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Review of energy storage allocation in power distribution networks: applications, methods and future research

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Abstract: Changes in the electricity business environment, dictated mostly by the increasing integration of renewable energy sources characterised by variable and uncertain generation, create new challenges especially in the liberalised market environment. The role of energy storage systems (ESS) is recognised as a mean to provide additional system security, reliability and flexibility to respond to changes that are still difficult to accurately forecast. However, there are still open questions about benefits these units bring to the generation side, system operators and the consumers. This study provides a comprehensive overview of the current research on ESS allocation (ESS sizing and siting), giving a unique insight into issues and challenges of integrating ESS into distribution networks and thus giving framework guidelines for future ESS research.

1 Introduction

Energy storage systems (ESS) do not present new energy subjects nor do they provide new concepts in the power systems operation as their role in providing arbitrage or contingency services exists for decades. However, the number and location, and consequently the power and energy capacity, of these usually larger ESS units such as hydro storage and compressed air storage are limited due to their specific geographical requirements. On the other hand, smaller ESS units do not suffer from the same limitations but require relatively high initial investment cost meaning they have so far been used only for specialised applications such as offering backup supply. Recently, constant increase of demand, high penetration of variable and uncertain generation such as wind and solar, together with the energy market liberalisation [1] created new opportunities for ESS integration at different levels of the electric power system [2–42]. Different requirements depending on the system level, different ESS technologies, as well as different technologies of a certain ESS type characterised by technical and economic constraints suggest that there is no unified solution for application, siting and sizing, or general conclusion on the benefits that ESS can bring to the future low carbon power system.

This paper presents a comprehensive review of different roles ESS can have in the system and the methodologies used to obtain ESS size and location and it mainly focuses on the methods and opportunities for ESS in distribution networks. The integration and planning of future ESS cannot be observed separately from their operation and thus the paper will capture and reflect on issues in different parts of the system going from generation to final user. However, the main focus is the integration of ESS in distribution networks.

The paper is organised as follows. Section 2 explains the general issues in defining the sizing and siting of ESS. Section 3 provides an overview of the different roles ESS can have in the system. Section 4 reviews various proposed methods for solving problems of placing and sizing ESS. Section 5 gives a comprehensive overview of models for ESS siting and sizing. Section 6 provides conclusions and directions for future research.

2 Sitting and sizing of ESS

A lot of research has been devoted to the optimisation and selection of ESS units type, location and size [2–42]. According to [43] ESS technologies can in general be identified by nine characteristics (power capacity, energy capacity, ramp rate, location, response granularity, response frequency, control/communication, response time and implementation requirements), where only the first six are physical characteristics. The complexity, and with it the number of relevant characteristics, could go further including for example variables relevant for investment and planning. However, ESS are in literature predominantly selected and optimised with relevance to their power rating (MW), energy capacity (MWh) and location in the network. Power rating and energy capacity should be treated as separate technical characteristics of a specific ESS technology and both need to be defined and dimensioned separately taking into account their investment cost. Although both characteristics are discrete and usually obtained as ‘building’ blocks, sometimes they are defined as continuous variables and solved using various optimisation methods. Defining power and energy size as discrete variables enables the use of exhaustive search methods often found in the surveyed literature. Another relevant constraint that needs to be taken into account when modelling ESS technical characteristics is its round circle efficiency or charging and discharging power. These two values are different and, in addition, they are different for each ESS technology. Fig. 1 shows different services that can be provided by storage units depending on the ESS capacity and discharge duration requirement.

Simultaneous determination of ESS location and size is a non-deterministic polynomial-time (NP) hard problem and up to now has not been solved efficiently for large-scale problems. A number of methods have been developed in the literature for determining the size and siting of ESS; however for the purpose of better analysis, in this paper they are clustered in four main groups according to the methodology used: analytical methods (AM), mathematical programming (MP), exhaustive search and heuristic methods. Each group will be further analysed in Section 4.

3 ESS applications in power systems

The role of ESS in the power system can, and probably will be in the future, diverse and multiple. Currently, there are very few papers elaborating on multiple services ESS can offer to different system stakeholders; they are rather focused on a single actor/stakeholder capability to exploit advantage of utilising ESS. In general, the

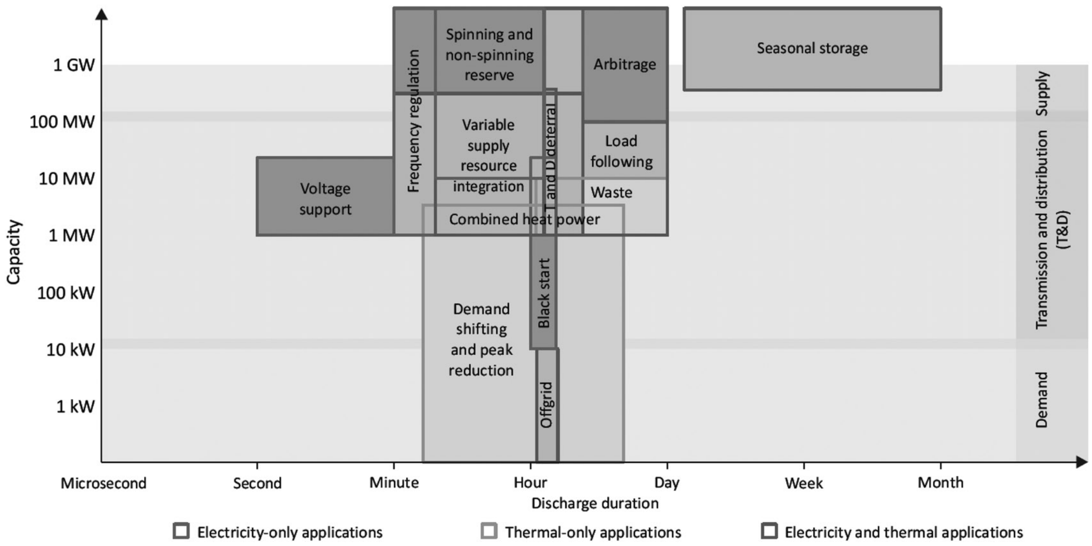

Fig. 1 *Power requirement versus discharge duration for some applications in today' s energy system [44]*

role of ESS is to maintain the power system within allowed system constraints and parameters, usually motivated purely by financial reasons. From the point of different power system stakeholders, the role of ESS is recognised either on the generation side, providing the system operator services, or at the end user side. With this respect, the reviewed papers are classified as follows:

- Generation side: avoid wind curtailment [10, 30, 45]; minimise investment and operational cost [6, 7, 14, 46–50]; provide firm capacity [11, 15, 21, 51]; minimise forecast error [20, 24].
- System operators: energy arbitrage [13, 52]; minimise production cost [4, 25]; operating reserve [8, 35, 40, 53, 54]; ramping [28, 33]; network replacement and deferral/network expansion planning [5, 18, 31, 41]; enable higher DG integration [19]; minimise electricity cost [12, 27, 32, 55]; minimise investment and operational cost [23, 34, 36–38, 42, 56]; avoid system violations [22, 39, 57]; island – reliability [3, 16]; island – dynamic security [9]; provide firm capacity [11, 15, 21]; minimise forecast error [20, 24]; improving reliability [58–61].
- Consumers: Backup power [17, 29, 62] capacity contract savings/ peak shaving [2, 63]; energy arbitrage [13]; demand response and smart home [64–66].

It should be also noted that each of the above-mentioned services can, for each stakeholder, be divided into fast and slow services, depending on the reaction time and frequency capability to provide a specific service. An interesting review of different technologies with respect to time frame in which they could provide a desired flexibility service to the system operator and enable higher integration of wind can be found in [67]. The authors of [52] analyse the requirements for storage for different penetrations of wind and solar for the case of Texas (ERCOT) and, although it is not explicitly shown in the paper, they limit their analyses on energy arbitrage service. A more detailed analysis can be found in [53], where the authors analyse the potential of storage for provision of energy, reserve and both energy and reserve services and demonstrate how, in low-flexibility systems, the integration of storage results in lower minimum stable generation enabling higher integration of wind. In [41, 54], the authors analyse the potential of storage to provide spinning reserve services and assess technical and economic implications on the UK power system. Focusing only on pumped storage technology, but taking into consideration both operation and investment costs, the conclusions of [56] suggest that storage is viable only for very large levels of integrated wind. The complexity of the above presented analyses increases with the inclusion of network constraints. Using Benders decomposition technique, the authors in [45] propose a methodology for joined wind and storage participation, focusing on remote locations for wind power plants and congestions issues that would occur without the integration of storage. The similar work is described in [50]; however, storage units are privately owned, meaning they are not the ownership of system operator or bulk generator units. In addition to the above, the authors in [57] take transmission system security constraints into account. A more comprehensive approach capturing several aspects (optimal storage technology, size and location as well as transmission constraints) is demonstrated in [60]. An interesting approach is presented in [68] where authors propose a model for multiple services provided to different interested parties. Each service from ESS is auctioned on a different time scale and the blocks of a preceding auction is transferred to the next auction as a constraint. It should be noted that consideration of different stakeholder utilising benefits of same storage [69], financial storage rights [70] and multiple services further increase the complexity of the problem. In should be, however, noticed that most of these papers focus on the whole system benefits, analysing potential to provide energy and reserve services or alleviate transmission network congestions. The aspect of storage role on the distribution side is slightly less represented.

4 Methods for ESS sitting and sizing

4.1 AM

AM presented in this paper are those which do not use the specific mathematical optimisation tools. They usually do not incorporate specific network data and use predefined network and operational constraints instead. AM are currently used only for the determination of the optimal size of the ESS in order to balance the production of renewable energy sources (RES). There has been a lot of debate on the concept of storage as a means to store energy from RES [71–73], and this is probably the most commonly studied benefit using AM. It is important to notice that, although AM are valuable in recognising the value of ESS in the system, they are usually limited to capturing benefits arising from energy arbitrage. This will be additionally emphasised in Sections 4.2–4.4 when discussion will be directed towards methodologies that can properly define these benefits.

AM are based on historical load demand curves [5, 11, 13, 16, 26] or on statistical data analysis [15, 17, 24, 28, 29, 33]. They do not include network constraints or consider multiple signal market-driven operation (such as energy and reserve). Having that in mind, the exception is the work [28], which considers the analysis of average interval prices in the network; however, battery energy storage system (BESS) location is predefined and only the BESS size is calculated.

One of the first papers on the potential role of ESS in power system planning can be found in [5]. Without choosing the specific ESS technology, the authors analysed possible technical issues that can be avoided with the use of ESS, which also defers network equipment investment. Although valuable to understand the ESS potential role, the paper does not provide an answer to the justification of such an investment. In [11], optimal size is found using exhaustive search defining optimal battery energy and power with the goal of maintaining constant wind power plant (WPP) generation from historical measurement data. BESS is placed on the DC side of the WPP avoiding additional cost for the inverter, while the BESS size is the difference between WPP unconstrained generation and load. In [15], the authors have determined BESS power rating based on statistical wind distribution, while the minimal energy rating (number of battery cells) is determined in order to satisfy additional battery' s electrical characteristic constraints. ESS power and energy in [24] are determined analytically from wind forecast error distribution and allowed unserved energy. In [16], the authors optimised photovoltaic (PV) with ESS system for islanded grid. For available solar irradiance and load data, ESS charging power is determined as a difference between PV output and load and discharge power is based on the assumption that ESS should solely cover all consumption when production from PV is unavailable. ESS capacity is calculated from those assumptions. In [17], ESS size for backup supply is determined based on the outage duration statistics and targeted reliability level. This concept is expanded in [29] where Sequential Monte Carlo Simulation is used to create reliability data for the observed network. Linear programming (LP) is then used for distributed generation (DG) and ESS dispatch that determines feasibility of power flow solutions. With reliability data obtained for every node, ESS size is analytically determined to meet reliability requirements. The capability of BESS to be used for peak shaving is demonstrated in [13]. BESS size is simply determined from real load data and chosen level of peak shaving. In [26], the authors used discrete Fourier transformation to approximate forecast error with four different periodic curves that can represent charge–discharge cycle of known ESS technologies. Statistical load and wind data analysis is used in [28] to find compressed air energy storage (CAES) size that maximises benefit from temporal arbitrage, wind curtailment and CO_2 savings. In [33], ESS is observed as flexible reserve. Its size is statistically determined for various levels of wind penetration from scaled historic data. The same paper uses rule-based simulation with predefined ESS size, using the same set of data, to find optimal ratings that satisfy ramping regulation requirements.

4.2 MP

MP captures different numerical methods that efficiently find optimal solution of the approximated model. In the context of ESS siting and sizing, MP is used for solving operational issues usually expressed as unit commitment (UC) and optimal power flow (OPF) problems. The most efficient method, meaning it is always capable of finding a single global optimum solution, is LP, which implies keeping the objective function and model constraints linear. In cases where the power system behaviour does not comply with linearity requirements, it is on occasion possible to use linearisation methods to keep the linearity of the problem. For example, in UC problems generators have non-linear cost curves, while OPF has non-linearities in power flow equations. Determining optimal location requires additional combinatorial effort and thus makes sizing and siting problems NP hard and MP algorithms impractical for large-scale power systems. The following section will offer an overview of ideas for integration of ESS using LP.

4.2.1 LP: A mix of WPP–diesel system with the addition of hydrogen storage is optimised finding the minimal investment, loss of load and operational cost in [6]. It is interesting to notice that, unlike in methods based on analytical procedures, there is a clear recognition that BESS is not cost effective under the considered market environment prices in the role of temporal arbitrage. Due to the high cost of hydrogen storage technologies, the authors could not justify investment in ESS with current prices. They have repeated calculation with same loading and predicted favourable prices in the future and obtained solution that promotes ESS integration. Using LP methods in [9] the authors determine improvements in islanded system dynamics by solving UC problem for isolated system with additional pumped storage and system dynamics constraints. Sensitivity analyses suggest that the dynamic security constraints are those who made the economic case for ESS. In [12], mixed integer LP (MILP) is used on a set of wind and load curves with attached probabilities to solve UC problem for islanded wind–diesel generation. Diesel generator and ESS are used as backup supply and the authors investigate the wind penetration level impacts and diesel generator operation strategy (generation constraints) on ESS sizing and electricity cost. The authors conclude that the ESS integration is justified only for medium to high RES integration levels. Diesel generator strategy, which relies on ESS and enables generator shut down periods, can provide additional savings in the system. In [19], simulation time is divided into two segments. During the off-peak period, the ESS is charged, while in the on-peak it is discharged. MILP is used to solve two separate OPF from two perspectives. First, from the producers' viewpoint; OPF is used to determine the cost of spilled wind energy. Second, OPF is used from distribution system operator (DSO) point of view as a tool to minimise electricity cost and network losses. In the second OPF, ESS created benefits for DG as well as ESS created benefit from the reduction in the amount of wind curtailed. ESS size is determined from the amount of spilled energy and its location is optimised to minimise network losses. A distribution system based on PV and ESS is optimised in [39] defining operation of the ESS and PV generation in order to keep voltage constraints within predefined limits. MILP is used in [41] to find optimal ESS size in future UK power system. ESS was observed as one of future solutions together with new generation capacities, network reinforcement, transmission expansion and demand management. Competing future technologies have reduced absolute value of energy storage in the system mostly by affecting its contribution to reducing system operation costs and supporting real time balancing.

4.2.2 Second-order cone programming (SOCP): In order to transform non-linear AC OPF problem for radial network to mixed integer second-order cone programming (MISOCP) formulation that is solved with primal–dual interior method some approximations are required as presented in [42]. MISOCP is used to solve multi-objective optimisation in which BESS investment cost and weighted operational cost are minimised. Weights in objective function are determined with analytic hierarchy process. The results suggest that for network with large number of DG units, network operation can be controlled with only a few optimally placed ESS units. This solution avoids control of every single DG in the network and large costs associated with telecommunication infrastructure. In [74], the authors use the same method to find a feasible investment case for ESS in distribution networks. While they capture only services of energy arbitrage and reduction in losses for the system operator, they do not find business case for ESS investment.

4.2.3 Dynamic programming (DP): Multi-pass DP (MPDP) is applied to simultaneously minimise grid contract cost and BESS investment in [2]. The paper evaluated BESS role in contract capacity savings.

4.2.4 Stochastic programming (SP): An SP method that minimises ESS investment and network operational cost is developed in [23]. The algorithm solves DC lossless OPF to determine ESS size, location and optimal dispatch.

4.3 Exhaustive search (ES)

ES guarantees finding of optimal solution in a limited discrete search space; however it requires significant computational time even for moderate size problems. In the reviewed papers, ES is used to determine ESS power and capacity while location was determined only in [40], separately from size. Power rating and capacities are divided in discrete levels and the system is evaluated using MP or simulation for every combination in the search space. Simultaneous solution of siting and sizing problem is practically unsolvable by ES due to the NP hard combinatorial nature of this problem.

The exhaustive search combined with simulation is used in [3] to find optimal PV-BESS size that minimises total cost for isolated system and maintains the required reliability level. Cost-effective battery power and capacity that maximises fuel savings are found for their various combinations using ES for search and DP for evaluation method in [4]. Search limits for hybrid system with WPP, PV and BSS in [7] are found from average daily demand data. ES is then used on every combination to find optimal cost, reliability and energy shedding. In [8], ES is used to determine battery power and capacity required for primary frequency support according to UCTE regulations. Authors used simulation to verify control algorithm and find optimal BESS sizes. In [10], the authors found that ESS is not profitable only by avoiding energy curtailment from wind power plant. Consequently they researched provision of other market services (capacity firming, voltage stability, reliability and environment benefits) using ES, representing these services analytically, finding a cost-effective solution for various ESS power and energy ratings. Box-Behnken Design with three input parameters (PV size, wind turbine size and battery size) is used as responsive surface method (RSM) to determine optimal sizes of those parameters and their mutual impact on hybrid energy system cost function [14]. RSM is a statistical approach that reduces the number of trials in exhaustive search. Different control strategies are simulated in [20]. Simulations with different controller (simple, fuzzy, artificial neural network) are performed for a range of ESS power and energy ratings to find optimal size that maintains WPP prediction error within 4% for 90% of the time. In [21], BESS charging/discharging power is determined based on historical data on WPP site with an objective to minimise number of battery full charge/discharge cycles. In the same paper, BESS energy rating is found numerically by applying this rule to various sizes, resulting in maximal ratio between BESS lifetime and investment. In [25], the microgrid UC problem is solved for every pair of power and energy sizes calculating net present value (NPV) of ESS installation. UC is solved by genetic algorithm (GA) considering cases with and without ESS installed. Paper [27] uses cost–benefit analysis to determine optimal size of ESS in the microgrid. Predefined ESS power and energy rating are used as constraints in UC problem. In islanded mode, UC is solved to minimise electricity cost and in grid-connected to maximise benefit at the market. Capability of BESS to provide primary frequency control is investigated in [35] determining only power rating. Determined BESS power rating is capable of providing stable frequency response and compensate for biggest mismatch recorded in the events from microgrid' s history data. ES is used in [37] to minimise imbalance penalties and ESS investment cost. Monte Carlo simulations are used to create various forecast error distributions and testing various combinations of ESS power and energy ratings. A framework for stochastic UC and MILP optimisation of revenues obtained on day ahead and hourly reserve market is developed in [40]. Optimal ESS size is determined with this framework using ES for various power and energy ratings.

4.4 Heuristic Methods (HM)

HM include all methods in which experience and knowledge about a specific problem are incorporated in the algorithm. In the past few decades they have also became a synonym for computational methods that search solution space in a smart manner emulating some natural behaviour or process. They do not guarantee finding a global optimal solution; however, they have proven to be robust and their solutions are acceptable in practice. These methods are usually computationally intensive. However, this is not critical in power system planning problems such as ESS siting and sizing. Almost all reviewed papers that are based on heuristic methods, are simultaneously solving siting and sizing problem. It should be noted that HM are solving the combinatorial part of the optimisation problem, while some other methods (usually used for solving UC or OPF) are used to evaluate the solutions obtained by HM.

4.4.1 GA: GA and sequential quadratic programming (SQP) are used in [18] to find optimal size and location of DG, ESS and capacitors in the system with reactive energy market. GA is searching the state space (size and location of units) and OPF is solved with SQP to determine optimal dispatch and operational costs for a given fitness function. GA combined with probabilistic OPF maximising wind power utilisation is presented in [30]. The results suggest that ESS enables higher integration of wind power. However, for low levels of wind generation, revenues obtained only from energy arbitrage do not justify investment in ESS and additional revenues from ancillary services market are required. For higher levels of wind energy integration, energy arbitrage is sufficient for ESS to be economically viable.

4.4.2 Particle swarm optimisation (PSO): PSO is applied to the dynamic network expansion problem in [31]. The method is extended with local search and used to solve combinatorial problem of network expansion in the first step and installation of additional DG and ESS in the second step. Instead of computationally intensive OPF, the authors used a set of operational rules to simulate DG and ESS behaviour in order to calculate the operational cost. In [32], PSO is used to determine DG and ESS size in a smart household. Operational cost is calculated by simulation with Monte Carlo determined parameters on rule-based energy management system. Fuzzy PSO is used in [34] to minimise load curve prediction errors from the markets point of view. BESS is also used for better electricity procurement and loss minimisation. Operational costs are obtained by simulation with operational rules.

4.4.3 Artificial bee colony (ABC): ABC method is proposed in [36] to find optimal size and location of battery-based vehicle charging stations. Authors did not use time analysis and BESS is modelled as controllable load assisting DG to obtain optimal dispatch and minimise power losses.

4.4.4 Bat algorithm (BA): An improved BA is presented in [38] with the goal function to minimise Microgrid generation, operation and BESS investment cost. BESS has fixed location and optimal BESS size and DG dispatch are found.

4.4.5 Practical heuristic algorithms (PHA): A practical heuristic approach is used to find minimal number of ESS nodes needed to mitigate DG impact on the network [22]. In the same paper, gradient search is used to dispatch ESS with previously known OPF for other units in order to satisfy network technical constraints.

5 Contributions

This paper summarises an extensive topic of the ESS role in the present and future power system. It elaborates on different modelling methodologies presented but also discusses different conclusions of those papers and models. As an additional benefit, the paper provides a summary of the reviewed work in Table 1 where taxonomy of reviewed ESS allocation papers is provided in a chronological order. The papers are categorised by: (a) characteristics of the model used for determining storage size or size and location (it means that the paper models only storage or it also includes the network constraints); (b) load model

Table 1 Taxonomy of the reviewed energy storage allocation papers

Reference	Design variables	Optimisation method	Storage technology	Load model	Network	Market	Objective	Objective function
[2]	size	DP	battery	variable power	no	no	single	min cost and investment
[3]	size	ES	battery	variable power	no	no	single	min. cost
[4]	size	ES	battery	variable power	no	no	single	min fuel cost
[5]	size	AM	any	variable power	no	no	-	investment deferral
[6]	size	LP	fuel cell	variable power	no	no	single	min inv. and oper. cost
[7]	size	ES	battery	variable power	no	no	single	min investment cost
[8]	size	ES	battery	variable frequency	no	no	single	min investment cost
[9]	size	LP	pumped hydro	variable power	no	no	single	min investment and fuel cost
[10]	size	AM	compressed air	variable power	no	no	single	min curtailment
[11]	size	AM	battery	constant power	no	no	single	cost benefit
[12]	size	LP	all	variable power	no	no	single	min cost
[13]	size	AM	battery	variable power	no	no	single	energy arbitrage
[14]	size	ES	battery	no load	no	no	single	min investment cost
[15]	size	AM	battery	constant power	no	no	single	firm capacity
[16]	size	AM	different	variable power	no	no	single	min cost
[17]	size	AM	all	constant power	no	no	single	satisfy reliability
[18]	location + size	GA	battery	variable power	yes	yes	single	min cost
[19]	location + size	LP	battery	variable power	yes	yes	single	min invest. and oper. cost
[20]	size	ES	battery	variable power	no	yes	single	min forecast error impact
[21]	size	ES	battery	variable power	no	no	single	max batt. life / invest.
[22]	location + size	PHA	all	variable power	yes	no	single	min cost
[23]	location + size	SP	all	variable power	yes	yes	single	min invest. and oper. cost
[24]	size	AM	all	variable power	no	no	single	satisfy reliability
[25]	size	ES	battery	variable power	no	yes	single	max NPV
[26]	size	AM	all	variable power	no	no	-	eliminate forecast error
[27]	size	ES	battery	variable power	no	yes	single	min cost / max benefit
[28]	size	AM	CAES	variable power	yes	yes	single	max benefit
[29]	size	AM	all	variable power	yes	no	single	satisfy reliability
[30]	location + size	GA	CAES	variable power	yes	yes	single	max WP utilisation
[31]	location + size	PSO	all	constant power	yes	no	single	min invest. and oper. cost
[32]	size	PSO	battery	variable power	no	yes	single	min. electricity cost
[33]	size	AM	all	variable power	no	no	single	satisfy regulation (ramping)
[34]	location + size	PSO	battery	variable power	yes	yes	single	min invest. and oper. cost
[35]	power rating	ES	battery	step response	yes	no	single	min power rating
[36]	location + size	ABC	battery	constant power	yes	no	single	min. losses
[37]	size	ES	all	variable power	no	yes	single	min. penalties and inv.
[38]	size	BA	battery	variable power	yes	yes	single	min. inv. and oper. cost
[39]	size	LP	battery	variable power	yes	no	single	avoid voltage violation
[40]	location + size	ES	battery	variable power	no	yes	single	max benefit
[41]	size	LP	all	variable power	yes	yes	single	min invest. and oper. cost
[42]	location + size	SOCP	battery	variable power	yes	yes	multi	multi

(distinguishing if the electrical load/demand is constant or variable and at what time scale, going from hourly to frequency-response time frames); (c) signals driving the belonging objective function (for example; is the operation market driven or not). Table 1 also provides, for each paper referenced, the abbreviation for the used optimization algorithm (DP for dynamic programming; ES for exhaustive search; AM for analytical method; LP for linear programming; GA for genetic algorithm; PHA for practical heuristic algorithm; SP for stochastic programming; PSO for particle swarm optimisation; ABC for artificial bee colony; BA for bat algorithm and SOCP for second-order cone programming). To complement that, Table 2 identifies the main contribution of the reviewed ESS allocation works, again in a chronological order, providing main contributions of each paper referenced.

6 Conclusions and future research

As the power system requirements change, there is a need for understanding which technologies, where and how will bring additional benefits in the transition to low carbon energy systems. Following this, the paper presents a thorough description of the state-of-the-art models and optimisation methods applied to the energy system storage sizing and siting problem. The solution methodologies for the problem of sizing and siting are classified into four major categories: analytical, MP, exhaustive search and heuristic methods. Siting and sizing of ESS cannot be defined separately from their operation or the role/services these units can provide to different stakeholders in the system.

The challenges for future research include capturing the value of specific services and creating a framework for simultaneous optimal sizing and siting in order to provide different services to multiple stakeholders and determining which ownership model is optimal for all participants. In addition, there is a lack of understanding of cost and benefits of various ESS technologies and their comparison with competing and/or complementing technologies such as demand response, electric vehicles, flexible generation and network enhancements. The following questions still need answers in future research of storage in distribution networks:

(a) Energy arbitrage is obviously not sufficient to make ESS profitable as clearly shown by research reviewed in this paper. The questions that need answers are: what are the ancillary services that can bring additional benefits and help improving ESS feasibility? How do different settlement periods for contracting various ancillary services impact ESS planning and operation? Is the future of active distribution grid in on-grid operation, or will they be capable of delivering system services as demand response microgrids in a concept of shedding off-grid operation? What is the role of ESS in those cases? Can it be the critical component in stabilising such off-grid systems? Can ESS integration in general improve system reliability and how would we value that?

(b) How will future electrified transport sector be integrated? Is everyone willing to wait several hours for their EV to be charged or charging will be conducted through fast charging DC? In the second case, the role of ESS becomes highly important, as it is expected to have major role in providing grid support and

Table 2 Contribution of the reviewed energy storage allocation papers

Reference	Published	Contribution
[2]	1995 September	MPDP is used to simultaneously determine grid capacity contract and BESS power and capacity. Contract violation penalties are allowed if economically justified. Additionally on MPDP, expert knowledge-based BESS controller is presented and errors compared to optimal results are acceptable
[3]	1996 June	Optimal BESS and PV size that minimises total investment cost for WPP–PV hybrid system is found. Required level of reliability must be satisfied for islanded system. Authors used exhaustive search and simulation to find optimal values
[4]	1999 September	MPDP is used to determine possible fuel savings by solving UC problem for every day in a week. Next, cost–benefit analysis is performed on various combinations of battery power and energy ratings to determine the best solution
[5]	2005 November	IT suggests possible investment saving using ESS to defer investment in distribution network elements that are near to their technical limits. It avoids economical and focuses on technical analysis and suggests required ESS size based on load curve shape and loading growth rates compared with allowed loadings
[6]	2006 January	Size of hydrogen ESS is optimised simultaneously with WPP–diesel system size in order to find minimal investment and operational cost. Unsupplied energy is included as operational cost. LP solved on historical data is used as benchmark for rule-based simulation. Simulation parameters are predefined and combination with minimum cost is searched
[7]	2006 September	ES is used to find optimal combination of WPP–PV system and BESS. Search limits are obtained based on measurement data analysis. WPP is calculated from average daily demand and then PV and battery size limits are found subtracting total demand and wind production and then PV generation. Optimal combination can be chosen based only on minimal cost or on minimal cost with required reliability parameters
[8]	2007 August	Battery control algorithm for primary frequency control is created in accordance to UCTE requirements. Revenue is fixed (auxiliary service market) and exhaustive search is performed on battery State of Charge range and charge/discharge power ratings to minimise battery size and consequently its price. Additional 'charging' energy for primary control can be obtained by emergency resistors
[9]	2008 May	Pumped hydro storage is investigated as improvement for island dynamic security. Optimal size and generation/pumping power are determined using LP UC extended with frequency control based on installed generators and system characteristics
[10]	2008 July	It studies the impact of ESS on WPP revenues from avoided energy curtailment and firm generation. Analytical approach with predefined costs and operational mode is conducted on various WPP sizes and optimal energy and power ratings are determined
[11]	2008 September	Battery storage is part of DC power buffer in permanent magnet synchronous generator wind turbine. Energy and power ratings are determined analytically from difference between constant power output and predefined wind generation. Battery size is optimised by exhaustive search to find WPP constant power output that will have the best revenue/investment ratio
[12]	2009 February	Two-stage stochastic LP is used to analyse the impact of ESS on electricity prices for island with WPP–diesel generation. Analysis is made for different diesel generator operation modes, including possible shut down, and sensitivity analysis is conducted
[13]	2009 June	It presents possible benefits for peak shaving with BESS in distribution feeder. BESS is following load, while scenarios are presented with and without predefined penetration of PV. ESS installation and operation costs are not elaborated
[14]	2009 July	Statistical response surface methodology (Box–Behnken design) is used to represent the cost function of wind–solar hybrid system with battery storage and to obtain variable impacts on optimal solution. This methodology replaced exhaustive search with a model that needs 15 experiments to obtain the optimal solution
[15]	2009 December	It presents ESS that consists of two identical batteries. One battery is charged by WPP and the other is discharged in the grid. When the other battery is empty, they change places. It investigates electro-chemical characteristics of batteries and determines their power based on some predefined values from wind statistical distribution. Battery energy rating is analytically determined on battery' s cell ability to deliver this power. Network impact and related costs are not presented
[16]	2010 January	It develops an analytical model to analyse PV-ESS systems cost with different storage technologies. Modelled PV–ESS system must supply islanded load for a predefined number of hours. Analytical model is based on monthly solar irradiation data and load profile curve. PV power is determined from maximum loading. ESS technology, power and capacity are then analysed for the set of discrete values
[17]	2010 May	It presents an analytical methodology to determine backup supply energy storage rating from primary power supply outage duration probability function and desired reliability target. Storage power rating is determined by protected load power. Modelled system is used only for backup
[18]	2010 September	It uses GA to search for optimal installation place of a predefined number of BESS, WPP and capacitors. SQP is then used to dispatch these devices. The objective function is the minimisation of investment and reactive power costs. Existence of reactive power market is assumed
[19]	2010 November	MILP OPF is used to determine allowable generation from renewable sources under network constraints. Similar OPF is then used to determine the size and location of ESS to prevent generation curtailment and minimize electricity cost.
[20]	2011 January	WPP with ESS is simulated for different storage control strategies. It presents simple, fuzzy, simple ANN and improved ANN controller. Control goal is to keep forecast error under 4% for more than 90% of time. ESS energy and power ratings are found using exhaustive search for every type of controller
[21]	2011 April	It presents a design scheme for WPP with BESS that enables WPP to participate on the market. Power and energy ratings are determined to maintain full charge-discharge cycle. Ratio between battery life time and investment is maximized.
[22]	2011 July	In a network with known UC solution, ESS and controllable generation are dispatched by Newton's method to mitigate system violations. Randomly created set of DG power outputs is used to determine optimal ESS location and size to minimise generation cost and system violations. The number of locations is heuristically reduced from all nodes to only a few. Storage size is determined from operation simulations
[23]	2011 August	SP is used to solve DC OPF for various networks. System operational cost and storage investment costs are minimised. There are cases with and without predefined storage locations
[24]	2011 August	AM is used to determine storage power and energy to compensate errors in wind forecasting. Power and energy are determined analytically from forecast error distribution and allowed level of unserved energy
[25]	2011 October	Modified GA with matrix presentation of UC is used to determine optimal dispatch in Microgrid. NPV analysis is conducted in order to determine optimal power and energy ratings for two types of BESS
[26]	2012 January	Power imbalance caused by generation, load and DG forecast error in observed area is transformed with discrete Fourier transformation in four independent cyclic signals (intraweek, intraday, intrahour and real time). Theoretical maximum ESS size required to eliminate this imbalance is determined. Size of ESS to eliminate only intrahour and real time error is significantly smaller (43.6% less power rating and 93.6% lower capacity) than complete imbalance elimination
[27]	2012 March	Storage power ratings and capacity are determined by multiple UC MILP calculations for different storage sizes (in steps) for islanded and grid connected Microgrid.
[28]	2012 May	Analytical model based on statistical analysis of load and wind data coupled with real system parameters is created for CAES capacity and power ratings optimisation. CAES power ratings are limited by system constraints (up and down power ramping), desired level of power shortage elimination and technological constraints. Analytical optimisation is conducted on real system data and benefits from load shifting and wind curtailment are evaluated
[29]	2012 November	Monte Carlo Simulation is used to simulate various conditions in the network. Objective function is a minimisation of load curtailment and LP is used to check solution feasibility. The optimal solution is then used to create reliability data. Storage power and capacity are determined as in [17]

Continued

Table 2 Continued

Reference	Published	Contribution
[30]	2013 April	GA with probabilistic OPF in fitness function is used to find optimal size and location of ESS for system with WPP. The algorithm maximises wind power utilisation. ESS buys otherwise curtailed energy from WPP by bilateral agreement and sells this energy on market when the prices are higher. For low level of wind penetration (under 45%) this business model alone is not profitable
[31]	2013 April	It uses modified PSO with local search to find expansion strategy with minimal investment, operational and reliability cost. It investigates DG and ESS benefits on peak shaving and network reliability. Every expansion phase is divided in two parts. First, only main feeders are found and then DG, ESS and backup feeders are optimised. OPF algorithm is replaced by DG and ESS operational strategies based on DG/load ratio and outage conditions
[32]	2013 December	Optimal BESS size is found by PSO algorithm with rule based simulation of storage control. Monte Carlo simulation of load levels and electricity rates is used for sensitivity analysis. DG and BESS investment cost are integrated in levelised cost over its lifetime
[33]	2014 January	ESS is used in Hungarian power system as flexible balancing unit that helps minimise WPP scheduling errors and other ramping events. Two methods are used. The first method uses statistical tools to calculate ESS size from the number of power correction occurrences and its sizes, while the second approach uses the same dataset but with rule based simulation. In the simulation, the user must predefine ESS size and rated power. Optimal size is found by exhaustive search in predefined range
[34]	2014 January	It optimises DSO market strategy for one distribution area with DG and ESS. Regulated and Local Marginal Price market are observed. Instead of using BESS on dedicated DG, it is used to track the forecasted demand curve for the whole distribution area, which leads to smaller (cheaper) solutions. PSO with fuzzy improvements for adaptive parameter control is used to solve size and location of ESS while simulation with constraint from PSO is used to calculate operational costs
[35]	2014 January	BESS is used for primary frequency control. Since of its speed, it is modelled to 'catch' frequency power change in Microgrid and the rest of generation then replaces it after some time. In this work, the main problem is BESS power rating. Battery overload is allowed in limited time to prevent damage. BESS power rating is found with exhaustive search using simulation and frequency stabilisation as stop criteria. BESS capacity is not determined
[36]	2014 February	BESS is placed in distribution network to minimise power losses in feeders. Initially, a fixed number of fixed size BESS is placed in the network, one by one, using greedy search and simple power flow calculation. Then, ABC is used on the same problem. Finally, BESS location with minimal losses is found for a predefined number of DG and BESS within available power rating range. All calculations are conducted for only one network time snapshot
[37]	2014 February	Impact on ESS sizing on different error probability distribution function for wind forecast error is presented. ESS power and capacity is found using exhaustive search with Monte Carlo simulation
[38]	2014 March	Improved Bat Algorithm is used to optimise microgrid operation with BESS. Objective includes microgrid generation and operation cost and BESS investment. BESS power and capacity are optimised together with DG output. The algorithm shows good convergence compared to other know HAs
[39]	2014 March	LP is used to find optimal BESS power rating to avoid voltage violations in the feeder. The concept is to use BESS as a flexible load that is activated after some PV generation power level is reached. This power level is optimized. BESS capacity is determined from the simulation
[40]	2014 March	It presents possible revenues that independent BESS can obtain on day ahead (DA) and hourly reserve (HR) market in a network with wind penetration. BESS size and location are separately analysed in stochastic framework that operates with stochastic parameters (prices on DA and HR market and BESS reserve) to solve MILP stochastic UC problem
[41]	2014 March	The whole system investment, expansion and operational cost are minimised using MILP. ESS is analysed as bulk or dispersed installation in the network. The goal is to find optimal ESS size for future UK system with significant amount of wind penetration. Various simulations are conducted to evaluate ESS against flexible generation, demand side management and network expansion
[42]	2014 September	Fixed number of BESS is placed in distribution network and optimally dispatched together with dispatchable DG units to minimise investment, maintenance and operational cost. Non-linear parts of operational cost are approximated with convex formulation and the whole OPF is translated into MISOCP formulation

postponing high grid investments. Also in the case of battery swapping stations (BSS), BESS will gain additional spatial and temporal role as charging will highly depend on the BSS where the service is procured as well as the size of each BSS.

To answer these questions a comprehensive modelling framework is needed, taking into account technologies, investment costs and different services for multiple stakeholders as well as planning horizons for optimal integration of the ESS into the distribution grid depending on uncertainties in deploying a specific technology. Such a framework needs to be able to answer the above-mentioned questions and give clear pathways for integration of ESS into the low carbon distribution grids.

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