[152]
PV-DG-BESS	HOMER	NPC	The most cost-effective model was obtained from several iterations	[81]
PV-WECS-BESS	HOMER	COE	Showed that the cost of energy can be greatly reduced if the HRES is grid connected	[153]
PV-WECS-HESS	HOMER	NPC	Two models of wind and wind/PV hybrid were compared and found that wind/PV hybrid to be more cost efficient	[154]

PV-DG	RETScreen	NPC	Sizing analysis of a PV and diesel system with variation in renewable energy fraction were performed to show merits and demerits of hybrid system	[155]
PV-WECS-BESS	HOMER	NPC	Cost optimization of HRES components were performed catering to a remote village load	[156]
PV-WECS-BESS-HESS/DG	HYBRID2	NPC	Compared hybrid system with DG/HESS and found DG to be more cost efficient because of the low efficiency of HRES	[157]
PV-WECS-Biogas	PoPA	COE	Peak and off-peak load shifting were performed to reduce the outsourced load demand and reducing the cost of energy	[122], [158]
PV- BESS	PoPA	ASC	The optimal number of PV for a rural load was found and suggested that BESS can be cost effective for large system	[60]
PV- BESS/ WECS-BESS	PoPA	Converter Loss	Applied PoPA analysis to two single RES systems to reduce the outsourced energy and power conversion losses	[159]

7. Conclusion

Renewable energy sources have been identified as the most feasible solution to the current energy scenario. The extraction of maximum energy from the renewable energy resources and mitigate the stochastic nature of power production have been the main aims for the system planners. This paper has reviewed various techniques and constraints on which a HRES is optimized. The literature review shows that under economic constraints the most important aspect is to reduce the cost of system and reliability constraints show that loss of power supply probability is the main challenge for designing the HRES. To reduce losses during power conversion within the system various architectures are reviewed. Also to improve the reliability of the HRES the types of storage units available are compared on their merits and their applications are reviewed. The optimization techniques can be broadly categorized into iterative based and artificial based, also a software tools available may be adopted for the optimization process. Although a lot of work is in progress in the field of renewable energy system, there exists a scope of further improvement in technologies and improvement in efficiency of the system catering not only to reduce the cost but also to increase renewable power fraction with reduction in losses.

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9. Appendix

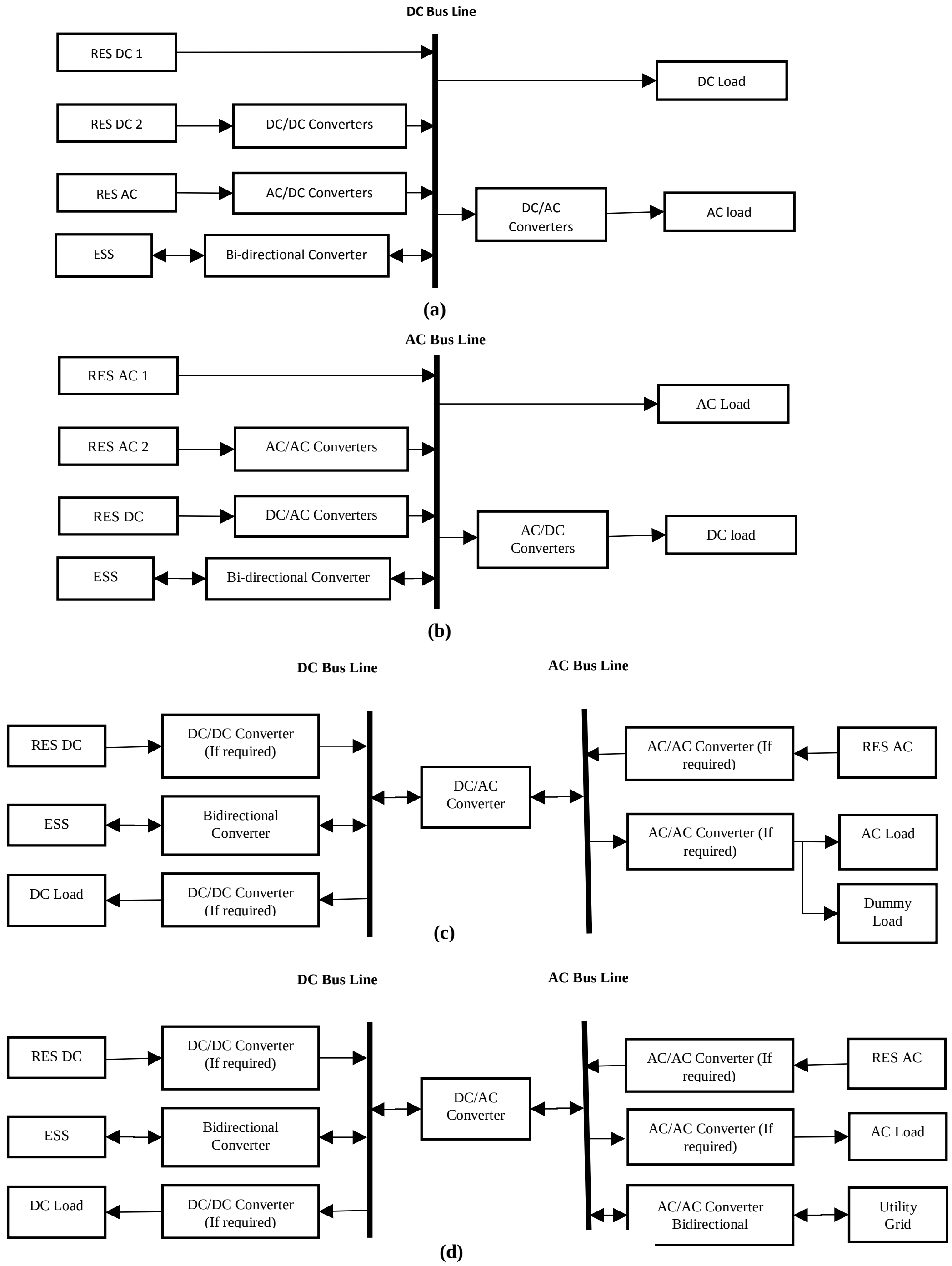

Fig. 4 *(a) DC coupled isolated system (b) AC coupled isolated system (c) Hybrid coupled isolated system (d) Hybrid grid connected system*