REVIEW OF OPTIMIZATION ALGORITHMS FOR SIZING ENERGY STORAGE SYSTEMS IN MICROGRID APPLICATIONS

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Abstract: Global warming is caused by fossil fuel carbon emissions. Climate change and global warming are among the most difficult concerns requiring rapid solutions. Renewable energy-based microgrids (MGs) can reduce electricity's carbon intensity and help meet the 2030 global decarburization objective. Optimizing the energy storage system (ESS) size can make the MG sustainable, durable, and economical. Hence, the optimal ESS must have strategies and algorithms for ESS sizing, power quality, dependability, connection mode, and low-carbon emission policy enforcement. The cost-effective optimal size strategy based on capacity minimization ignores other difficulties in the literature. To solve their deficiencies, this study examines ideal ESS sizing methods and algorithms, their properties, and MG applications including ESS and decarburization. Analyze ESS storage type, energy density, efficiency, benefits, and drawbacks. This paper discusses ESS sizing to optimize storage capacity, reduce consumption, minimize storage cost, establish ideal placement, and prevent carbon emissions for decarburization. Decarburization and ESS utilization in MG scenarios are thoroughly analyzed. ESS sizing for next-generation MG development research gaps, difficulties, and concerns are also emphasized. This review will help researchers and industrialists create an appropriately sized ESS for future MGs to help decarbonizes.

Keywords: Renewable energy, Hybrid Microgrid, Battery Energy Storage, Particle Swarm Optimization.

I. Intoduction

Analysts say decarburization, digitalization, and decentralisation will drive global prosperity. These drivers cause stakeholder conflict in all sectors. The last two create communicative energy business models. Digitalization involves using digital technologies to change a business model and generate cost-effective revenue and value. Distributed generators connected to low- and medium-voltage grids create and control electric power near to load demands. Electricity decarbonization reduces carbon intensity [1]. Low-carbon energy generation and energy storage increase the usage of renewable energy sources (RESs) and decarbonization. Low-carbon electricity supplies must address energy, environmental sustainability, and economic effectiveness (3 E) to reduce CO_2 emissions [2].

GHG emission reduction has been studied extensively. In 2050, GDP energy intensity will drop 64% from 2010 levels, and power carbon emissions would drop to almost nil. Current electrical sector GHG reduction studies [3] reflect shifting policy conditions. Since 1990, global electricity and industrial emissions have climbed 2.3% year [4].

Technical strategy affects PV and solar thermal impact. Onshore wind balances massive renewable electricity needs. Ref. [9] presents a generic model including solar photovoltaic (PV), wind turbine (WT), microturbines, electric boiler, gas-fired boiler, and lead-acid battery bank. To minimise cost, a 20-year optimal design incorporates emission taxation, emission reduction, and minimum system autonomy. Wind and solar power trends in Fig. 2 are noteworthy. Fig. 3 shows relative emission trends for increasing MG power contribution. Renewables reduce emissions. To achieve sustainability, 100% renewables will substantially reduce emissions.

BESSs can be pooled or disseminated [10]. Energy storage allows extra energy to be stored and used when needed [11,12]. To run MG sustainably, resiliently, and economically, optimise the storage system size [13]. Size determines BESS investment cost, including energy and power rating, capital, annual maintenance, and installation. Oversized BESSs are uneconomical, whereas smaller ones may not benefit. Fig. 4 shows how BESS size affects MG expansion planning cost [14]. An increase in size linearly increases RES investment cost but nonlinearly reduces operating cost. The ideal position is where these two expenses are lowest. Ref. [15] examines compressed air storage (CAES), pumped hydro (PHS), lead acid (PbA), sodium sulphur (NaS), lithium-ion (Li-ion), and vanadium redox flow (VRB) BESS topologies. The lowest renewable possibilities combined with batteries are affected by storage cost uncertainty [16]. Hence, appropriate ESS sizing is a surefire way to increase MG performance and reduce carbon emissions for sustainable development [17].

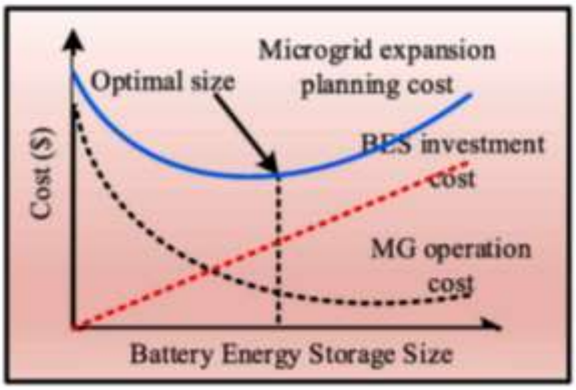

Figure 1 MG expansion planning cost versus BESS size

Decarbonization-optimal sizing research is scarce. Ref. [2] states that electrical energy storage is closely connected with decarbonization. Ref. [3] described how photovoltaics might halve EU GHG emissions by 2030 and make Europe the first climate-neutral continent by 2050. PHS and CAES are urged to use battery storage because of their low environmental effect [3]. Refs. [4] provide policymaker recommendations for decarbonization. [5,6] detailed China's decarbonization future in power, transport, heat, and industry. Ref. [7] shows a two-level energy modelling approach with electrical storage for cost-effective decarbonization. The European roadmap 2050 uses general algebraic modelling to suggest lithium-ion storage for decarbonization [8]. None of these articles considered appropriate energy storage sizing for the current system. Ref. [9] shows the ideal storage size, but this research ignores decarbonization policies. In Ref. [10], 60% emission reduction in Canada by 2050 was shown using TIMES optimization model with just PHS storage. Ref. [11] proposes a similar emission reduction model for Japan. In Ref. [12], fuel cell, combined heat and power storage-based optimal economic emission model was shown. This article solely analyses multi-objective optimization model. Additional researches to decarbonize the electric power system include two-stage stochastic model [13] with thermal storage system, iterative approach with PHS [14], capacity expansion model with PHS [15], integrated assessment modelling with bulk energy storage, CAES, and PHS [16]. None of these publications have covered the literature on energy storage optimal sizing and decarbonization.

This work creates decarbonization architecture and a framework (Fig. 5) for optimal battery sizing with lower emission for MG environment application. This study first discussed storage sizing methods and decarbonization problems and regulations based on the literature. Therefore, detail literature about optimal sizing algorithm of energy storage with their benefits and drawbacks, present status and future aspects of decarbonization scenario, relationship between optimal sizing and decarbonization, issues and challenges to decarbonization have been extensively discussed. RES integration reduces CO2 and GHG emissions [32]. ESS controls intermittent RESs and fluctuating load. Optimize ESS numbers and capacity.Researchers, technology providers, and industries can use this study to create a greener environment by introducing the optimal-sized battery, which will provide a cost-effective, dependable, and secure power transmission and distribution network. This work's key contributions are:

- This paper reviews the decarbonization scenario, policies, and current trends of several countries and creates a full emission reduction framework.
- This research depicts MG problems, ESS characteristics and selection, and their environmental impact; critically describes ESS sizing and optimization; and highlights recent techniques and their success, advantages, and downsides. It also covers many studies by

different researchers on the simulation software, algorithm, and ideal sizing circumstances, as well as their limitations and scope, appropriateness, modelling, and analysis of their application types.

- This paper discusses optimal sizing and decarbonization, examines current research and their weaknesses for low-carbon effects with ESS sizing, and recommends criteria for future development based on recent literature.
- This paper critically explores the problems and main constraints to appropriate ESS sizing and its contributions to safe, dependable, stable, and cost-effective power for consumers.

II. ESS attributes and relationships with MG

Mechanical, electrochemical, electrical (supercapacitor and super magnetic energy storage), chemical (hydrogen), and thermal technologies are the five basic categories of ESS (sensible and latent heat storage). Using SWOT analysis, ESS installation depends on capacity, life expectancy, response time, energy density, cost, and efficiency. The limitations of the various ESS methods depend on the materials and power electronic interface. ESS materials and their recycling can release damaging greenhouse gases (GHGs) such as CO, CO2, NOx, SOx, CH4, and N2O. For example, nickel-metal hydride (NiMH) is hazardous and recyclable to a limited extent.

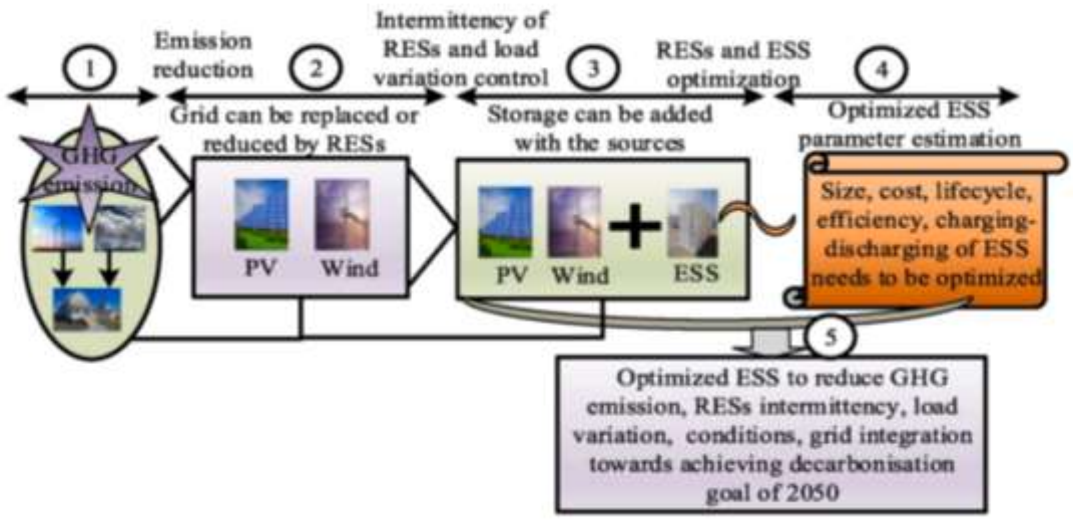

Figure 2 Comprehensive structure for achieving decarbonization and appropriate ESS sizing

Storage technologies also have similar environmental impacts. GHG emissions per kilogramme of battery are somewhat higher than CO2. Inhaled, swallowed, or injected GHG emissions above thresholds are harmful to human health. Many scientists and corporations find ESS emission reduction difficult. Electrical sectors worldwide use current battery storage systems. ESS is aggregated or distributed. The aggregated mode maintains a consistent power flow from distributed sources to the common coupling point, while the distributed mode directly couples the ESS to specific distributed sources.

Because it can manage surplus generation and has energy arbitrage, peak shaving, load following, voltage support, frequency regulation, spinning reserve, capacity firming, and time-shifting, an ESS with MG increases power system efficiency [10]. Energy arbitrage is less suitable for storage systems with high power but low energy. Frequency regulation requires less energy than power capacity. Hence, selecting and maintaining an ESS with MG is crucial for reducing power system network anomalies and improving reliability and quality. Mechanical storage systems like pumped-hydro and flywheel are mature due to their flexible storage operation and high power quality, transient stability, peak shaving, and uninterrupted power supply. CAES is used for high-power, long-term peak-hour load levelling, but it is sluggish and has a big environmental impact. Lead-acid batteries are best for load levelling, grid stabilisation, spinning reserve, and frequency adjustment. It has limited discharge depth and duration, significant maintenance costs, and low dependability. Long-term chemical storage uses inefficient storage. Electrochemical storage solutions, including battery storage technologies, benefit high-capacity and scattered systems. Because to their high capacity, power quality, and peak load levelling, flow batteries are excellent for time-shifting.

At high temperatures, sodium-sulfur batteries level load and deliver electricity. Li-ion batteries are popular due to their power quality, frequency management, and capacity. SMES has high specific power, and the supercapacitor has high power density and quality power. Both are fast-reacting power quality and frequency management tools. Supercapacitor regulation remains tricky. Large ESSs lower earnings and have little economic value. ESS may not supply enough power to load, making it ineffective for users. Consumers can get good power quality, peak shaving, spinning reserve, capacity firming, and frequency management from proper ESS sizing with MG.

ESS-MG technology development faces legal and regulatory uncertainties, interconnection policy, utility regulation, and utility opposition. Interconnection policy considers DERs in terms of grid failure, while legal and regulatory uncertainty controls potential costs and benefits. If MG cannot connect to the main grid, it should be run in islanded mode. Utility regulation refers to municipal approval, while utility opposition discusses About self-consumption, reluctance to add DERs to the grid, and management, safety, and protection issues. This MG technology relies more on the competitive smart grid paradigm and recent market structure for decarbonization [56]. So, MG development with ESS depends on the degree of legal and regulatory ambiguity implementation and the economic advantage to owners and users, including power quality, environmental effect, and reliability difficulties.

III. ESS optimum sizing algorithms

Several researchers calculate BESS size and location using various approaches [71–73]. Single-objective and multi-objective optimal sizing approaches are studied. Multi-objective evolutionary algorithms can maximise power system reliability and minimise cost, while single-objective optimal approaches minimise cost. Ref. [74] uses system upgrading and wind generating losses to predict BESS size and placement. Ref. [75] examines how network reconfiguration and fault currents affect BESS size and location. In Ref. [76], a bi-level programming-based model minimises the cost function to find ideal BESS placements and sizes. Ref. [77] proposes a detailed economic study to size the integrated PV unit and storage based on solar irradiation, electric load estimation, and component ratings. [78,79] show zinc bromine flow battery storage system optimal sizing and control. A dynamic programming (DP) methodology is presented to tackle the day-ahead unit commitment problem for the MG [81] and optimal VRB battery sizing [80]. The appropriate grid-connected and freestanding ESS size is determined by typical demand and renewable profiles. MOC and day-ahead scheduling optimise battery capacity in Ref. [82]. In solo mode, the ideal ESS lowers MG operation costs by 3.2%. Grid-connected mode costs 14.1% less.

3.1.1. Filter-based optimal sizing

For appropriate storage sizing and to overcome the restrictions, a WSB-HPS with high power supply reliability in islanded mode is introduced. M.A. Hannan et al. introduced to optimise grid-connected fluctuation control. Fig. 3 shows how the energy filter optimises BESS capacity. Energy filters remove low- and high-frequency components from grid-injected power. The battery can handle high fluctuations.

Fig. 3 depicts the model's programme flow chart. The figure shows that annual weather and load data determine total power. Connecting storage to the network system accounts for power supply fluctuation and loss. These issues determine PV, WT, and battery costs and combinations. The best storage size may end due to combination expense.

3.1.2. DFT-based ESS optimal sizing

DFT-based optimal sizing uses the 3-step technique to control RE fluctuation. The 3-D concept reduces grid fluctuation. Daily scheduling independence does not guarantee average daily grid injection. In this approach, the filter separates low and high frequencies (Table 3).

This method shows that renewable PM and F influence storage size. Optimizing F storage is expensive. This study determines the optimal F via derivative-free mode-pursuing sampling. For randomly selected days, PM segment sizing requirements are computed. A storage device's throughput () during the nth day at a certain period t is kh h.

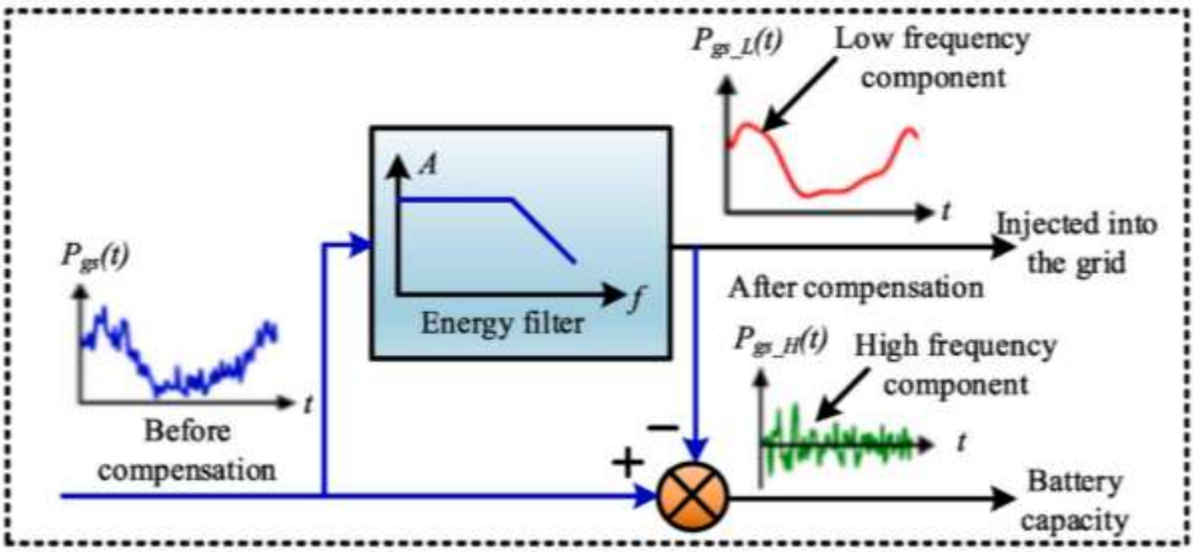

Figure 3 Optimizing the battery capacity using an energy filter

3.1.3. ESS optimal sizing simulation.

Researchers have examined optimal sizing simulation programmes. Hybrid optimization model for electric renewables developed by the National Renewable Energy Laboratory, Improved Hybrid Optimization by Genetic Algorithms (GA), HYBRID2, HYBRIDS (Solaris Homes), Improved Grid-connected Renewable Hybrid System Optimization (Spain), Transient Energy System Simulation Program. These applications restrict component selection, sophisticated mathematical computations, optimization, and control options, making them outdated. Hence, efficient storage sizing requires an advanced programming approach. The next topic shows optimal sizing algorithm literature.

Ref. [17] uses a hybrid Tabu search/particle swarm optimization method to decrease wind power generation costs by locating and sizing BESSs. The grey wolf optimization algorithm addresses similar concerns in Ref. [18]. This research ignores the maximising of life cycles, which can dramatically raise battery replacement costs.

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To address these concerns, Refs. [19] suggested a model that considered battery replacement costs annually. This study solves single-objective optimization. In Refs. [19], battery size is determined by operating temperature, depth-of-discharge (DOD), and charging/discharging currents. The optimization method and voltage regulation algorithm are integrated to control distribution system voltage fluctuation and size the BESS optimally.

Figure 4 Program flow chart of the proposed optimal sizing method

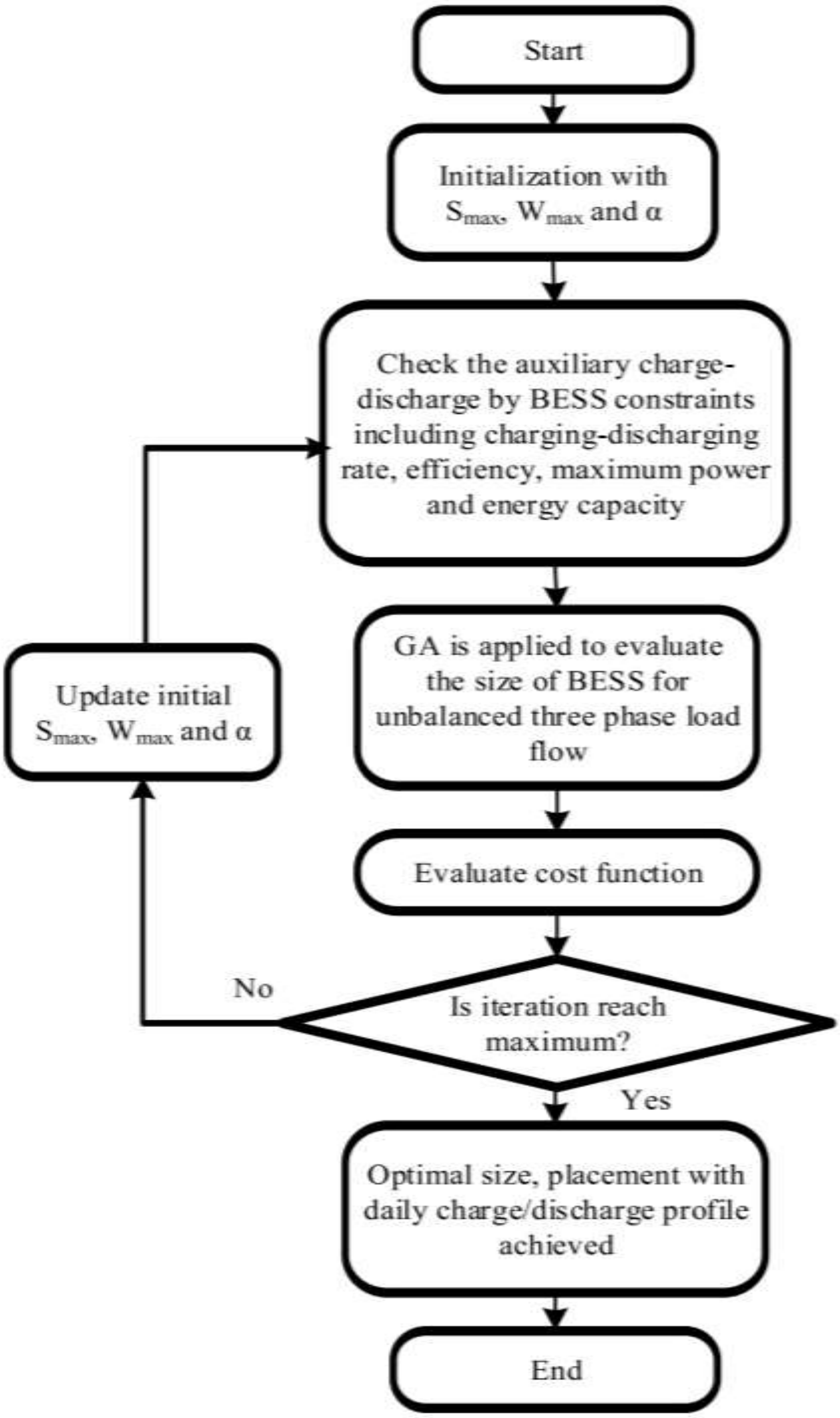

Figure 5 Flow chart for optimal sizing using GA

Many researchers suggested ESS sizing algorithms. Genetic algorithm, particle swarm optimization, dynamic programming model, mixed integer linear programming, optimal power flow mechanism, and grey wolf optimization are commonly utilized for optimal ESS sizing. Studies divide optimization methods into probabilistic, analytical, artificial intelligence, and hybrid categories. Probabilistic optimization approaches are useful for limited historical data and changeable uncertainty parameters. Chance-constrained, stochastic, and robust optimization-based methods are examples. This technique's main drawback is that the enormous number of generated scenarios increases computational complexity. Analytical or deterministic optimization methods calculate system benchmarks. This method degrades computational performance when considering numerous objectives. Artificial intelligence, a sophisticated analytical method, refines the searching space after each iteration for quick performance.

Figure 6 Flow chart for Proposed HOM for optimal sizing of ESS

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IV Decarburization and ESS sizing issues

Storage size and placement depend on its purpose and projected operational strategy. Lowering battery storage investment costs alone is inefficient. Efficiency depends on energy storage size, placement, and number. Renewable energy integration reduces grid energy pressure and reduces CO2 emissions. Nevertheless, RESs are unpredictable, making ESS-grid operational strategies difficult. No decarbonized optimal storage sizing option exists. The literature's main problems are listed below.

- Emission reduction policy

Authorities must act quickly to ensure suppliers and consumers follow the agreed criteria. This encourages the grid-to-renewable power supply shift. Grouping countries by CO2 mitigation strategy allows comparison. Increased emission tax and economic incentives for low-carbon technologies can cut CO2 emissions by 5%–10% [9]. Motivating individuals to adopt renewable sources improves decarbonization. By integrating public policy and environmental scenarios, a novel model can optimise storage size and considerably reduce CO2 emissions.

- Storage choice

Li-ion, PHS, CAES, liquid air, flywheel, NaS, lead acid, Ni–Cd, VRB, and supercapacitor are sustainable and techno-economic battery technologies. Ref. [1] illustrates a multi-criteria decision-making strategy that incorporates ESS structure, technology, economy, social impact, and environmental considerations. Power quality and frequency regulation applications fit high-power density, fast-response ESS. Long-term applications like peak shaving and energy arbitrage benefit from storage with high energy density and lengthy discharge time. Due to limited shelf and usage lives, battery materials can produce a lot of hazardous waste, GHG emissions, and poisonous gases [3]. Because ESS performance and cost are hard to balance, selecting storage (single or hybrid) for an application is crucial. Storage selection should emphasise ESS topics including material selection to limit emission, metal recovery, recyclability, technologies, capacities, and application purpose. Selecting the right storage type is the first step to finding an efficient, low-emission ESS.

- Cost-benefit evaluation

Renewable sources are costly [177]. Cost/benefit analysis parameters including future α, ESS lifetime, operation, and maintenance cost are hard to estimate [178]. Oversize, installation, investment, maintenance, and operating expenditures may increase ESS costs. Undersized ESS may reduce electricity demand poorly. Overrated ESS controls frequency cycling and peak power loading stress. This method is costly. Global integrated assessment models can calculate the ideal economic efficiency solution and tackle these challenges. Such models lack national policy and context. Cost/benefit analysis addressing the stochastic unit commitment problem with integrated spinning reserve, generation forecasts, and load uncertainty helps optimise storage size. This will lower storage costs and reduce emissions.

- Discharge depth

Calendared and cyclic ageing produce BES degradation, which strongly impacts the system's economic assessment. Even unused BES cells are harmed by calendared ageing. BESS consumption, DOD, and cycle number greatly affect cyclic ageing.

- Connection mode

The large-capacity BESS is aggregated. The distributed mode installs the tiny BESS. Distributed BESS gives the MG the redundancy and flexibility to respond to electricity prices and ensures load/generation profiles, battery life expectancy, efficiency, and safety. Storage capacity increases BESS control difficulty. So, the best operation method should reduce storage size and expense.

- Charge/discharge optimally

Sizing depends on storage selection and proper charging–discharging [13]. Optimizing storage size requires fast charging, slow discharging, efficiency, and extended lifetime. Several studies have offered ways, however managing storage charging and discharging remains a challenge. Load variation, frequency regulation, and voltage regulation strongly affect storage when grid-connected or islanded [4, 10]. Current management and regulatory systems cannot handle high ESS-based renewable generation (>50%) [14]. Considering bulk and small capacity storage and the factors above, an optimum sizing approach can be designed for efficient charging–discharging in islanded and grid-connected modes.

- Peak-load shaving

The ESS helps time shift energy output, which is beneficial because power cost relies on usage [7]. Off-peak pricing is lower than peak pricing. Shifting peak loads to off-peak hours can reduce the difference. Reduce storage and electricity costs. Peak load shaving researchers use feedback-based control system, MILP, hybrid tabu-search, OPF, and day-ahead scheduling. These analyses ignore electricity tariff changes, forecasting mistakes, and outage mitigation at different times. To reduce storage space and peak load shaving, a sophisticated optimization approach might be used.

- Power dependability, quality, and voltage control

Frequency and voltage can lower power quality in fast-generation power output. Ramping allows ESS to balance power fluctuation by quick charging and gradual discharge. End users need efficient power and energy delivery to improve power dependability.

- MG management technology

MG sources connected with ESS through power electronic interfaces like DC/AC and DC/AC/DC are crucial to ESS technology development due to their robustness and dependability. Energy security, economic gain, and renewable energy integration are Key development trends. Ref. [17] illustrates the importance of DER modelling to solve uncertainties of DER input (availability of power, price, discount rate, and emission), equipment (technical characteristics, such as conversion efficiency and storage loss, and investment costs), and output (energy demand) for optimal storage sizing. Solar applications use typical meteorological years to forecast weather [18]. Wind applications can use non-parametric and empirical distribution estimation [19]. Inverter control, energy trading, power routing, voltage regulation, and load forecasting are technical management considerations [20]. Generation forecast error attributes and power electronic interfacing can help the MG management system achieve optimal ESS sizing.

- MG RES integration uncertainties

Due to climate variability, renewable energies like solar and wind are unpredictable. Renewable source penetration can affect MG operations including remote sensing, data transport, data handling, decision-making, and system control. Hence, optimal operational and financial decisions during MG applications require thorough modelling and analytical management of these uncertainties by considering geographical situation.

- Uncertainties in ESS sizing algorithms

Uncertainty management limits source use according to constraints and budget to achieve sustained optimal ESS sizing solutions. Wind generation uncertainty smoothes the load curve, reduces energy capacity, and enhances longevity [17]. Iterative optimum technique with PV power uncertainty maximises net present value and voltage profiles [18]. Weather conditions in optimal power flow algorithm speed convergence to optimal solution [20]. Hybrid tabu search/particle swarm optimization reduces system computing cost by using solar irradiance and load demand uncertainties. Stochastic mixed integer optimization minimises solar power system average cost. Genetic algorithm with linear programming model energy price arbitrage uncertainty considerably minimises PV daily power production energy losses [20]. Cuckoo Search method provides the lowest-cost solution compared to GA and PSO by considering component and operation and maintenance costs [21].

V. CONCLUSION

MGs with ESS are potential technology for sustainable development with lower GHG emissions. Several studies work on MG technology's control, stability, reliability, cost, and GHG emissions. To maintain power balance, affordability, and reliability, ESS controlling mechanisms must match the MG. Many research have suggested appropriate storage sizing to lower costs. ESS sizing neglects several concerns. A thorough assessment found that intermittency and types of RESs, manner of connection with the ESS and grid, voltage and frequency control, power quality, peak load shaving, optimal charging–discharging of ESS, and public policy are important obstacles to achieving the goal. Several considerations must be considered when developing the best methodology for ESS sizing. Because decarbonization is a global concern for lowering GHG emissions and providing a safe environment, the algorithm must evaluate the influence of optimal ESS sizing on decarbonization.

Based on the studied literature, this study examines ESS features, applied architecture of optimal techniques and algorithm for optimal ESS sizing, decarbonization concerns with the DDPP goal, optimal ESS sizing, and decarbonization. It exposes the technology's limitations to maximise performance. This research analyses the ideal ESS technology sizing and decarbonization scenarios to provide a complete picture of the deployment of an advanced algorithm. This research suggests crucial and selected technology developments for ESS scaling and decarbonization in MG applications.

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