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Battery energy storage system size determination in renewable energy systems: A review

Yuqing Yang[a,*], Stephen Bremner[a], Chris Menictas[b], Merlinde Kay[a]

[a] School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, New South Wales 2052, Australia
[b] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, New South Wales 2052, Australia

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ABSTRACT

Renewable energy, such as hydro power, photovoltaics and wind turbines, has become the most widely applied solutions for addressing issues associated with oil depletion, increasing energy demand and anthropogenic global warming. Solar and wind energy are strongly dependent on weather resources with intermittent and fluctuating features. To filter these variabilities, battery energy storage systems have been broadly accepted as one of the potential solutions, with advantages such as fast response capability, sustained power delivery, and geographical independence. During the implementation of battery energy storage systems, one of the most crucial issues is to optimally determine the size of the battery for balancing the trade-off between the technical improvements brought by the battery and the additional overall cost. Numerous studies have been performed to optimise battery sizing for different renewable energy systems using a range of criteria and methods. This paper provides a comprehensive review of battery sizing criteria, methods and its applications in various renewable energy systems. The applications for storage systems have been categorised based on the specific renewable energy system that the battery storage will be a part. This is in contrast to previous studies where the battery sizing approaches were either arranged as an optimised component in renewable systems or only accounted for one category of renewable system. By taking this approach, it becomes clear that the critical metrics for battery sizing, and by extension the most suitable method for determining battery size, are determined by the type of renewable energy system application, as well as its size. This has important implications for the design process as the renewable energy system application will drive the battery energy storage system sizing methodology chosen.

1. Introduction

Renewable energy (RE), especially solar and wind energy, has been widely regarded as one of the most effective and efficient solutions to address the increasingly important issues of oil depletion, carbon emissions and increasing energy consumption demand [1,2]. At the same time, numerous solar and wind energy projects have been developed, or are under construction, to meet renewable energy targets [3–5] and increase renewable penetration. Policies for renewable energy development strategies and incentives have also been launched by various governments [5]. Moreover, it is expected that by 2025, solar PV and onshore wind energy will experience a price reduction of 43% and 26%, respectively [6].

Despite the environmental advantages and sustainability of renewable energy, there remain two major issues when integrating it into the power grid. Firstly, it is well-known that renewable energy production strongly depends on local weather and climate conditions. The consequent intermittent and stochastic characteristics of non-dispatchable renewable energy can bring about instability into power systems [7]. These stability issues, due to the fluctuating features of the resources, can be exacerbated when a high penetration of RE is present. Secondly, as the penetration of renewable energy increases, it is more difficult for existing conventional power systems to accommodate the increase in renewable energy generation. For example, in recent studies [8,9], the

Abbreviations: BA, Bat algorithm; BESS, Battery energy storage system(s); CAES, Compressed air energy storage; CHP, Combined heat and power; CPLEX, IBM ILOG CPLEX optimisation studio; DE, Differential evolution; DG, Distributed generations; DOD, Depth of discharge; DP, Dynamic programming; ESS, Energy storage system(s); GA, Genetic algorithm; GAMS, General algebraic modelling system; GHI, Global horizontal irradiation; HESS, Hybrid energy storage system(s); HRES, Hybrid renewable energy system(s); LA, Lead-acid battery; LCC, Life Cycle Cost; LCOE, The levelised cost of electricity; LOLE, Loss of Load Expectation; NEM, National electricity market; NPV, Net Present Value; O&M, Operation and Maintenance; PCC, Point of common connection; PSO, Particle swarm optimisation; RE, Renewable energy; RES, Renewable energy system(s); SC, Super-capacitor; SOC, State of charge; TOU, Time of use; VRB, Vanadium redox flow battery; VRLA, Valve-regulated lead-acid battery

* Corresponding author.
E-mail address: yuqing.yang@unsw.edu.au (Y. Yang).

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overgeneration of PV led to a very low net demand during midday in California, but the net demand in the morning and evening, when PV cannot deliver power, was still high. This net demand profile, when further PV is included, would see the net demand trough in the middle portion of the day deepen, leading to the so called "duck" curve. As a consequence, with a limited capability to accommodate this huge ramp, solar energy needs to be curtailed, thereby reducing the economic and environmental benefits of renewable energy integration.

One of the possible solutions for the above issues is to use Hybrid Renewable Energy Systems (HRES), integrating various renewable energy resources in an optimal combination [8]. In this regard, the periods with low generation of one resource could naturally be compensated by other resources with high generation [10]. A good example is the complementary nature of solar and wind energy [11]. Thus, the potential system efficiency and supply reliability can be enhanced [12–15]. There are some detailed reviews on the optimal sizing of generation units [16–19], energy management and control [20–22] in such HRES. However, in most hybrid systems, a conventional generator or connection to the main grid is still required to guarantee reliability and stability. The use of Energy Storage Systems (ESS) to facilitate the increasing penetration of renewable energy by absorbing and releasing power in different time horizons has been extensively studied [23–26]. Of the various types of ESS technology available, Battery Energy Storage Systems (BESS) have attracted considerable attention with clear advantages like fast response, controllability, and geographical independence [5,27]. Besides the advantages mentioned, BESS also have a wide scope of applications ranging from short-time power quality enhancement to long-term energy management, as well as reliability enhancement, uninterrupted power supply and transmission upgrade deferral [28–31].

Although certain battery storage technologies may be mature and reliable from a technological perspective [27], with further cost reductions expected [32], the economic concern of battery systems is still a major barrier to be overcome before BESS can be fully utilised as a mainstream storage solution in the energy sector. Therefore, the trade-off between using BESS to improve renewable energy system performance and to achieve profitable investment is a critical decision to make for project developers. In this regard, the optimisation of BESS sizing is a vital issue to balance this trade-off, by attaining the best solution for multiple, or even contradictive, requirements.

It is noted that considering the variability of renewable resources, numerous studies have attempted to solve BESS size determination in different Renewable Energy Systems (RES). However, to the authors' knowledge, there has not been a thorough review on battery sizing issues in various RES, although there have been comprehensive reviews done for battery applications in power systems [33,34], battery sizing in standalone systems [35,36], storage sizing for solar and wind power plants [37] and HRES sizing reviews where the battery is included as a component [10,38,39]. Therefore, this overview focuses on the state-of-art battery sizing studies providing researchers with a fast reference of work done on this important problem. The review also has the added benefit of informing project investors and designers of more detailed factors to consider during the BESS sizing procedure. Research papers using energy storage to enable renewable systems are also included in this review if the specific type of ESS was not clarified and its characteristics were regarded to be compatible with BESS.

The paper is organised as follows. Numerous BESS sizing studies in terms of sizing criteria and solution techniques are summarised in Sections 2 and 3. BESS's applications and related sizing studies in different renewable energy systems are overviewed in Section 4 to show the spectrum of BESS's functions. The justification of the classification of RES and the range of battery sizing outcomes are discussed in Section 5. By categorising BESS's applications based on specific RES, it becomes clear that critical metrics for battery sizing are associated with the type of RES application, as well as its size. This implies that the battery size determination process in specific RES will influence the BESS sizing methods and criteria chosen. Finally, some conclusions are presented in Section 6.

2. Battery energy storage system sizing criteria

There are a range of performance indicators for determining the size of BESS, which can be used either individually or combined to optimise the system. Studies on sizing BESS in terms of optimisation criteria can be divided into three classifications: financial, technical and hybrid criteria.

2.1. Financial indicators

One key driver for determining the size of a BESS, and indeed the overall design of a RES, is the financial return for the operation of the system. A key attraction of financial indicators is that there is a common unit for making decisions, namely the local currency, enabling the comparison of different alternatives. Even with the benefit of a common unit for comparison, there are several different indicators that can be used as optimisable parameters for designs. Many studies have looked at the overall costs and benefits of the battery system in RES over the operational lifetime of the system. These approaches used the time value of money, via a discount rate, to determine overall costs on a lifetime basis, including levelised upfront capital costs, annual/daily operation and maintenance (O&M) costs, as well as fuel costs if the corresponding generators were applied. The indicator to be optimised can then be the Net Present Value (NPV) of the system [40], which should be maximised, or the levelised cost of electricity (LCOE) on an annual basis [41] or daily basis [42,43], which should be minimised. The NPV in [40] was formulated as the difference of levelised daily operation costs with and without ESS, whereas the LCOE in [41] took the annualised investment cost, annual operation cost and fuel cost into account directly. During the formulation, the modelling of a BESS's cost is a key issue. Therefore, it is worthwhile to mention the study of [44], where a detailed explanation of the methodology for calculating and analysing a BESS's total cost and annualised life cycle cost (LCC) can be found. However, the modelling of BESS costs in most studies associated with BESS sizing used neither the total cost nor LCC. They generally included the capital cost of BESS, which was then converted into an annual/daily cost by taking into account the interest rate [45], and the annual/daily O&M cost of BESS. The replacement cost of BESS was included in the formulations in [40] and [41], but the disposal and recycling costs of BESS were rarely considered.

Another financial indicator approach is to look at maximising the market benefit of the inclusion of a battery system in a RES. One significant case is microgrids, where the total benefits in grid-connected mode are maximised and the total costs associated with being in islanded mode are minimised [46,47]. The total costs of microgrids include the levelised operating costs from BESS and other running components, whereas the total benefits were calculated through the difference between the benefits from selling electricity and the total operating costs. More details about these formulations can be found in [46,47]. Other examples looked at partial financial values, rather than the total costs/benefits, for instance, maximising the difference between the sale of electricity to the grid and purchase from the grid for a grid-connected system [48]. A more extreme example was to examine only the day to day operating profitability of the RES, namely a 24-h optimisation horizon, by exploiting time shifting of energy output to match profitably against the electricity spot price with no regard for lifetime running cost [49]. A contrasting example looking at operating profits was to minimise the overall investment cost, which included the capital cost of BESS and other components, for determining the power and energy rating of the battery system [50].

2.2. Technical indicators

As opposed to financial indicators, technical indicators do not have a common unit and so direct comparisons in different cases with a number of technical criteria can be difficult. Consequently, popular ways to integrate the technical indicators is to achieve a single optimisation goal or to include them as constraints during the sizing process. In the optimisation, technical indicators can be quantified by binary variables, i.e. do they meet (or not meet) the requirements, or as a specific value goal, such as renewable curtailment and forecast errors which can be minimised. When considering technical indicators for battery inclusion in renewable systems, it is worth noting that they all serve to quantify the support of the BESS for the dynamic or steady state characteristics of the RES.

To improve the dynamic characteristics (with time horizons less than 1 min) of RES, two main technical criteria for both autonomous systems and grid-connected systems are frequency regulation and voltage stability. Both of these indicators can be regarded as binary variables, in other words, to dispatch the battery to meet the frequency and voltage requirements. Frequency regulation by BESS is to adjust the frequency back to the rated frequency level through dispatching the battery when any disturbance is introduced into the system. For example, the rated frequency is 50 Hz, and when the frequency reaches 50.02 Hz or 49.98 Hz, the BESS is triggered for frequency response until the frequency reaches 50 Hz [51]. Similarly, voltage regulation is to adjust the voltage level back to normal. For example, the maximum voltage deviation was set as ± 5% based on the American National Standard for Electric Power Systems and Equipment [52]. In power systems, frequency regulation is strongly related to the balance between real power supply and demand, while voltage stability is more associated with the reactive power balance. BESS with the inclusion of power conditioning facilities can provide both active and reactive power within its power capacity, which means the BESS can play a vital role in both frequency and voltage regulation. Many studies focus on using battery systems to achieve frequency regulation in a microgrid, especially in islanded microgrids, replacing the main grid to provide a constant reference for frequency and voltage control to stabilize the microgrid. During grid-connected mode, a BESS with fast dynamic response can still assist frequency and voltage regulation processes, especially when dynamic disturbances such as renewable energy/load fluctuations or any instantaneous failures are occurring. There is an example of using battery systems to handle various disturbances including generator failure, variation of solar generation and a solar plant failure in the grid-connected conditions [53]. BESS have been often used for providing primary frequency regulation for standalone HRES [54,51] and power systems [55], as the imbalance between real power generation and loads that can introduce frequency instability may readily occur in autonomous AC systems and power systems. However, compared with frequency regulation, voltage stability tends to be a more significant issue for distribution networks with high renewable penetration [7]. This is because the voltage in a distribution network may drop considerably due to a heavy load or the long distance between substation and end-users [56], or significantly rise due to a large amount of renewable energy integration [57]. Hence, optimally dispatched battery systems can effectively mitigate the voltage decrease/increase and ensure voltage stability [58,59].

Other than dynamic enhancements, a number of criteria concerning steady-state operation (with time horizons greater than 1 min) are also actively applied for BESS sizing, such as reliability [60] and renewable energy curtailment [61]. Curtailment is defined as a deliberate decrease in renewable energy power output to avoid overgeneration, transmission congestions or the risk of instability in the grid. Renewable energy curtailment can be readily quantified as a dumped power profile, i.e. the difference between the dispatched power and the potentially produced power given available resources (wind and sunlight) [62], or accumulated dumped energy, which can be quantified as kWh by integrating the dumped power with respect to time. Thus, curtailment has been adopted as a technical indicator for BESS sizing. Another important technical aspect of dispatching a battery is to improve the features of the power profiles such as peak shaving, constant power output and smoothing of variability. An example of using peak shaving as a sizing indicator is to determine the capacity by regulating the ESS to achieve the daily mean wind power equals to the daily mean load [63]. Another extreme example is to size the battery by delivering a constant power generation for a wind farm [64]. Furthermore, the variability of renewable energy can be smoothed by dispatching the ESS as a low-pass filter, therefore, the size of the ESS can be determined through the behaviours of the ESS [65,66]. Indicators related to reliability are more commonly adopted for standalone RES, or microgrids operating in islanded mode, to replace limited or expensive backup options. An example of considering reliability in a microgrid is to use the Loss of Load Expectation (LOLE) as the assessment, defined as the expected fraction of unserved load in the microgrid during the simulation period, and 0.1 days/year was defined as the target for the reliability of power supply [67]. Another important approach for determining battery size is to consider the BESS operating to compensate for forecasting errors in the RE sources [68,69]. This is an important application, especially when the renewable generators are registered to participate in the electricity market dispatch, since excess generation would be required. Therefore, using battery systems to compensate for forecasting errors can improve the utilisation of renewable energy and avoid any potential penalties for non-delivery of bid power/energy.

It is worthwhile mentioning that battery cycle life and operational parameters such as Depth of Discharge (DOD), and charge/discharge rates can also be regarded as significant indicators for battery size determination, more often serving as a constraint during the sizing process. There are many ways to evaluate the degradation of BESS. Dragicevic et al. [50] counted the number of cycles over the time horizon for the assessment of battery degradation [50]. Alternatively, State of Health (SOH) can be used to identify the degradation degree of the battery [70], accounting for the aging from cycling as well as the calendrical aging [58]. The key battery system parameters and cycle life are technology dependent and system characteristics need to be considered when adopting BESS in a RES.

2.3. Hybrid indicators

In more recent studies there has been a growing emphasis on considering both financial and technical indicators simultaneously with regards to battery sizing. There have been two major approaches to combine these indicators; the first of these has been mentioned previously, where technical indicators act as constraints within which the financial indicators need to be optimised. A good example of this type of approach was given by Bahramirad et al. [67], where the size of the ESS was determined by minimising the investment and operating costs under the restriction of guaranteed reliability. The other major approach is multi-objective optimisation for hybrid indicators that consist of both financial and technical metrics. A good example of this type of approach is outlined by Korpaas et al. [49], where the exchange power was smoothed whilst maximising the benefits of the wind farm.

In summary, it can be seen that there are a number of criteria that may be selected to allow the determination of BESS size from either a technical or financial perspective. It should also be noted that the critical functions of BESS change with different criteria being used in size determination. A specific example of this is when technical indicators are selected to improve the dynamic characteristics of a RES, the power capacity of a BESS plays a far more critical role than the total energy capacity. In other words, how rapidly the BESS can deliver power is more important than the overall energy it can deliver. This aspect has manifested itself in studies such as Nazaripouya et al. [59], where battery sizing was found in terms of per unit multiplied voltage regulation duration and for the case of frequency regulation [54].

Generally speaking, the energy and power capacities are both equally important, particularly when looking at multiple technical indicators, but as highlighted by these cases there are specific functions of a BESS where this ceases to be the case. A further way to make the energy capacity (and by extension the physical size of the BESS) a less critical component is the use of advanced dispatch strategies to achieve multiple functions, allowing an existing BESS to be used more effectively and for system design to more effectively use the energy and power capacity of a BESS.

3. Battery energy storage system sizing techniques

The sizing of battery storage systems can be determined using a wide variety of techniques, with each approach having its own strengths and weaknesses. The complexity of the techniques employed also varies considerably, with approaches spanning simple probabilistic techniques through to mathematical optimisation strategies and nature inspired methods. The concentration in this section is on the most common techniques encountered in the literature. In classifying the techniques, continuity with previous reviews [10,16] has been maintained with some important differentiation being offered. Whilst there is a close relationship between the criteria and indicators discussed in Section 2, and the techniques used, the following section will introduce the general classifications of approaches, which can be applied to each of the indicators discussed in Section 2. The techniques described and discussed are: probabilistic methods, analytical methods, directed search-based methods and hybrid methods.

3.1. Probabilistic methods

Probabilistic methods are perhaps the most intuitively appealing and simplest approaches to battery sizing. A flowchart explaining probabilistic methods can be found in Fig. 3.1. The key concept is to use the stochastic nature of the renewable resources, typically solar or wind, to optimise the battery size for the selected criteria. Probabilistic methods have the advantage that the need for a large amount of resource data is lessened, making them useful for situations with limited data availability. One key drawback is that the number of performance criteria being optimised in these approaches tends to be small (often only one or two), which makes their applicability for detailed designs limited. A typical approach is to construct models of the generation capability of the RE power system in question and combine them with a load model in order to create a risk model of the power system. Performance criteria can then be optimised against this risk model. One straight-forward approach based around this process is to use statistical methods to generate simulated samples as in Wu et al., where a mixed distribution based on Laplace and normal distributions was used to model forecast errors of a single wind farm over multiple timescales [71]. Global Horizontal Irradiance (GHI) data of solar irradiance have also been generated through a Markov-chain approach for battery size determination, as detailed in [70].

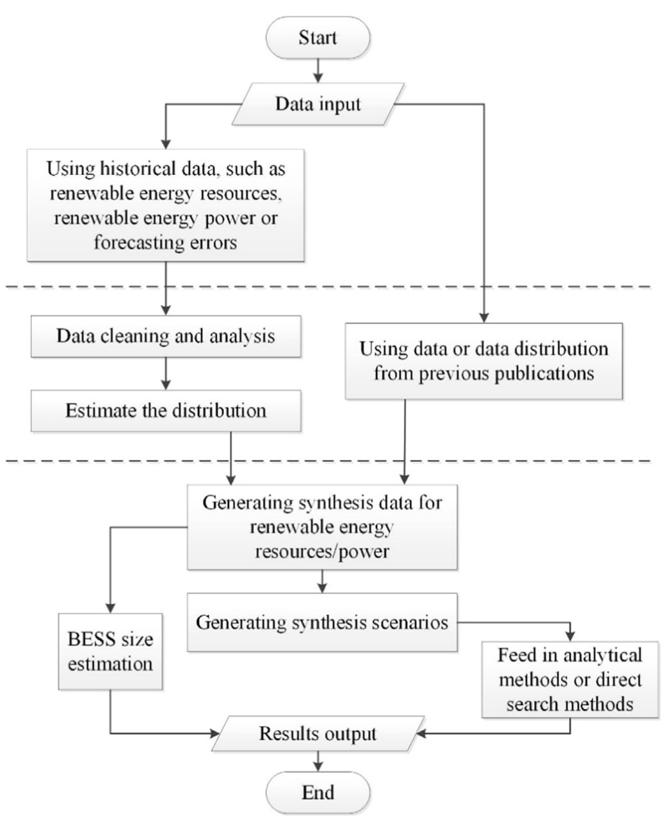

Fig. 3.1. Flowchart of probabilistic methods.

Besides implementing probabilistic methods for data generation, stochastic optimisation methods have also been deployed in many studies. The most popular of these is the Monte Carlo approach, in which a large number of scenarios (samples) are generated according to the statistical behaviour of random variables. By surveying the outcomes from a large number of scenarios generated, the optimum configuration can be deduced. By its very nature, Monte Carlo simulation usually entails considerable computation, but it does offer a comprehensive strategy for making a design decision. Monte Carlo approach has also been used for the dual objectives of demand shift and outage protection in building integrated PV systems considering uncertain building load, weather information and local historical outage distribution [72]. Other applications of Monte Carlo approach for battery storage includes minimising the power imbalances from inaccurate wind forecasting considering the uncertainty from forecasting [73], and frequency control with regards to statistical data of wind speed, solar irradiance and load [51]. Apart from the Monte Carlo approach, chance-constrained optimisation [74], robust optimisation [50] and stochastic control strategy [75] have also been employed to determine the size of the battery system taking into account uncertain random variables.

3.2. Analytical methods

Analytical methods, sometimes referred to as deterministic methods, are amongst the most broadly used methodologies for BESS size determination. These methods are based around analysing a series of power system configurations with the system elements varied being those that need to be optimised against performance criteria. A flowchart explaining analytical methods can be found in Fig. 3.2. Analytical methods can be very straight-forward, such as when sizing for absorbing spilled wind energy, the battery's power and energy capacity can be derived directly from its daily spilled wind power profile [76]. Another simple example includes battery sizing for a constant wind farm output [64]. However, analytical methods are typically implemented by repetitive calculations or simulations performed over fixed intervals for the relevant system elements (usually the varying power and energy capacity). Using this approach, where performance for varying sizes of the battery storage against the corresponding performance criteria (financial or technical metrics) are found, a selection for battery sizing can be made. Another similar example is to conduct a sensitivity analysis to observe the impact of different battery sizes over performance criteria (financial or technical metrics), such as the battery sizes over the payback periods in [77].

The detailed implementation of specific strategies in different studies varies considerably in terms of the underlying system models. These can be based on numerical models, where the relationship between battery capacities and the assessed criteria can be directly formulated by equations. Dynamic models, where relationships are

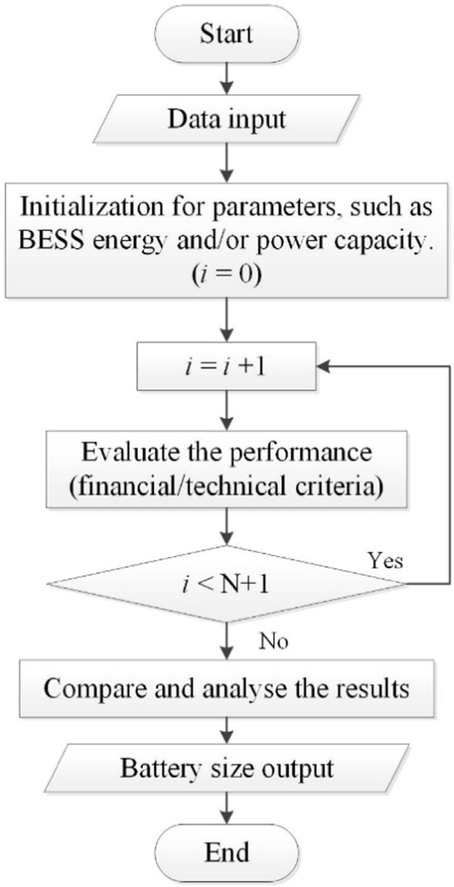

Fig. 3.2. Flowchart of analytical methods.

typically represented by differential equations requiring sophisticated numerical techniques to solve, are also included. Often professional software is used for the simulations of dynamic cases. A good illustrative example of applying analytical methods through a numerical model is given in Rodrigues et al. [61], in which several simulations with varying battery capacities were performed, analysing the annualised cost of corresponding storage systems and wind power curtailment. Using these techno-economic indicators, the size of the battery system can be chosen [61]. Other examples include Aghamohammadi et al., in which a number of dynamic simulations were performed with decreasing the allowable overloading coefficients for primary frequency control, until the BESS is able to capture the frequency mismatch, a condition indicating an optimum battery size [54].

Whilst the use of analytical methods is very effective in many cases, a key concern is the need for a large number of simulations with combinations of single/multiple techno-economic performance indices. This inevitably leads to a trade-off in the resolution of the solution, since, while it is obvious that smaller intervals would lead to more accurate results, the quantity of computations will generally increase at an exponential rate. This becomes problematic when limited computational resources are available, and can, in extreme cases, make the calculation of the full solution space untenable. From this point of view, improvements in high performance computing to improve the efficiency of large quantity computational simulations may allow for the use of analytical methods at higher resolutions [78,79].

3.3. Directed search-based methods

An obvious refinement to analytical methods is to reduce the need for simulations across the entire configurational space of the system

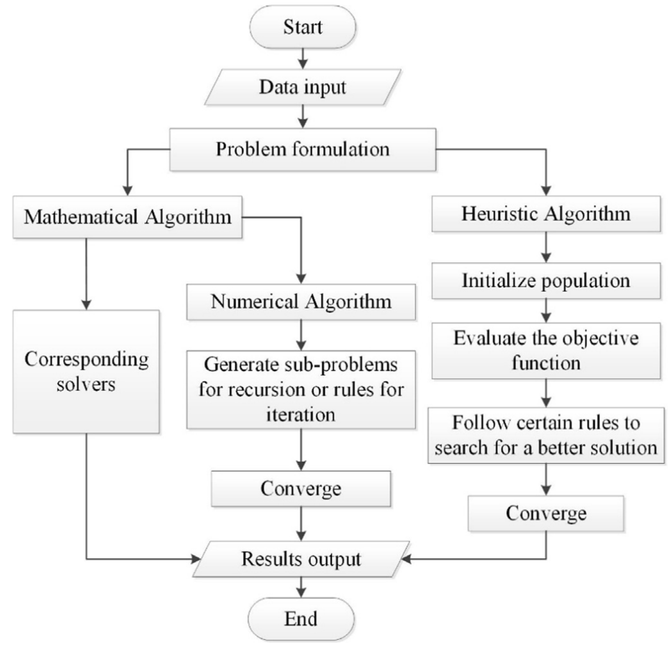

Fig. 3.3. Flowchart of direct search-based methods.

being analysed to reach the optimum solution in a computationally efficient manner. There is a vast array of techniques developed for such optimisation problems, with many of them being used for BESS sizing. These can be conveniently split into mathematical optimisation techniques, based on mathematical properties of the solution space, and heuristic techniques, where tailored search parameters can be used to deliver an efficient algorithm, often based around nature inspired selection methods. A flowchart demonstrating direct search-based methods can be found in Fig. 3.3.

3.3.1. Mathematical optimisation based methods

From the perspective of mathematical optimisation theory, BESS sizing optimisations may be expressed as linear programming, mixed-integer programming or even non-linear programming problems. Performance of BESS using these methods consists of constructing an objective function, which can be assessed by an iterative process that stops when the best result is reached. Optimisation problems can also be solved using classic numerical methods such as interior point algorithm, gradient descending algorithm, or Newton's method. These methods can find the solution in a limited number of steps, reducing computational load considerably. Moreover, due to the relatively mature nature of these methods, professional software is available for solving optimisation problems, such as MATLAB optimisation toolbox and General Algebraic Modelling System (GAMS) amongst others. For example, the study performed by Bahramira et al. was an application using IBM ILOG CPLEX Optimisation Studio (CPLEX) to optimise the size of an ESS which was formulated as a mixed-integer programming problem [67]. One significant case of using recursive techniques is dynamic programming (DP), which can solve optimisation problems through the construction of solution sets from the solutions of smaller sub-problems. DP has been applied in many studies for a spectrum of targets, including to minimise daily total cost [42] and to maximise expected daily operating profits [49].

It must be stressed, however, that while the application of these mathematical optimisation techniques can vastly improve computational efficiency, when the formulation becomes more complex, especially for non-linear programming problems, these tools face difficulties in converging to an optimum solution. This issue of robustness has led to the widespread use of heuristic-based solution methods as detailed below.

3.3.2. Heuristic methods

Heuristic methods allow non-optimal or not perfect (usually near optimum) solutions, which are sufficient for practical purposes. The distinct advantages of heuristic methods are that they can avoid complicated derivatives, especially for non-linear optimisation problems, thereby using reasonable memory and computation time [80,81].

Despite often having no mathematically proven basis for obtaining optimal solutions, heuristic approaches such as nature-inspired algorithms like Genetic Algorithms (GA), Particle Swarm Optimisation (PSO), and Tabu searches, etc., tend to offer fast convergence, simple implementation and strong flexibility.

In fact, there are many previous studies solving BESS size determination problems by using nature-inspired algorithms. For battery sizing problems, PSO has been proven to be a popular algorithm to solve for minimising the cost of energy not supplied and ESS costs (mixed-integer nonlinear programming) [82] and to minimise the levelised cost of electricity [41]. Other heuristic algorithms such as genetic algorithm based methods [45], Tabu search [83] and bat algorithms (BA) [43] that are nature inspired evolutionary techniques are also actively applied for battery size determination.

3.4. Hybrid methods

The sizing techniques outlined above each have their own specific advantages for the BESS sizing process, along with weaknesses. For example, while analytical methods usually return more accurate results, a poorly selected optimisation interval may miss the exact solution, or a high resolution may increase the computation burden significantly. Also, search-based methods may not guarantee an optimal result due to the possibility there is a convergence to a local optimum, rather than to the global optimum. Moreover, when using probabilistic methods, a large quantity of scenarios are generated, which may place a heavy burden on computational capability. It stands to reason that if the advantages of different methods can be combined to enhance the effectiveness and efficiency, of the optimisation procedure, whilst simultaneously removing inherent weaknesses, these so-called hybrid methods should deliver both robust procedures and the ability to ensure the global optimum being guaranteed with the required resolution.

The hybridisation of different methods can occur in either a de-coupled or coupled way, where de-coupled indicates that two optimisation methods are mutually exclusive processes, whereas coupled suggests two methods working together concomitantly. An example of a de-coupled application of hybrid methods is given in Cervone et al. [70], where both a probabilistic method and an analytical method were used to determine the BESS size for a grid-scale PV plant in separate steps. A discrete-time Markov Chains approach was first implemented to generate a 20-year time series of irradiance, then an economic analysis of various energy storage systems was used to reduce the imbalance costs associated with renewable energy integration, thereby obtaining the optimal size of the battery system [70]. This approach is in contrast to the coupling of probabilistic and search-based methods via robust mixed-integer linear programming that Dragicevic et al. implemented for minimising the overall investment cost considering the uncertainty of PV, wind energy and demand [50]. Another example of coupled hybrid methods was the use of a chance-constrained stochastic optimisation model, where a Monte Carlo embedded Differential Evolution (DE) algorithm was applied as a solver to maximise wind power utilisation and minimise the investment and operation costs as reported by Zhang et al. [74].

In summary, there has been a wide range of approaches implemented when solving the problem of battery sizing in RE systems. In Table 3.1, the implementations, advantages and disadvantages of sizing techniques mentioned are summarised. The tailored simulation cases in each study can make it difficult to compare the effectiveness of each of the different methods, but there are some studies comparing between techniques. For example, both analytical and search-based methods were performed to minimise the battery power for load shedding in Kerdphol et al. [84]. Their results showed that the optimal battery power capacity based on search-based methods showed better frequency and voltage performance than the capacity found using analytical methods. However, it must be cautioned that this is one case, and it does not mean that search-based methods should be regarded as superior to analytical methods for all purposes. Overall, BESS size determination in RES can be seen to be a multi-faceted problem, involving single/multiple-objective optimisation, decision-making and multiple systems simulation. It should also be noted that more advanced solution techniques are being continually developed with these potential new hybrid methods combining advantages from different optimisation approaches.

4. Renewable energy systems with BESS applications

Hybrid renewable energy systems can comprise of a range of components such as renewable and non-renewable energy generators. The integration of these generators with an Energy Storage System (ESS) may also take into account the loads, and the utility if it is a grid-connected system [16]. The ESS is often used in the hybrid renewable energy systems or power system to maintain reliability and stability [33,34]. Previous reviews classified RES as either grid-connected or standalone [2]; or broke the category down further into dc-coupled, ac-coupled and hybrid coupled [1]. Fig. 4.1 illustrates how this review will classify RES applications into four categories: from small to large - distributed energy system [85,86], microgrid [87–89], standalone HRES [38,90–92], and renewable energy power plant [93]. These four categories are determined based on the operation and control regimes for each system, which also leads to different BESS sizing criteria. As an example, a commercial sized renewable power plant will use a BESS in different ways to a microgrid. Hence the sizing of the battery will also require a different set of sizing criteria. A renewable energy power plant can use the battery to ride through lulls in the weather, hence to decrease ancillary services costs or penalties [94–96]. Therefore, the purpose of the battery also determines the sizing. By using the four categories in Fig. 4.1, battery sizing studies in RES will be summarised in the following section. This section will also include the studies that determine the optimal connection point for battery, along with auxiliary technologies that enhance storage capabilities within the renewable energy system.

4.1. BESS sizing in distributed renewable energy systems

Distributed energy resources refer to renewable energy technologies, mostly solar PV, where the PV is directly integrated into the distribution network either for end-user applications (e.g. rooftop PV [29]), or for regional distribution network applications. As the penetration of distributed energy increases, the fluctuation characteristics that can arise from such things as passing cloud cover, or unpredictable weather spread out over regions, can have an adverse influence on the operating state of the distribution network, such as oscillation and power quality issues. In this regard, BESS are the ideal systems to address these side effects introduced by distributed energy resources. Batteries as a storage system have the power capacity to charge or discharge at a fast rate, and energy capacity to absorb and release energy in the longer-term to reduce electricity costs to the consumers.

For residential roof-top PV, the inclusion of a BESS gives the end-users greater control by deciding whether to release the power back to the grid or store the energy, depending on the electricity price, to attain minimal electricity cost. On the other hand, at the distributed network level, the regional centre can optimally control the charge/discharge process of the BESS to compensate for any voltage changes introduced by renewable energy fluctuation or to guarantee distribution network reliability and stability.

Fig. 4.2 shows the basic structure of distributed renewable energy

Table 3.1
Summary of the pros and cons of BESS sizing techniques.

Technique (Time Horizon)	Implementation	Pros	Cons
Probabilistic (depends on data resolution, more likely intra-hour, hourly data for long duration)	• Generates synthetic weather resources and PV/wind power generation data • Generates synthetic scenarios for stochastic optimisation	• Overcomes the restriction of limited data availability • Gives results with confidence levels	• Accuracy relies on the availability of historical data • May require computational extensive resources
Analytical (Applications for optimisation horizons ranging from repeated intra-hour simulations to several years assessment)	• Direct calculation based on intuitive criteria • Repeated computation/simulation with fixed intervals • Sensitivity analysis	• Better visualization with the change of battery sizes • Strong flexibility for all criteria and simulation environments	• Computational intensive • May miss global optimum if the data resolution is not high enough
Mathematical optimisation (Applications for hourly, intra-day or daily optimisation)	• Linear, mixed-integer, quadratic programming problems • Problems that can be linearized • Problems that can be solved by numerical methods	• Strong capability to find the global optimum • Fast convergence and high robustness for linear problems	• High efficiency limited to linear/mixed-integer/quadratic programming problems • Linearization may require extra derivations • Explicit mathematical formulation required
Heuristic (Applications for hourly, intra-day or daily optimisation)	• Non-linear optimisation problems • Apply nature-inspired algorithms such as GA, PSO, Tabu search and Bat Algorithms	• Strong flexibility to solve all optimisation problems • Avoid complicated derivatives • Use less computational resources • Simple implementation • Large assortment of algorithms	• May converge in local optimum instead of global optimum • Less robustness and accuracy for linear problems
Hybrid (Applications for hourly, intra-day or daily optimisation)	• Decoupled methods combined sequentially • Hybridisation of different methods in a coupled way	• Combines strengths of different methods • Improves robustness and ensures global optimum found	• Likely to increase the complexity • May require high computational resources than heuristic methods

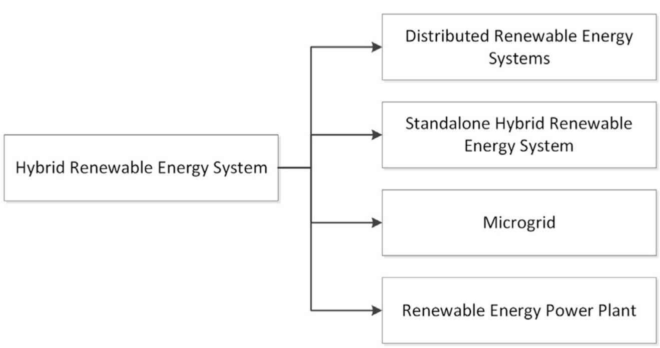

Fig. 4.1. Categories of renewable energy systems.

systems using battery storage to enhance the performance of both end-users and the regional distribution network. In the figure, the orange arrows indicate the information flows and the black arrows denote the energy flows (these same characteristics apply to Figs. 4.2–4.5).

As discussed earlier, sizing of the BESS involves many criteria, and numerous methods have been used in this process. Some of these criteria/methods are very specific to the size, components and economics of the particular renewable energy system, while other methods can be applied equally well to any sized system. For example, one aspect that is relevant to all sized systems is the ability to reduce the amount of renewable generation that would need to be curtailed due to over-production during lower periods of demand, such as applications for distributed renewable energy systems [76], standalone HRES [61] and renewable energy power plants [97]. Voltage stability is also relevant to all systems, but only those connected to the distribution network use it for battery sizing [58,59].

Table 4.1 summarises a selection of studies that looked at solving battery size with regards to the applications of distributed renewable energy systems. The table is sorted by the methods used for battery sizing, taking into account the energy resources, criteria and reporting the key findings. Note that the sizing criteria and methods were discussed in detail in Sections 2 and 3. The method most widely used for distributed systems was analytical, and overall, technical indicators were the main factor in determining the size of the BESS. Furthermore, in terms of the sizing results in Table 4.1, we can see that batteries ranging in size from approximately 10 kWh to 50 MWh can be used in distributed renewable energy systems for a range of purposes. It is reasonable to install around 10 kWh of battery capacity to feed a small residential load with low renewable penetration. For example, a PV array of 1.5 kW with 1 kW peak load can be supported by using a battery sized between 13.8 kWh to 16.7 kWh [48]. However, in other cases, a much larger BESS will be needed to support the system. Taking the study of [76] as an example, a system with three wind turbines rated at 8.5 MW, 4 MW, and 10.3 MW which are connected to a rural distribution network was modelled. To accommodate spilled wind and minimise annual cost, a battery with an energy capacity of 51.95 MWh and power capacity of 6 MW (represented as 51.95 MWh/6 MW) was required to achieve the targets.

The key goal for residential applications is to use the battery system to reduce electricity costs, use the stored energy when the price is high and store the energy when the price is low [48,102]. Hence, installing a battery can significantly influence end-users' utility bills. However, from the perspective of a regional distribution power system operator, the BESS would be expected to achieve technical improvements, such as improving the characteristics of the load profile [99], delaying upgrading of facilities [27] and maintaining voltage quality [58,59].

4.2. BESS sizing in microgrids

Fig. 4.3 demonstrates a typical microgrid with two operation modes, namely grid-connected and islanded modes. There is a switch on Point of Common Coupling (PCC, AC bus in Fig. 4.3) that allows the microgrid to connect/disconnect with the grid. In the grid-connected mode, the integrated renewable energy plays a similar role to that of distributed renewable energy systems in Section 4.1, with the grid serving as the constant voltage and frequency provider. On the other hand, in islanded mode, the microgrid acts as an autonomous system. In this mode, constant voltage and frequency references are required to stabilize the islanded microgrid's operation. Therefore, BESS is widely accepted to be one of the natural replacements of traditional generators to act as a voltage source in the islanded mode [103], and also as the

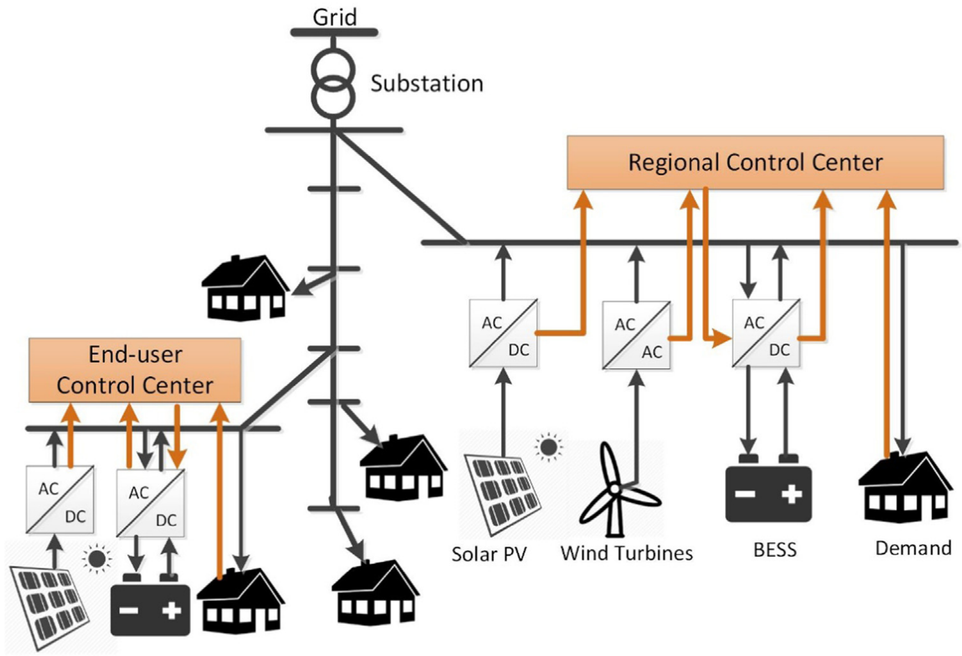

Fig. 4.2. The structure of a distributed renewable energy system.

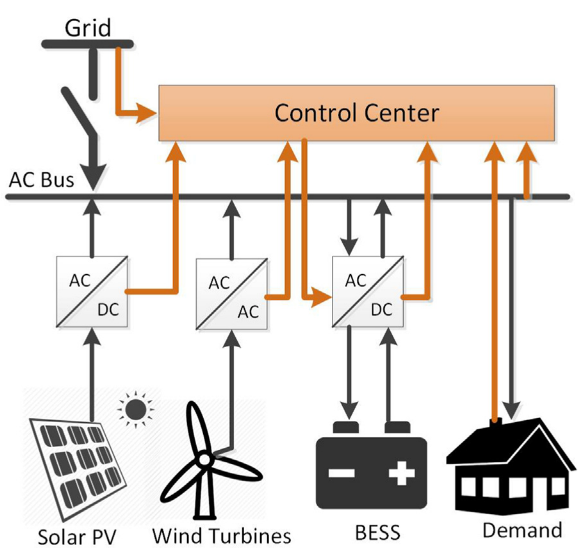

Fig. 4.3. The structure of a microgrid.

microgrid performance enhancer in the grid-connected mode.

There are a range of studies conducted to solve BESS size determination in microgrid systems, with a selection summarised in Table 4.2. For these systems, search-based methods are the most commonly used approach, with financial indicators the most common used criteria for battery sizing. As mentioned in Section 3.3, implementing search-based methods usually requires explicit formulations, making the methodology more complex. However, there is a greater use of financial indicators as the sizing criteria, namely costs/profits, which are easier indicators to formulate. One possible reason for this use of financial indicators could be that it reduces the complexity when integrated with a search-based method. It also shows consistency with more search-based methods incorporating with financial criteria in Table 4.2.

From the studies analysed in Table 4.2, battery size optimisation for the lowest cost was the primary objective in microgrids. Battery storage systems investigated ranged in size from 65 kWh/5 kW [42] to 18MWh/3.6 MW (where the capacity of the line connecting the microgrid to the grid is 10 MW) [67], naturally depending on the size of the microgrid. Apart from the financial criteria applied to minimise the microgrid's costs or maximise its profits, the battery can also provide other technical functions in the microgrid, such as enhancing load management [84] and reliability [67]. These criteria are also used to determine the battery size in a microgrid.

4.3. BESS sizing in standalone hybrid renewable energy systems

In many cases, electricity consumption in remote areas is too low to justify the investment to connect them to the main grid. In the past, fossil fuel generators such as diesel generators have been heavily used for power supply in those areas. However, the rising cost of fuel for the generators, the decreasing cost of renewable energy technologies, as well as environmental concerns, has led to standalone HRES as an attractive solution for remote area power supply.

Standalone HRES generally include single or various kinds of non-renewable and renewable energy resources, e.g., diesel generators, solar PV, wind turbines or others. All standalone hybrid systems require a form of back-up power supply to ensure reliability and continuity of supply. In most cases, this is supplied by either a diesel generator or some form of energy storage system. The basic structure of a standalone HRES is shown in Fig. 4.4, where we show a 100% renewable energy system. The renewable energy resources are solar and wind energy, with the BESS used as the ancillary component to supply any shortfall in demand. The control centre receives the operation status of each component which then relays commands on how to dispatch the battery to meet the operation requirements.

The key objective of employing a BESS in a standalone HRES is to match the imbalance between renewable energy generation and electricity demand to ensure continuity of power supply. In this sense, the functions of diesel generators in standalone HRES can be partially or completely replaced by renewable energy and BESS. The studies listed in Table 4.3 summarise the potential for diesel generators to be replaced by renewable systems incorporating battery storage and the methods that were used to determine the optimal size of the storage systems. Unlike what was seen in Sections 4.1–4.2, there is no clear method or criteria that has been favoured to determine the optimum battery storage size. With systems of this size, what becomes more

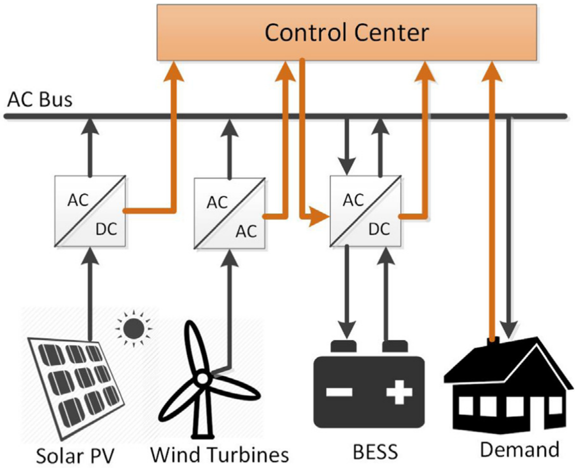

Fig. 4.4. The structure of a standalone HRES.

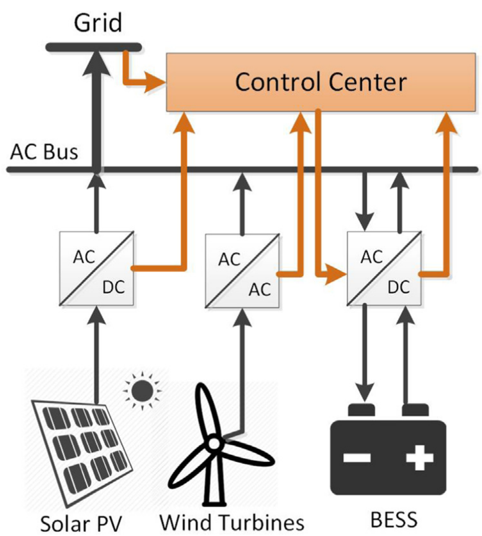

Fig. 4.5. The structure of a renewable energy power plant.

apparent is that when looking at an optimum storage size the criteria focuses on either the technical aspects such as reliability [60] and stability [54] of the standalone HRES, or financial metrics by reducing its own capital cost, e.g. by choosing a smaller battery size (studies like [50] include battery's capital cost in its objective function), operational cost [106], or annual costs [41,107]. From the studies reviewed in Table 4.3, the optimum battery size is also naturally dependent on the size of the renewable systems. Hence, the battery sizes for each case ranged from 14.65 kWh in [50] (power capacity is not mentioned) to 288 MWh/40 MW in [61]. The latter case required this size of battery to achieve the needed power supply and accommodate wind curtailment in an island.

4.4. BESS sizing in renewable energy power plants

When discussing sizing of storage systems for renewable energy plants, it is important to realise it is large-scale generation, which is dispatchable within an electricity market. Taking Australia's National Electricity Market (NEM) as an example, each registered generator must be classified as either “market” or “non-market”. A renewable power plant with a capacity of 30 MW or more usually participates in the market and is classified as semi-scheduled [110]. Therefore, the scale of the renewable power plants is much larger than that of the systems previously discussed, hence the sizing of the battery will also be based

Table 4.1
Studies of BESS sizing in distributed renewable energy systems.

Method	Sizing criteria	Energy sources	Findings	Reference
Analytical method	Financial indicators	PV (around 1.5 kW), BESS	The size of the battery was obtained as 16.714 kWh for residential load and 13.816 kWh for commercial load by minimising the electricity cost and the cost of battery capacity loss.	Yu et al. [48]
Analytical method	Technical indicator	Distributed Generations (DG), BESS	A simple case was performed in a residential household through levelising power consumption, and 8 kWh of battery capacity was calculated to be the size of the battery.	Hussein et al. [98]
Analytical method	Technical indicator	Wind (850 kW), ESS	The ESS sized as 3.72–8.31 kWh was targeted to minimise the difference squared between wind output and desired output for a wind generator.	Wang et al. [99]
Analytical method	Technical indicators	PV (from 0 to peak load), BESS	For voltage regulation and peak load shaving, the determined sizes of batteries ranged from 1.5 to 3 h of peak load.	Yang et al. [58]
Analytical method	Technical indicator	PV (1 per unit), BESS	To perform voltage regulation, the calculated optimal size of the battery was 0.1196 per unit multiplied by the desired time of voltage regulation.	Nazaripouya et al. [59]
Analytical method	Technical indicator	PV (2.5 kW), Wind (1.5 kW), Combined heat and power (CHP, 1 kW), Lead-acid (LA) battery	The optimum size of the battery depends on the energy exported and battery lifetime. The battery sizes ranging from 21 to 63 kWh were expected to increase the percentage of exported energy from 92% to 99%.	Jenkins et al. [100]
Analytical method	Hybrid indicators	Wind (22.8 MW), BESS	For sizing battery, two goals were set, including accommodating the spilled wind and minimising the annual cost. The results showed the only economically feasible ESS technology is Zn/Br with the size 51.94 MWh/6 MW.	Atwa et al. [76]
Search-based methods	Hybrid indicators	PV, Wind (2.5 MW), BESS (Li-ion battery and LA battery)	Multiple criteria were applied for battery sizing, including maximising the benefits of distribution companies, reducing the energy exchange at substation and minimising the power loss. The optimised battery was around 25% of rated renewable energy capacity, ranging from 0.82 to 2.14 MWh.	Zheng et al. [101]
Hybrid method	Financial indicators	PV (27 kW), BESS	The ESS was targeted to minimise the total cost of the storage system and energy supply. The ESS size changed from 26 to 37 kWh with DOD ranging from 100% to 70%.	Schneidar et al. [102]
Hybrid method	Hybrid indicators	Wind (2.55 MW), BESS, Micro-turbine	The optimised battery of 2.56 MWh showed 100% confidence level by maximising the wind power utilisation and minimising the investment and operation costs.	Zhang et al. [74]

Table 4.2
Studies of BESS sizing in microgrids.

Method	Sizing criteria	Energy sources	Findings	Reference
Analytical method	Financial indicator	PV (15 kW), Diesel Generator (8 kW), Vanadium Redox Battery (VRB)	The results showed VRB rated 65 kWh/5 kW for the islanded mode and 5 kWh/5 kW for the grid-connected mode can achieve the minimum total cost.	Nguyen et al. [42]
Search-based methods	Financial indicator	Micro-turbine (30 kW), Fuel Cell (30 kW), PV (25 kW), Wind (15 kW), Li-ion battery	The study was performed by minimising the total cost. The results showed the level of initial charge in battery can lead to significant difference on battery sizes from 150 kWh to 250 kWh/30 kW.	Bahmani-Firouzi et al. [43]
Search-based methods	Financial indicator	Gas Generators (10 MW), Wind turbine (1 MW), PV (1.5 MW), ESS	The optimal energy and power ratings of the ESS were 6 MWh/0.75 kW in microgrid with minimum total cost.	Gao et al. [104]
Search-based methods	Financial indicators	Wind (1000 kW), PV (around 1100 kW), Li-ion Battery, Micro-turbine (3000 kW), Fuel Cell (1000 kW)	In the grid-connected case, the battery of 500 kWh was operated to maximise the total benefit and in the islanded mode 1400 kWh to minimise the total cost.	Chen et al. [46]
Search-based methods	Financial indicator	Micro-turbine (30 kW), Fuel Cell (50 kW), PV (20 kW), LA Battery, VRB	The battery size was calculated through Net Present Value. The optimal sizes were 300 kWh/30 kW for LA battery and 400 kWh/40 kW for VRB.	Chen et al. [40]
Search-based methods	Financial indicators	Generators (16 MW), ESS	The optimal size of the ESS was found around 900 kW with the lowest capital and operation cost.	Bahramirad et al. [105]
Search-based methods	Financial indicator	Wind (20 kW), Micro-turbine (30 kW), Fuel Cell (50 kW), Diesel Generator (100 kW), ESS	By minimising operating cost of the microgrid, the optimal capacity for the ESS was 300 kWh/30 kW in the islanded mode and 400 kWh/50 kW for the grid-connected mode, respectively.	Fossati et al. [45]
Search-based methods	Technical indicator	PV (3 MW), Hydro Power (3.2 MW), BESS	Through minimising the battery power for load shedding, the optimal battery power capacity was calculated as 1.3124 MW by analytical method, and the method of Particle Swarm Optimisation (PSO) showed better frequency and voltage performance.	Kerdphol et al. [84]
Search-based methods	Hybrid indicators	Gas Generators (16 MW), Wind (1 MW), ESS	The best size of the ESS (18 MWh/3.6 MW) was obtained by minimising ESS investment cost, operating cost and maintaining the reliability.	Bahramirad et al. [67]
Hybrid method	Financial indicators	Wind (1000 kW), PV (around 1100 kW), Micro-turbine (3000 kW), Fuel Cell (1000 kW), BESS	In the grid-connected case, the battery of 400–1100 kWh was operated to maximise the total benefit and in the islanded mode that of 1400–1600 kWh to minimise the total cost.	Khorramdel et al. [47]

Table 4.3
Studies of BESS sizing in standalone HRES.

Method	Sizing Criteria	Energy sources	Findings	Reference
Probabilistic method	Technical indicator	PV, BESS	A methodology for determining the battery capacity thresholds was proposed to maintain steady power output of hybrid system for storm-resilient.	Birnie III [108]
Analytical method	Technical indicator	PV (160 W), Wind (160 W), BESS	Hybrid system with PV and wind can reduce battery size from 114.5 kWh to 49.8 kWh compared to PV and battery system without any loss of load.	Alex et al. [60]
Analytical method	Technical indicator	Micro-turbine (31.1 kVA), Diesel Generator (31.1 kVA), Fuel Cell (10 kW), PV (13 kW), BESS	For frequency regulation, the permissible overloading power and duration of the BESS was discussed. 4 kW of the BESS power rate was enough to support both surplus and shortage scenarios.	Aghamohammadi et al. [54]
Analytical method	Hybrid indicators	Wind (170 MW), NaS Battery	A battery bank of 288 MWh/40 MW was expected to reduce both wind curtailment and annual cost.	Rodrigues et al. [61]
Analytical method	Hybrid indicators	Diesel Generator (1230 kW), Wind (600 kW), ESS	By comparison, the lowest cost technology was LA battery (2196 kWh/246.4 kW) to minimise the dump energy and minimise the operation cost.	Ross et al. [109]
Search-based methods	Financial indicator	PV, Wind, BESS, Diesel Generator	The results showed that 600 kWh of the BESS will optimally perform for 1200 kW renewable energy with minimum annual levelised cost of electricity.	Shang et al. [41]
Search-based methods	Financial indicator	Wind (125 MW), NaS Battery	To supply Nan'ao island demand and wind energy, the expected optimal NaS battery is 36.4 MWh/5.5 MW to achieve the lowest annual cost.	Luo et al. [107]
Hybrid method	Financial indicator	PV, Wind, Fuel Cell, VRLA and Li-ion Battery	By minimising overall investment cost, the optimal battery sizes were obtained to be VRLA battery (18.04 kWh) and Li-ion battery (14.65 kWh) among various scenarios.	Dragicevic et al. [50]
Hybrid method	Financial indicators	Wind, Diesel Generator, ESS	The energy and power capacity of the ESS had significant differences ranging within 0.279–0.774 kWh/0.048–0.159 kW among different scenarios for the lowest capital and operation cost.	Abbey et al. [106]

on more options associated with market rules than just financial or power management.

Fig. 4.5 illustrates the basic structure of a solar PV-wind-BESS hybrid power plant. The power management centre can optimally dispatch the BESS to obtain the best performance for the renewable energy power plant. Similar to the other systems described above, due to the intermittent and fluctuating nature of the renewable resources, a BESS can play an essential role in smoothing the power output, load management and minimising the operation costs. However, with large-scale systems, the battery can also be used to compensate for the mismatch between forecasted generation and actual generation, ride through lulls in generation output due to the weather, as well as arbitrage by storing electricity when the market price is lower and then selling it back when the market price is higher. Determining the battery size for these systems is also greatly dependent on how you want the battery to function. If it is only for short-term transients in the weather such as passing clouds or wind gusts, then you will size the system differently to the case where you are wanting to cover any shortfall in generation due to either forecast errors or longer-term weather patterns which cause one technology to have extended periods of downtime. Larger generation systems can also make use of the battery to avoid curtailment due to high renewable generation periods but low periods of demand - a common phenomenon in power systems with high renewable penetration.

The studies summarised in Table 4.4 relate to battery sizing for renewable energy power plants. Most of the studies have used the BESS to enhance the performance of solar PV farms or wind farms, namely PV-BESS power plants and Wind-BESS power plants.

As can be seen from Table 4.4, the key uses of the battery/storage system were to reduce curtailment [97], improve frequency stability [53], compensate for forecasting errors [68] and smooth production profiles [70,112,114]. As with the other sized systems described in Sections 4.1–4.3, different optimisation methods/criteria were applied to improve the performance of the renewable energy power plants. The main indicators for determining the battery sizing were technical, as some other indicators are not as suitable due to the size of the renewable system and the market connection requirements, in particular operation rules within the electricity market. The studies investigated sized the batteries in the range from 80 kWh [70] to 300 MWh [112] depending on the size of the power plant and criteria for dispatching the battery. Due to the complementary nature of solar and wind plants, a hybrid solar and wind power plant would be expected to exceed the performance of the individual systems [115–117]. For hybrid power plants, BESS would take more responsibility to tackle the variability of solar and wind resources simultaneously.

4.5. BESS siting in renewable energy systems

Determining the optimum battery size is the most common issue that is addressed when integrating a storage system into a renewable energy system, and the key aspect this review has concentrated on. It is, however, worth mentioning another important aspect that is determining the optimal integration site for BESS, i.e. the best node in the power grid to connect the BESS into. This is especially relevant to the case of distributed energy resources. In fact, when deploying the BESS into the grid network, although battery size plays an essential role in enhancing the performance of the renewable energy system, different integration sites can also result in noticeable differences in the performance of the battery when the size is kept constant [118]. The issue of correct siting is not just relevant to the distribution network, many studies have also investigated the optimal integration site for the transmission network [119] (both transmission and distribution networks are considered in [120]). Here, the battery is used to buffer electricity congestion, avoid network upgrades and mitigate the working stress of voltage regulation facilities. A collection of studies in the application of distributed energy systems that look at both siting and sizing are summarised in Table 4.5. From Table 4.5, we can see that BESS siting requires both qualitative and quantitative analysis in order to compare and optimise different locations. Siting is affected by the overall network topology and the resulting power flows within the network. Most studies in the literature applied sizing and siting in the distribution network using an IEEE standard simulation network but modified with renewable energy integration. It is worth noting that the methods and criteria of BESS siting and sizing are also consistent with that discussed in Sections 2 and 3.

4.6. BESS sizing with auxiliary technologies in renewable energy systems

Batteries as energy storage systems have a drawback in that they degrade with charge/discharge cycling over time. We, therefore, have extended the review to also include BESS sizing with auxiliary technologies. To prolong the lifetime of the battery, a wide range of strategies and technologies are used, including smarter management of the battery's operation to avoid frequent cycles and using auxiliary facilities for the same purpose. The combination of different energy storage technologies is usually defined as Hybrid Energy Storage Systems (HESS), which is actually a broader term than just a battery with auxiliary facilities. The most widely used auxiliary technology is the super-capacitor (SC, or ultra-capacitor) [79,121]. The super-capacitor has a fast dynamic response rate which can provide a higher power density rate but a lower energy density rate, making it a natural complementary technology to increase the capability of the battery system, and battery's cycle life for certain batteries which have significant degradation from cycling. The studies listed in Table 4.6 show the sizing studies for HESS using batteries and other ESS, especially super-capacitors. It is broadly accepted that super-capacitors can be used for filtering the high-frequency components of power fluctuations due to their fast response, while battery storage can be dispatched to address the low-frequency components. A direct example of this approach is to use both technologies to achieve power smoothing [66]. The other important factors of sizing HESS are the power rating ratio of battery and super-capacitor, which can vary from 5:1 [79] to 7:1 [63], and the energy rating ratio, which can range from 9:1 [66] to 190:1 [63], due to different system settings and expected functions of the HESS, etc. The other technology mentioned in studies involving large-scale systems is compressed air energy storage (CAES). The CAES used in the study was combined with a NaS battery for a renewable energy power plant [69].

5. Discussion

5.1. Categories of renewable energy systems

This literature review has classified studies into four categories, based on the size of the system and purpose of the storage system. These categories were explored to identify the effectiveness and functions of the BESS. As an example, while both categories of distributed energy systems and renewable energy power plants are grid-connected applications, the BESS in a renewable energy power plant can be used to compensate for any forecasting errors, provide frequency regulation and optimise trading in the energy market. These are currently not necessary for distributed energy resources. Standalone HRES and microgrids have some overlap, as the operation of an islanded microgrid is the same as a standalone HRES. There are two main reasons we chose to separate them into different categories - One is because the two operation modes are considered in most microgrid studies, which makes it distinguishable from the one operation mode of standalone HRES. The other reason is simply because of the terminology used to describe the different systems, hence, we have also separated the studies according to the terminology used.

Whilst sorting the studies into the various categories, it can be observed from Tables 4.1–4.4 that there are similarities between some of the expected functions of the BESS. For instance, when determining the

Table 4.4
Studies of BESS sizing in renewable energy power plants.

Method	Sizing criteria	Energy sources	Findings	Reference
Probabilistic method	Financial indicators	Wind (45 MW/30 MW), ESS	By minimising the penalty cost from forecast errors and the cost of the ESS, the optimal energy and power capacity of the ESS can be obtained as 1.98 MW for wind farm (45 MW) and 1.32 MW for wind farm (30 MW).	Wu et al. [71]
Probabilistic Method	Technical indicator	Wind (1 MW), ESS	The ESS power and energy capacity was 22 MWh/300 kW if 5% unserved energy was permitted, which is defined as the energy that cannot be absorbed or supplied by ESS, whereas an ESS with 46 MWh/800 kW would be necessary for 100% compensation.	Bludszuweit et al. [111]
Probabilistic method	Technical indicator	Wind (multi-MW), ESS	The sizing results of the ESS depend on the level of energy imbalances introduced by limited forecast accuracy. An ESS of 4.82 per unit can achieve 100% compensation.	Pinson et al. [73]
Probabilistic method	Technical indicator	PV (around 6300 MW), BESS, Generators (18,000 MW)	The size of the battery with 0.053 GWh can significantly improve the probability of maintaining frequency stability from 0.946 to 0.977 when generator failure and solar plant transients.	Meng et al. [53]
Analytical method	Technical indicator	PV (80 MW), Wind (20 MW), ESS	The size of the ESS was determined through using the ESS to stabilize the power variance caused by fluctuating renewable energies and varying grid load. The sizing results can range from 0 to 300 MWh.	Li et al. [112]
Analytical method	Technical indicators	Wind (34 MW), BESS	4 MWh of the BESS capacity can have significant effects of reducing overloading and curtailment.	Etherden et al. [97]
Analytical method	Technical indicator	Coal-fired generators (1700 MW), Wind (200 MW), ESS	The size of the ESS was dependent on frequency response requirements to ensure the grid frequency deviation within the limitation. The size increased from 0.6731/0.0279 per unit to 0.8925/0.0325 per unit when one of the four coal-fired generators was shut down.	Liu et al. [113]
Analytical method	Hybrid indicators	Wind (2.83 MW), BESS	Two indicators were applied to determine the battery size (0.68 MWh/1.33 MW) - minimising the capital cost of the BESS and maintaining the constant wind production.	Wang et al. [64]
Analytical method	Hybrid indicators	Wind (10 MW), ESS	The ESS size was determined as 150 MWh/8 MW to follow the scheduling plan, and maximise the expected operation benefit.	Korpaas et al. [49]
Search-based methods	Hybrid indicators	Wind (50 MW), VRB	The battery was sized as 3 MWh/5.3 MW to maximise the income of wind power plant with the consideration of frequency regulation.	Johnston et al. [55]
Search-based methods	Hybrid indicators	Wind (100 MW), Zinc-bromine Flow Battery	The optimal size of the battery was attained by advanced controllers to minimise the cost of the energy storage system and mitigate the forecasting errors. The required BESS would be 40 MWh/34 MW using a simple controller.	Brekken et al. [68]
Hybrid method	Technical indicator	Wind (1650 kW), ESS	The energy capacities of the ESS were shown with different confidence levels and data resolution, ranging from 4278 kWh to 64233 kWh.	Shokrzadeh et al. [114]
Hybrid method	Technical indicator	PV (99.36 kW), LA Battery, NaS Battery, Li-ion Battery	To reduce the variability of PV production, the best sizes of the battery were determined to be 100 kWh, 80 kWh and 90 kWh for LA, NaS and Li-ion battery, respectively.	Cervone et al. [70]

Table 4.5
Studies considering both siting and sizing of BESS.

Method	Sizing criteria	Energy sources	Simulation platform	Findings	Reference
Analytical method	Hybrid indicators	Wind; BESS	A typical 41-bus rural distribution system	Two goals were set, including accommodating the spilled wind and minimising the annual cost, and the results showed the only economically feasible ESS technology is Zn/Br.	Atwa et al. [76]
Analytical method	Technical indicator	PV, BESS	14-bus IEEE benchmark	To perform voltage regulation, the calculated optimal size of the battery was 11.96% of maximum solar power multiplied by the desired time of voltage regulation.	Nazaripouya et al. [59]
Search-based methods	Hybrid indicators	PV, Wind, BESS (Li-ion battery and LA battery)	Modified IEEE 15-bus distribution radial system	Multiple criteria were applied, including maximising the benefits of distribution companies, reducing the energy exchange at substation and minimising the power loss.	Zheng et al. [101]
Search-based methods	Hybrid indicators	PV, Wind, BESS	A modified IEEE 33-bus system	A bi-level optimisation model was proposed with outer level to minimising the total net present value and inner level to achieve the optimal power flow and BESS capacity adjustment.	Xiao et al. [118]
Hybrid method	Hybrid indicators	Wind, BESS, Micro-turbine	A modified IEEE 15-bus system	This study aims to minimise the investment operation costs with the constraint of satisfying wind utilisation level.	Zhang et al. [74]

Table 4.6
Studies of BESS sizing with auxiliary technologies.

Category	Method	Sizing criteria	Energy sources	Storage	Findings	Reference
Distributed energy system	Probabilistic method	Hybrid indicator	Wind	BESS, SC	Results show that SC helps with high frequency and peak fluctuations of wind power.	Wang et al. [121]
Distributed energy system	Analytical method	Technical indicator	PV	BESS, Capacitor	A method based on cloud cover was proposed to suppress the fluctuation of PV output.	Watanabe et al. [65]
Standalone HRES	Hybrid method	Technical indicator	PV, Wind	Battery, SC	A new frequency control strategy based on hysteretic loop was developed for HESS to extend the battery's life.	Jia et al. [51]
microgrid	Search-based method	Hybrid indicator	Wind	lead-acid Battery, SC	Power smoothing is achieved by dispatching SC and batteries to buffer the high and low frequency components of fluctuating wind power.	Yuan et al. [66]
RE Power Plant	Analytical method	Technical indicator	Wind, Conventional generators	NaS battery, CAES	Wind forecasting errors were decomposed by signal processing techniques for cycling of each energy storage technology.	Bitaraf et al. [69]
RE Power Plant	Analytical method	Financial indicator	PV	VRB, SC	High performance computing was employed to seek a high energy yield and low ancillary service in a PV power plant.	Wang et al. [79]
RE Power Plant	Analytical method	Technical indicator	Wind	HESS	Spectral analysis method was applied to achieve peak shaving for power imbalance between load and wind power output.	Zhao et al. [63]

size of the battery for a microgrid, the financial indicators tended to be the most common criteria, hence the economics of the systems was the greatest priority in size determination. We still saw financial indicators for the other sized systems, however for standalone HRES and renewable energy power plants, both financial and technical criteria are used for battery sizing. Therefore, to effectively size a renewable system, a range of criteria (hybrid criteria) would be the most advantageous way to improve the battery sizing process.

5.2. Discussion on BESS sizing outcomes

When analysing the BESS sizing outcomes of different studies, it is noticeable that the sizing results from various studies can be difficult to compare. One example is that BESS sizing outcomes from various studies are expressed in different formations. The BESS size outcomes were denoted by the hours of peak load in [58], per unit value multiplied by desired voltage regulation duration in [59], by the percentage of rated renewable energy in [71,101] and more commonly, through the energy capacity and/or power capacity.

Although some of the BESS size indicators above can reveal the relationship between BESS capacity and other performance criteria, such as voltage regulation, energy capacity and power capacity are still the most accepted way to denote the size of the battery system. In many previous studies, only battery energy capacity is considered to determine the battery size, especially for lead-acid batteries, where the power capacity and energy capacity are highly coupled [42]. Newer battery technologies such as vanadium redox flow batteries have the energy density and power density de-coupled, therefore, the new trend in battery sizing is that both properties are specified as battery ratings [42]. Hence, in [64], the capital cost of the battery system can be manifested based on both the power and energy capacities rather than only energy capacity. Another reason to include both energy and power capacity is that the quotient between energy capacity and power capacity can directly tell the minimal hours the battery can supply a system with its rated power.

Another finding from the battery sizing studies is that the sizing results can vary significantly. Three main reasons are apparent. Firstly, the energy and power capacity of BESS is highly related to the application scale that indicates the capacity of demand and/or renewable energy for BESS to accommodate. For example, for applications of distributed energy resources, to accommodate the renewable energy at the regional distribution network scale in [76] and [101], more than 1MWh of BESS is required. Relatively speaking, for integration into household applications, 100kWh of BESS would be more than enough for most functions [48,100]. Also, from Table 4.4, the BESS applications for renewable energy power plants including large-scale solar and/or wind applications are in MWh (energy capacity unit)/MW (power capacity unit) levels.

Secondly, the BESS sizing results also strongly depend on the expected functions of the battery in the renewable system. For example, a 10 kWh ESS was enough to minimise the difference squared between wind output and desired output for 850 kW wind integration in Table 4.1 [99], whereas 16.7 kWh of battery capacity is required to minimise electricity cost and cost of the battery capacity loss for 1 kW peak demand and a PV array around 1.5 kW [48]. This is because when BESS was implemented to compensate for the difference between desired wind production and actual wind generation, a smaller capacity was required when the desired wind production was set properly. This means the desired reference can balance the difference between desired and actual wind generation, whereas, if the target cannot be balanced well, for example, using battery to compensate for forecast errors within a tight tolerance (within 4% of forecast power, 90% of the time) required a larger battery sized as 40 MWh/30 MW for a 100 MW wind farm [68]. In contrast to minimising the power deviation, a large amount of energy is needed to be stored and released to achieve the minimum electricity cost based on time-of-use (TOU) tariff, which results in a relatively larger battery energy capacity. To clarify, installing a battery for energy arbitrage by using a TOU tariff can increase the profitability of the system. In the example we mentioned above, around 15–25% cost can be saved by using a battery with a TOU tariff than single rate tariff [48]. Moreover, it was found that the outcomes were more consistent if similar criteria were chosen for battery sizing. For instance, the expected functions of BESS were to minimise total cost in the islanded mode and maximise total benefit in the grid-connected mode, which leads to optimum battery capacities of 1400–1600 kWh and 400–1100 kWh, respectively [47]. Furthermore, the optimised size of BESS in [46] were 500 kWh battery in the grid-connected case and 1400 kWh in the islanded case. In both studies, these cases resulted in a larger BESS capacity for islanded mode and a relatively smaller battery capacity for the grid-connected mode. The larger capacity of the BESS in islanded operation is simply because the main function of the BESS in this scenario is to replace the higher cost of fossil fuel with a lower cost renewable energy, thereby reducing the total cost. Also, a larger capacity of storage is required to achieve constant production, peak-shaving, 100% renewable energy and arbitrage, etc. Hence, with various expectations, BESS can be configured with different capacities.

Thirdly, the characteristics of the battery, including battery type, cost and other operation constraints, can be another reason that affects the sizing results. There are some studies that conducted battery sizing with different battery technologies and compared their effectiveness. In [76], it was demonstrated that the only economically feasible BESS technology to accommodate spilled wind and minimise annual cost is Zn/Br battery, when compared with lead-acid (LA), valve-regulated lead-acid (VRLA), NaS and Vanadium redox battery (VRB). In addition, compared to VRLA, Li-ion batteries tend to be more attractive due to their infrequent replacements [50]. Moreover, some charging/discharging features of the battery also play a significant role in battery size determination, such as cycle life of the battery, depth of discharge (DOD) and round-trip efficiency. For example, when the optimal usable storage capacity was 26 kWh and assuming 70% DOD, it meant the optimal physical capacity was 37 kWh [102]. In this regard, we can see that the calculated battery sizes are also dependent on the battery's constraints.

5.3. Discussions on future BESS sizing trends

Studies on BESS sizing tend to give a capacity selection range with changeable parameters [112] or confidence regions [114] rather than exact values for BESS power and energy capacity. This means that decision-makers will have more flexibility to decide their battery size depending on the specific requirements. Currently, choice of battery size uses more analytical methods for technical indicators and search-based methods are more often used for financial indicators. A simple explanation is that financial indicators, using the same unit are more easily expressed in one optimisation formulation. Hence, search-based methods can be effectively applied to obtain the optimum. On the contrary, to improve some technical indicators, specific professional software may be required for simulations, and it is relatively difficult to be incorporated with search-based methods. In this way, those technical indicators need to be optimised by analytical methods. For future applications, more factors will be considered for battery sizing, such as hybrid criteria with financial and technical considerations, and even environmental concerns can be quantified and integrated into the sizing process. Moreover, the sizing techniques would be more deeply combined and offer more accurate solutions.

Besides the discussion above, it is also interesting to mention that some studies support the contention that the results of BESS size can be more promising and achievable if partial fulfillments are permitted [63,111]. Partial fulfillments indicate the functions of BESS are partially achieved, for example 90%, which can almost fulfil its duty, but significantly reduce its capital cost.

6. Conclusion

Battery storage has the capability to store and release energy at high frequencies, ensuring frequency and voltage stability, as well as for extended periods, providing an effective avenue for optimising the energy management of RES and the ability to ride through lulls in the weather. There are a range of performance indicators used in the optimisation process, with financial, technical and hybrid (combining both financial and technical) indicators being the main items considered in literature. Financial indicators are more notably used for smaller sized systems, with hybrid indicators more prevalent for larger sized renewable systems. The methods used for obtaining the optimum size of BESS were also reviewed, with a variety of techniques assessed. The complexity of the techniques varies depending on the approach taken, with methods falling into categories such as probabilistic, analytical, or directed search-based. It was noted that particular optimisation methods can be preferred for particular indicators, with an example being the use of search-based methods considering financial indicators. A growing trend was found to be the use of nature inspired heuristic methods such as genetic algorithms, with a growing body of literature detailing hybrid optimisation approaches combining heuristic and other techniques.

In contrast to previous reviews on BESS size optimisation, this review has been organised according to the energy application type of the RES. By considering the cases of distributed, standalone, microgrid, and power plant systems, respectively, new insights have been gained about which optimisation criteria prove to be most critical for system design, and by extension the most appropriate optimisation technique for sizing of the BESS. This will prove crucial for system designers as more RES generated power is harnessed, allowing designers to ascertain the critical design parameters for a system based on the intended application, as well as the size of the system. As the transition to more RE energy generation continues, more sophisticated optimisation tools will be developed. As highlighted in this review, environmental considerations and criteria will take on greater importance moving forward, in addition to financial and technical indicators already being considered.

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