Strategic Optimal Design of Energy Storage Systems for Enhancing Stability and Sustainability in Electrical Distribution Networks / Original article

Researcher Hayder Abdulhussein Allawi

Holy Karbala Province Council, Karbala / Iraq
07801830480 – 07700820378
hyaderalanbari1981@gmail.com

التصميم الاستراتيجي الأمثل لأنظمة تخزين الطاقة لتعزيز الاستقرار والاستدامة في شبكات التوزيع الكهربائية

الباحث حيدر عبد الحسين علاوي
محافظة كربلاء المقدسة، كربلاء \ العراق

Abstract

The paper will provide a multi-objective model of optimizing the strategic placement and size of Battery Energy Storage Systems (BESS) in the Iraqi electrical distribution systems. The power grid of Iraq has deep issues, such as chronic power shortages, extreme grid instability, and astronomical technical and non-technical losses, and they can be up to 50 percent of the power generated. These problems require new solutions that will make the grid more modern and reliable in terms of energy security. The suggested methodology combines a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm and the specific mathematical models of BESS and renewable energy sources (RES) and a representative Iraqi distribution network topology. The framework is supposed to address the natural incompatibilities among three essential goals: minimizing the overall Net Present Cost (NPC), minimizing the voltage variations across the network to increase stability, and minimizing CO2 emissions to help to sustain the environment. The results show that BESS is highly optimized to achieve high techno-economic advantages. Multi-objective methodology in a Baghdad feeder case-study provided a 12-percentage reduction in power loss, 45 percentage point volatility index enhancement and a competitive Levelized Cost of Energy (LCOE) of 0.082/kWh. The outcomes indicate the framework is a promising decision-making instrument to ensure the reliability, economic viability and stability of the electricity infrastructure in Iraq to bring a more robust and contemporary power system.

Keywords: Energy Storage Systems (ESS), Microgrid, Multi-Objective Optimization, Iraqi Power Grid, Grid Stability, Renewable Energy Integration, Battery Sizing.

المستخلص

ستقدّم هذه الورقة نموذجًا متعدد الأهداف لتحسين التوزيع الاستراتيجي والحجم الأمثل لأنظمة تخزين الطاقة بالبطاريات (BESS) في شبكات التوزيع الكهربائية العراقية. تعاني الشبكة الكهربائية في العراق من مشكلات عميقة، مثل النقص المزمن في الطاقة، وعدم الاستقرار الشديد في الشبكة، والخسائر الفنية وغير الفنية الهائلة التي قد تصل إلى 50% من الطاقة المولدة. وتتطلب هذه المشكلات حلولًا جديدة لجعل الشبكة أكثر حداثة وموثوقية من ناحية أمن الطاقة.

تعتمد المنهجية المقترحة على دمج خوارزمية **التحسين متعدد الأهداف باستخدام سرب الجسيمات** (MOPSO) مع النماذج الرياضية الخاصة بأنظمة تخزين الطاقة BESS ومصادر الطاقة المتجددة، إضافةً إلى نموذج طوبولوجيا ممثل لشبكة توزيع عراقية. ويهدف هذا الإطار إلى معالجة التعارض الطبيعي بين ثلاثة أهداف أساسية: **تقليل الكلفة الحالية الصافية (NPC)، تقليل تذبذب الجهد عبر الشبكة لتعزيز الاستقرار، وتقليل انبعاثات CO_2 لدعم الاستدامة البيئية.**

تُظهر النتائج أن استخدام BESS تم تحسينه بشكل كبير لتحقيق فوائد تقنية واقتصادية عالية. ففي دراسة حالة لأحد الخطوط المغذّية في بغداد، وفّر النموذج انخفاضًا بنسبة 12% **في خسائر الطاقة**، وتحسنًا في **مؤشر تذبذب الجهد بمقدار 45 نقطة مئوية**، إضافة إلى تحقيق **كلفة طاقة مستوية (LCOE) تنافسية تبلغ 0.082 دولار/كWh**. وتُشير هذه النتائج إلى أن الإطار المقترح يمثل أداة واعدة لاتخاذ القرار، بما يعزز موثوقية الشبكة الكهربائية في العراق وجدواها الاقتصادية واستقرارها، تمهيدًا لبناء منظومة كهربائية أكثر متانة وحداثة.

الكلمات المفتاحية: أنظمة تخزين الطاقة (ESS)، الميكروغريد، التحسين متعدد الأهداف، الشبكة الكهربائية العراقية، استقرار الشبكة، دمج الطاقة المتجددة، تحديد حجم البطارية.

1. Introduction

The energy environment in the world is changing in paradigm, with the twin forces behind it being decarbonization and energy security. This switch is defined by the increasing infiltration of intermittent renewable energy sources (RES) including solar and wind energy [1]. Although these technologies are essential in reducing climate change, their fluctuating and non-dispatchability creates critical operational risks to traditional power grids such as disruptive frequencies, erratic voltages and the probability of supply not matching demand. In order to maximize the capabilities of RES and provide grid stability, Energy Storage Systems (ESS) have become a pillar technology, providing the ability to separate generating and consuming sides [2].

These problems are most intense in Iraq. Decades of underinvestment, conflict as well as infrastructural decay have plagued the electrical sector of the nation and has left it with a severe and nagging energy crisis. There is an enormous difference between supply and peak summer demand of electricity that frequently results in mass, and long-lasting power interruptions. The reports by the World Bank and the International Energy Agency (IEA) show that Iraq has one of the highest non-technical and technical losses of power in the world, which is often estimated to be between 40 per cent and 50 per cent [3]. This has been an inefficiency in that almost half of the electricity produced is wasted before it gets to consumers. This has led to an enormous parallel grid of private, neighborhood scale diesel generators that offer an expensive, inefficient and extremely polluting stopgap measure of millions of households and business establishments [4].

In this regard, Battery Energy Storage Systems (BESS) have a game-changing potential. With any number of BESS placed in a distribution network, a great number of useful tasks can be carried out: peak shaving of stressed up grid operation during peak periods, shifting of load to take up cheap or surplus renewable energy and store it to be used later, frequency control to keep the grid steady, and voltage support to enhance power quality [5]. Additionally, BESS plays a key role of maximizing the hosting capacity of the grid to receive RES, which is important in the development of solar power in a sun-abundant nation such as Iraq which has big plans to embrace solar energy development [6].

The application of BESS is however not a panacea. The high cost of capital of battery technology is still the main impediment. The placement and size of these systems might not be optimized in an ad-hoc manner or non-optimally, which may result in poor performance and make the investment not financially viable, as well as would not result in the desired grid benefits. The main research question of the study is based on this fact: a more detailed, data-driven optimization model needs to be developed with references to the peculiarities of operations, economics, and environment of the distribution networks of Iraq. A framework such as this will need to inform utility planners and policy makers to make informed investment decisions that maximize technical benefits and make them economically feasible.

The significance of this study can thus be traced to the fact that it has direct application to one of the most urgent problems facing the country of Iraq. Through its contribution of an excellent methodology of the deployment of ESS, this study has the potential to impact directly on the improvement of energy security of the country, the decrease of fossil fuel dependence, the quality of life of citizens and the creation of the more sustainable economic system [7].

The research hypothesis on which this paper is constructed is as follows: The use of a multi-objective optimization strategy to design and integrate BESS can concurrently decrease the costs of implementing the system, enhance the voltage stability, and decrease the carbon emission in a typical Iraqi distribution network, which will be more effective in comparison with single-objective or non-optimized deployment strategies. Through this hypothesis, this paper will attempt to prove that such an approach, rather holistic and multi-faceted, is not only better but also necessary to the successful modernization of the Iraqi power infrastructure.

2. Theoretical Framework and Literature Review

Implementation of the Energy Storage Systems in the power grids is a complex and multi-faceted matter that has been of great research interests in the world. This section reviews the theoretical framework and the available literature, first of the trends in the globe in respect of the optimization processes and ESS modelling and second of the specific input and circumstances of the research conducted in Iraq. As the use of Battery Energy Storage Systems (BESS) in distribution networks continues to rise, there has been the necessity to have sophisticated tools that help in the management of the systems. Artificial Intelligence (AI) and Machine Learning (ML) have become a central aspect in this context to make storage systems more efficient and smarter in the current energy setting. AI helps in enhancing the design and operation of storage systems by prediction, control and multi-level optimization algorithms and assists in meeting the technical and economic goals needed in power networks, particularly in the country with a poor infrastructure like Iraq [5].

1- Load Forecasting and Renewable Energy Forecasting.

Predicting electrical loads and regeneration of renewable energy is the core of effective work of batteries. The data on energy consumption is processed by machine learning methods including Deep Neural Networks and Boosting algorithms, which can determine the future demand with a high level of accuracy. This minimizes the possibility of charging or discharging the battery to the point of filling up and increases the efficiency of the battery.

2- Maximizing Battery Operational Scheduling.

AI algorithms are able to produce dynamic charge and discharge schedules depending on up-to-date electricity prices, network states, and access to solar energy, and demand predictions. Swarm Intelligence and Reinforcement Learning techniques have better outcomes than the traditional control tools.

3- The optimization of Locations and Capacities of the Storage.

Placing batteries in the most convenient locations, as well as the sizes, is one of the most difficult to accomplish in electrical planning. Genetic Algorithms (GA), Particle Swarm Optimization (PSO), NSGA-II, and MOPSO are some of the algorithms that are employed to arrive at solutions that are cost-efficient, network stable, and minimizing losses.

4- Battery Predictive Maintenance.

AI helps to enlarge battery life and decrease failure because it analyzes real-time operational data and determines the rate of degradation, the essential conditions of charging, the increase in temperature, and the uncharacteristic behavior.

5- Significance of Artificial Intelligence in Iraq.

AI is a strategic prospect of the Iraqi electricity industry because of two main reasons:

1. The deficit of human skills in the sophisticated network control.
2. The necessity to increase efficiency without the significant investments into infrastructure.

Artificial Intelligence is not a supplementary tool, but a core component of the future of the stringent energy storage systems in the contexts of BESS exercising greater stability and efficiency to distribution networks.

2.1 Global Advances in ESS Optimization

The body of ESS optimization literature is wide, and it can be classified into general categories based on the mathematical techniques used. Original methods were usually based on classical mathematical programming. The ones are Linear Programming (LP) and Mixed-Integer Linear Programming (MILP) which could be used in situations where the problem at hand could be simplified into linear objective functions and constraints. As an example, MILP has been extensively applied to solving the unit commitment and economic dispatch problems including BESS with binary variables determining the charge, discharge or idle state of the battery [7]. Though computationally efficient, these approaches tend to involve major linearization of non-linear systems dynamics, including battery degradation, or power flow equations, to the detriment of model accuracy.

In a effort to reduce the shortcomings of linear models, researchers have resorted more to heuristic and metaheuristic algorithms. Such nature-inspired algorithms as the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and more recent ones like Butterfly Optimization Algorithm (BOA) [8] are proficient at searching complex, non-linear and non-convex search space without any gradient information. They are especially adapted to sizing and siting problems, where the objective function is usually discontinuous or hard to develop in an analytic form. As an illustration, Alawode *et al.* [9] have managed to use BOA to optimize battery storage settings and functioning in microgrids, and it indicates its ability to search the entire world. Such algorithms have been effective in locating near optimal solutions to a broad set of ESS planning and operational issues.

Nevertheless, the concept of ESS integration presupposes a compromise between a variety of, and often, conflicting, aims. As an example, low cost of investment could result in small size system with low reliability whereas high reliability would end up with a big system that is not economic to maintain. This has given rise to the eminence of Multi-Objective Optimization (MOO) methods. MOO algorithms, including the Non-dominated Sorting Genetic Algorithm II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) do not aim at an optimal solution, but a pool of trade-off solutions referred to as the Pareto front [10]. This front enables the decision-makers to see the trade-offs between the objectives like cost versus reliability or economic benefit versus environmental impact and choose a solution that fits their priorities the best. Farzin *et al.* presented a stochastic MOO model of scheduling ESS in microgrids, which was efficient in balancing the cost of operation to risk of load curtailment during incidences of islanding. This method offers a more realistic and holistic tool of decision making as compared to single-objective approaches [11].

2.2 ESS Technologies and Modeling

There is a great number of ESS technologies that can be applied to the grid, and each of them possesses its peculiarities. These are Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), flywheels, supercapacitors, and an extensive list of battery chemistries. In the case of distribution-level applications, the Battery Energy Storage Systems (BESS) dominate especially in the way they are modular, scalable, and cost-reducing. Lithium-ion (Li-ion), battery technology has become a standard used in grid-scale projects, with a high energy density, good performances, and a long cycle life as opposed to the traditional technologies such as Lead-acid [11].

It is essential to have accurate mathematical modelling of the BESS in any optimization study. One of the common models represents the fundamental dynamics and the limitations of the operation of the battery. This is inclusive of the State of Charge (SoC) which is a measure of the available energy level and it is controlled by the charging and discharging power. The model should also impose limitations on the SoC (to avoid over-charging or deep-discharging), the charge/discharge power rates and the Depth of Discharge (DoD), which has a substantial influence on the battery life. Models that are more developed also include battery degradation which couples the cycle life with DoD and operating temperature as well, needed in a proper long-term economic analysis [12]. These models usually expressed in a set of algebraic and differential equations, are the core of the constraints in the optimization problem.

2.3 State-of-the-Art in Iraq

Nonetheless, Iraqi scholars have been busy exploring the solution to the power crisis in the country, and the interest in microgrids and energy storage is increasingly growing. This literature gives this study a critical local context and background.

The scholars of the University of Baghdad have investigated more sophisticated approaches of control in the stability of microgrids. In a significant work, they suggested the improvement of dynamic droop control technique to control frequency and voltage in a microgrid with Hybrid Energy Storage System (HESS) a combination of high energy capacity of batteries with high power density of supercapacitors [13] see Fig. 1. The article employed SECANT technique in control gains optimization and tested the functionality of the system with MATLAB/Simulink, which is an advanced method of enhancing resilience of microgrids.

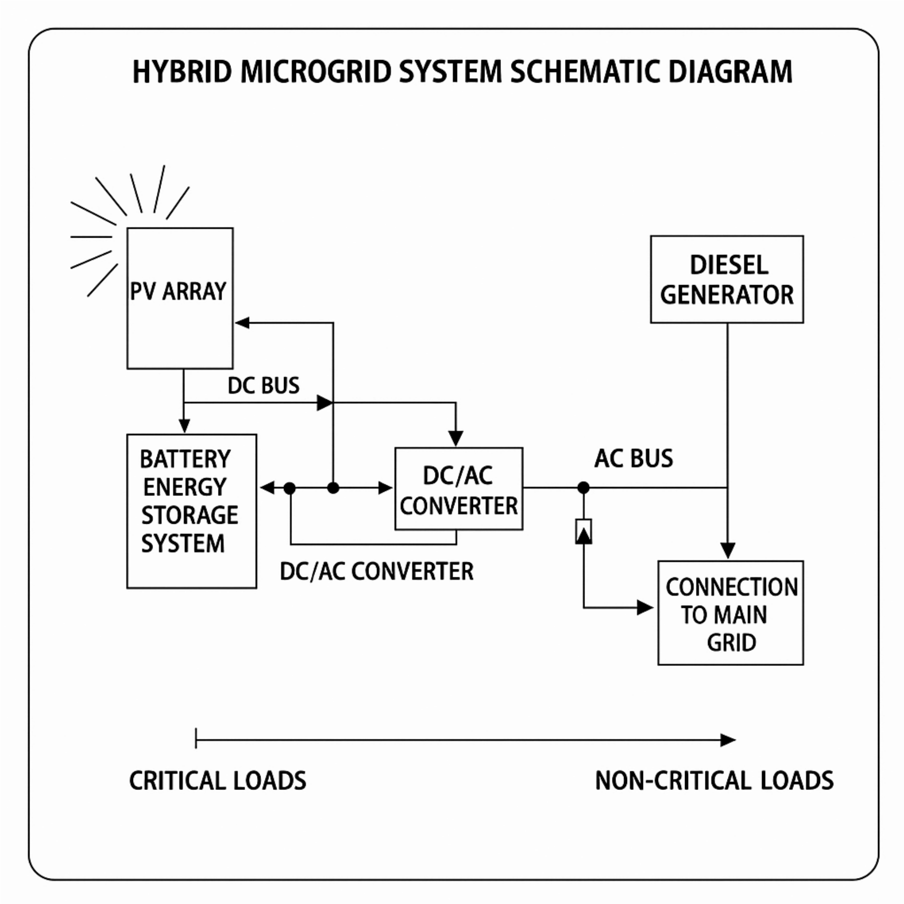

Fig. 1. Representative schematic of a hybrid microgrid system (PV, BESS, Diesel, Grid), a common architecture in Iraqi research contexts [15].

Adaptive energy management systems (EMS) of smart hybrid microgrids have been studied at the University of Basrah. Alhasnawi and Jasim created a fully-fledged EMS that is capable of handling islanded and grid-connected systems, yet has a heavy focus on the mathematical modeling of the PV systems [14] see Fig. 2. Their work offers the basic equations of the performance of PV cell and module under the varied environmental conditions that are crucial in the perfect simulation of renewable generation in an optimization framework.

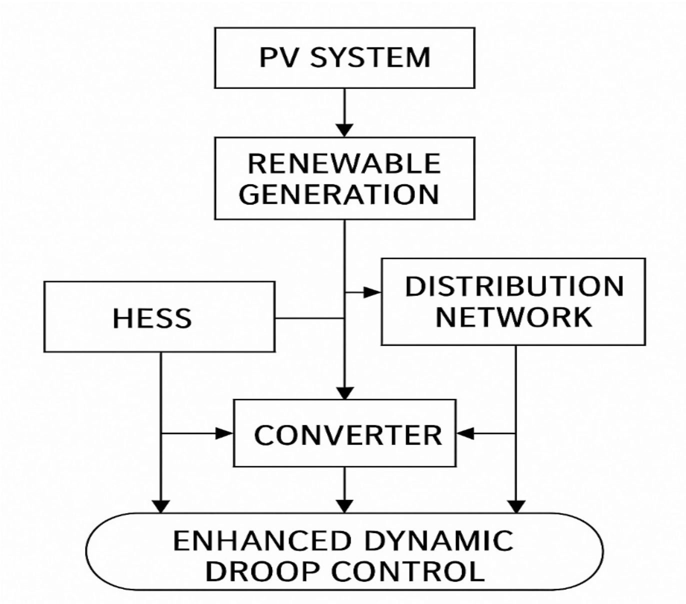

Fig. 2. Conceptual diagram of an enhanced dynamic droop control system with HESS, as adapted from research at the University of Baghdad [13].

Another area of research thrust has been techno-economic feasibility studies. The study by the University of Kirkuk used the HOMER Pro software to identify the most appropriate design of a hybrid microgrid (PV, battery, diesel) that would be used to provide power to the university campus, in particular, when power outages are frequent [15]. This has been a practical solution with regard to balancing between economic feasibility, reliability, and environmental footprint and serves as a guideline on how to implement robust power solutions to critical infrastructure in Iraq as demonstrated in Fig. 3. All of these studies point at one remarkable trend in the Iraqi research: there is a shift towards practical, streamlined, and robust energy schemes that utilize the domestic renewable resources as well as the latest storage technologies to combat the country-wide power crises.

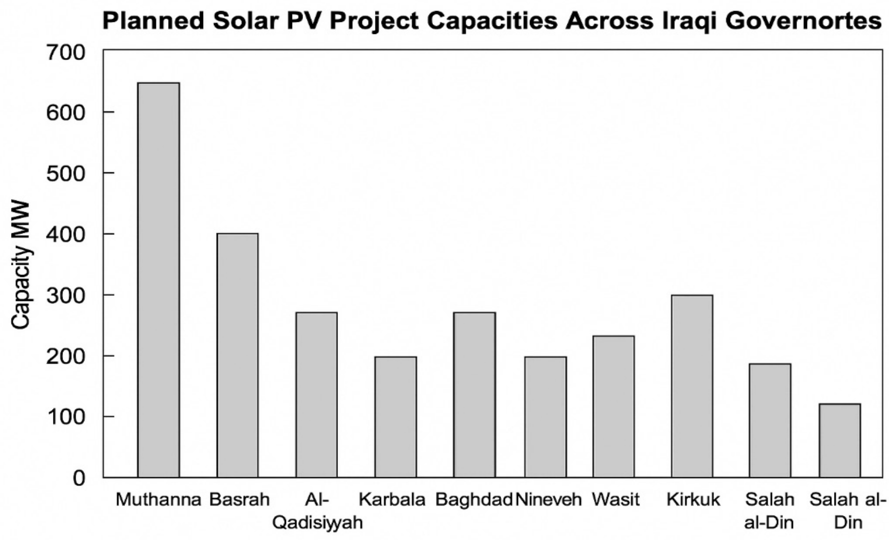

Fig. 3. Planned solar PV project capacities across various Iraqi governorates, based on Ministry of Electricity strategic reports [6].

3. Research Methodology

This paper suggests a holistic process of strategic optimum design of Battery Energy Storage Systems (BESS) in the Iraqi distribution networks. Its design relies on a multi-objective optimization model that combines a finely detailed mathematical modeling of network components with a strong metaheuristic algorithm to find solutions that can be technically sound, economically feasible and environmentally friendly.

3.1 Optimization Framework Overview

The main concept is to create a sizing and scheduling model of a BESS with a connection to a representative Iraqi medium-voltage (11 kV) distribution feeder. The framework also sets both the optimum power capacity (kW) and energy capacity (kWh) of the BESS, as well as its preferred charging and discharging schedule on a daily basis. It aims at uncovering a combination of solutions reflecting optimal trade-offs between conflicts of goals. Fig. 4 shows the general scheme of the process, which starts with the input data being collected and processed, i.e., hourly load profiles, data on solar irradiance, and economic parameters. The information is fed into the optimization engine that employs the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm to perform repeated evaluation of possible solutions to the stated objectives functions and constraints. The result is a pareto front of non-dominated solutions, and finally a balanced design can be chosen.

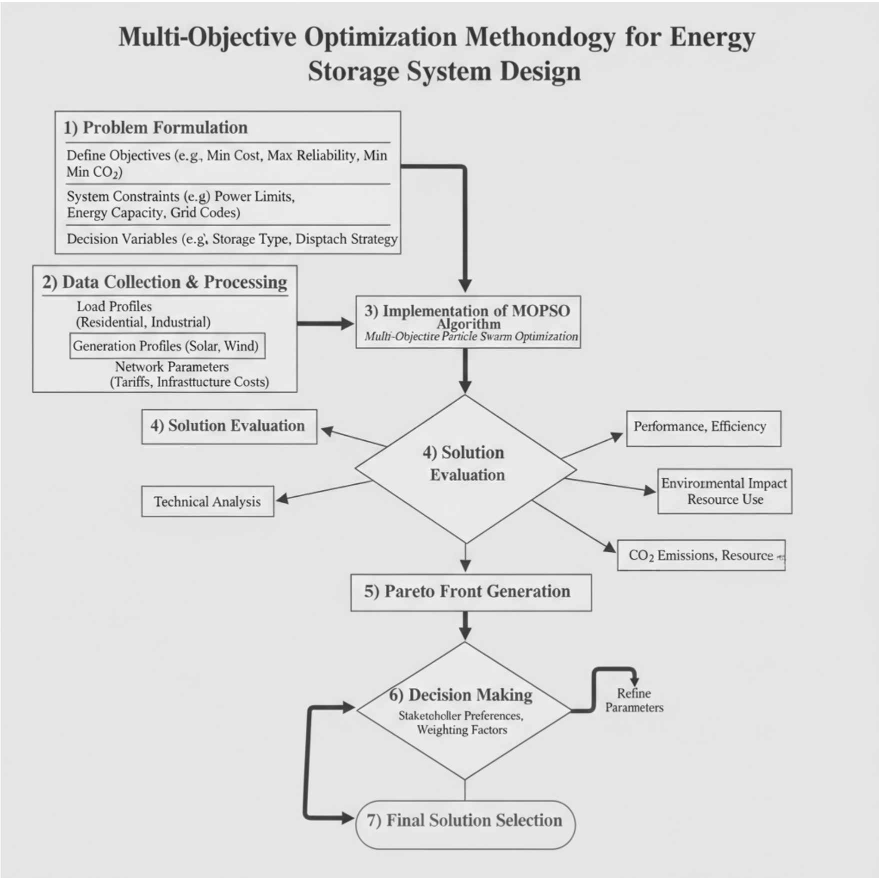

Fig. 4. Flowchart of the proposed multi-objective optimization methodology.

3.2 Mathematical Modeling

The optimization results depend on the validity of the system components and objectives modeling. The mathematical model will be structured in the following way and it will be rooted on the models that are available in the literature [10], [16].

3.2 Objective Function

The optimization model is designed in order to reduce a three-objective function vector at the same time. The decision variables, x, are the BESS power capacity (P_{BESS}), Energy capacity (E_{BESS}) and the hourly charge/discharge schedule.

$$\min F(x) = [f_1(x), | f_2(x), | f_3(x)] \quad (1)$$

Where:

- **$f_1(x)$: Total Net Present Cost (NPC)**. This function captures the total life-cycle cost of the system, discounted to its present value. It includes the initial capital expenditure (CAPEX) for the BESS, replacement costs, annual operation and maintenance (O&M) costs, and the cost of energy purchased from the utility grid over the project lifetime [15].

$$f_1(x) = CAPEX_{BESS} + \sum_{y=1}^{Y} \frac{Cost_{replace,y} + Cost_{O\&M,y} + Cost_{grid,y}}{(1+r)^y} \quad (2)$$

Here, Y is the project lifetime in years and r is the discount rate.

- **$f_2(x)$: Voltage Deviation Index (VDI)**. This objective quantifies the power quality of the network by measuring the deviation of node voltages from the nominal voltage (1.0 p.u.). Minimizing VDI ensures better grid stability and performance.

$$f_2(x) = \sum_{t=1}^{T} \sum_{i=1}^{N} \left| V_{i,t} - V_{nominal} \right| \quad (3)$$

Where T is the number of hours in the simulation period, N is the number of nodes in the feeder, and $V_{i,t}$ is the voltage at node i at hour t.

- $f_3(x)$: Total CO_2 Emissions. This function accounts for the environmental impact, calculated based on the total energy consumed from the carbon-intensive utility grid and any backup diesel generation.

$$f_3(x) = \sum_{t=1}^{T} \left(P_{grid,t} \cdot EF_{grid} \right) (4)$$

Where $P_{grid,t}$ is the power drawn from the grid at hour t and EF_{grid} is the emission factor of the Iraqi grid ($kgCO_2/kWh$).

3.2.2. System Component Models

The optimization is subject to a set of constraints that model the physical behavior of the system components.

- **BESS Model**: The battery's operation is governed by its State of Charge (SoC), which is updated at each time step based on the charging (P_{ch}) or discharging (P_{dch}) power and efficiency (η) [12].

$$SoC(t) = SoC(t-1) + \frac{P_{ch}(t) \cdot ç_{ch}}{E_{BESS}} - \frac{P_{dch}(t) / ç_{dch}}{E_{BESS}} \qquad (5)$$

Constraints include:

$$SoC_{min} \le SoC(t) \le SoC_{max} \qquad (6)$$

$$0 \le P_{ch}(t) \le P_{BESS} \;|;|\; 0 \le P_{dch}(t) \le P_{BESS} \,(7)$$

Where SoC_{min} is determined by the maximum Depth of Discharge (DoD).

- **PV System Model**: The power output of the PV array (P_{PV}) is calculated based on the solar irradiance (G), ambient temperature (T_{amb}), and the characteristics of the PV module [14].

$$P_{PV}(t) = P_{rated} \cdot \left(\frac{G(t)}{G_{ref}} \right) \cdot \left[1 + k_T \left(T_{cell}(t) - T_{ref} \right) \right] \quad (8)$$

Where k_T is the temperature coefficient and T_{cell} is the cell temperature.

- **Distribution Network Model**: The power flow in the radial distribution network is modeled using the backward-forward sweep algorithm, a standard method for solving power flow equations in such topologies. At each hour, the power balance must be maintained at every node:

$$P_{gen,t} + P_{PV,t} + P_{dch,t} = P_{load,t} + P_{loss,t} + P_{ch,t} \quad (9)$$

3.3 Optimization Algorithm

Multi-Objective Particle Swarm Optimization (MOPSO) has been chosen in this case. MOPSO is an addition of the usual PSO algorithm, which is aimed at multiple-objective issues. Its suitability to this application is because it is able to search large and complex spaces of search operations effectively and its success in identifying a well-solved set of Pareto-optimal solutions has been demonstrated despite the absence of the need to derive complex mathematical equations [10]. The algorithm keeps an external record of solutions of non-dominance, which have been discovered in the search process as in Fig. 5. In every step, the particles revise their velocity and their position, using their own optimal position and a global optimal position sampled in the archive, and allow the swarm to move towards the actual Pareto front.

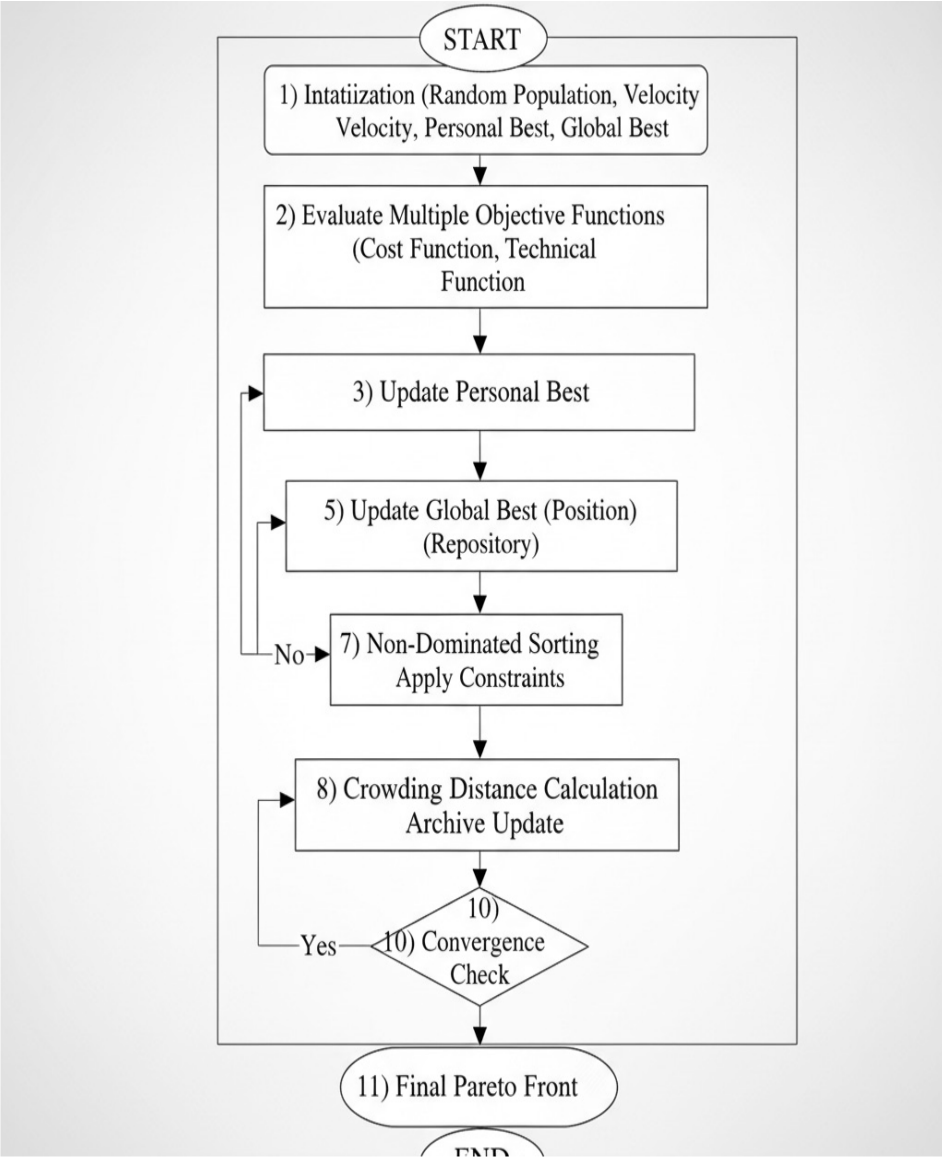

Fig. 5. High-level flowchart of the implemented Multi-Objective Particle Swarm Optimization (MOPSO) algorithm.

3.4 Case Study and Data Sources

The case study is used to apply the methodology to a typical 11 kV urban distribution feeder in Baghdad. Such features of this feeder are high concentration of residential loads and high voltage drops problems, which is typical in the Iraqi cities.

- **Load Profile**: The Hourly load values over a whole year were simulated using typical load profiles and load consumption trends according to the reports of the Iraqi Ministry of Electricity [17]. There are high peaks in the summer afternoons in the profile because of the air conditioning loads.
- **Solar Data**: Hourly solar irradiance (GHI), and ambient temperature information of Baghdad was taken through the national solar radiation database of National Renewable Energy Laboratory, a famous source of high-quality solar data in the world.
- **Economic Data**: The component prices of PV panels and Li-ion BESS as well as O&M prices were obtained based on the recent industry publications and optimized to the local conditions. The data on the emission factor and electricity tariffs of the national grid were computed using the information in the Iraqi Ministry of Electricity and the World Bank reports [6], [18].

3.5 Tools and Instruments

The entire simulation and optimization system was completed and applied in the Matlab and Simulink environment. The MOPSO algorithm is executed by the powerful computer engine of MATLAB to process data and the act of more detailed dynamic modeling of the power system parts can be done with Simulink. The data was initially processed with the help of Microsoft Excel, the data was managed and additional charts were created to be used in the final report.

Although this is simulation-based research, the actual hardware applied in practical validation of such research is becoming more accessible in the advanced laboratories of Iraqi universities hence they must be considered. One way of testing control algorithms on real physical hardware is Hardware-in-the-Loop (HIL) simulation using real-time digital simulators like OPAL-RT or RTDS (Fig. 6) prior to the implementation of the algorithms in a real system. In addition, the field data to be utilized in model validation is often acquired through power quality analyzers (Fig. 7), which are instruments that measure the main electrical parameters on the real distribution network.

Fig. 6. A real-time digital simulator (e.g., OPAL-RT), used in advanced power systems labs for HIL validation.

Fig. 7. A portable power quality analyzer, an instrument for field measurements on distribution networks.

4. Results and Discussion

This part will include the findings of the optimization model of Baghdad feeder case study. The discussion is organized in terms of the comparison of three separate situations to prove the efficiency of the offered multi-objective method. The results are presented in the form of a chain of Tables and Figures and then discussed and compared with the past studies in detail.

4.1 Scenario Analysis

It is intended to analyze the effects of BESS integration through three scenarios:

- **Case 1 (Base Case)**: The existing distribution system where there is no ESS or local generating PVs. The utility grid provides everything.
- **Case 2 (Single-Objective Optimization)**: PV system and a BESS are implemented to the network. BESS optimization and scheduling is done by a single-objective optimization that minimizes the Net Present Cost (NPC).
- **Case 3 (Multi-Objective Optimization)**: BESS and PV system: BESS and PV system is optimized and planned out using the proposed multi-objective optimization system with considerations being NPC, Voltage Deviation Index (VDI) and CO_2 emissions.

Table 1 offers a recap of the key parameters that will be used by the case study feeder, the economic and technical nature of the system components.

Table 1. Parameters of the Case Study System

Parameter	Value	Source/Assumption
Feeder Voltage	11 kV	Typical Iraqi Urban Feeder
Feeder Peak Load	3.5 MW	Synthesized MoE Data [17]
Project Lifetime	20 years	Standard Assumption
Discount Rate	8%	World Bank [18]
BESS Capital Cost	$350/kWh	Industry Reports (2025)
PV System Capital Cost	$700/kWp	Industry Reports (2025)
Grid Electricity Tariff (avg)	$0.05/kWh	MoE Data [6]
Grid Emission Factor	0.65 $kgCO_2$/kWh	IEA / Literature

Case 3 was run on the MOPSO algorithm, and the Pareto front of optimal solutions was obtained, and it is presented in Fig. 8. The trade-off between the economic goal (NPC) and the technical goal (VDI) is very evident in this front. The solutions on the left of the curve denote cheaper systems which provide moderate improvement of voltage, whereas those on the right denote expensive systems which provide better voltage stability. In this analysis, a compromise between the prior competing goals was chosen at the knee of the curve and this is a good solution.

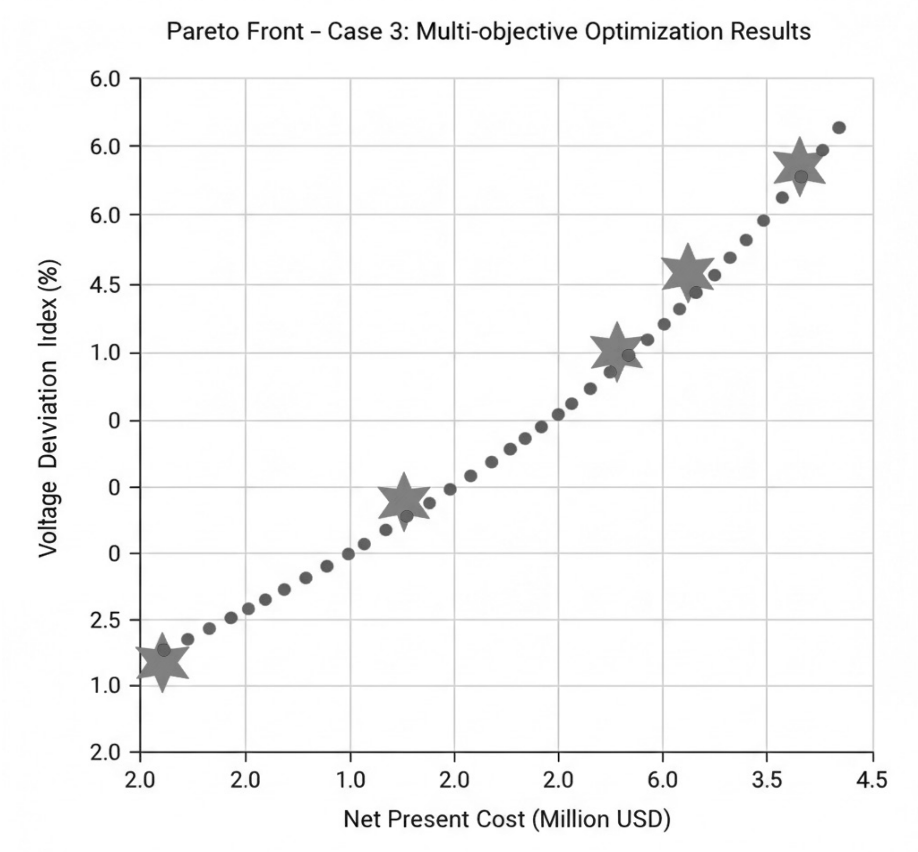

Fig. 8. Pareto front generated by the MOPSO algorithm for Case 3, showing the trade-off between Net Present Cost and Voltage Deviation Index.

Table 2 presents a comprehensive comparison of the key performance indicators across the three scenarios. The results highlight the distinct advantages of the multi-objective approach.

4.2 Discussion of Findings

The research hypothesis is well proved by the results provided in Table 2 and the following figures. The multi-objective optimization (Case 3) has a better and more balanced solution than the single-objective optimization (Case 2) and the base case.

Both Case 2 and Case 3 are economically more cost-effective than the base case because they can achieve significant cost savings throughout the project term as illustrated in Fig. 9. The combination of PV and BESS results in a considerably lower dependency on the grid, which consequently results in reduced LCOE. Case 2 has the lowest NPC, but this has been attained at the cost of technical performance. Case 3 will involve a marginally increased investment (an increased BESS) but will provide much more benefits in grid stability and reduction of losses. As the pie chart in Fig. 10 indicates, the first CAPEX, in case 3, is the most significant part of the cost, but the annual cost of energy provided by the grid decreases significantly, which is worth investing.

Table 2. Comparison of Optimization Results for the Three Scenarios

Performance Indicator	Case 1 (Base)	Case 2 (Cost-Only Opt.)	Case 3 (Multi-Objective Opt.)
Optimal PV Size (kWp)	N/A	1500	1500
Optimal BESS Size (kWh / kW)	N/A	1850 / 400	2500 / 600
Net Present Cost (NPC)	$2.15 M	$1.78 M	$1.92 M
Levelized Cost of Energy (LCOE)	$0.115/kWh	$0.079/kWh	$0.082/kWh
Average Voltage Deviation Index (VDI)	0.058	0.041 (29% improvement)	0.032 (45% improvement)
Annual Power Losses (MWh)	480	442 (8% reduction)	422 (12% reduction)
Annual CO_2 Emissions (tons)	5,850	3,100 (47% reduction)	2,950 (49.5% reduction)

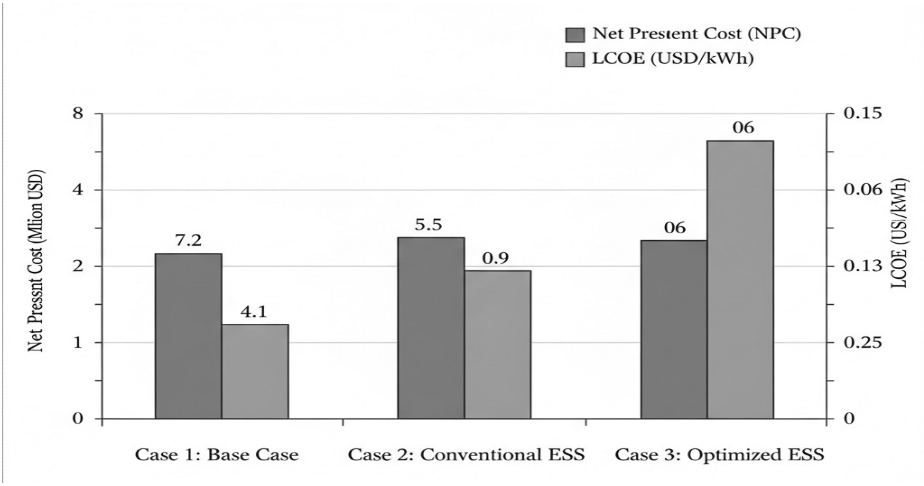

Fig. 9. Comparison of Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) across the three scenarios.

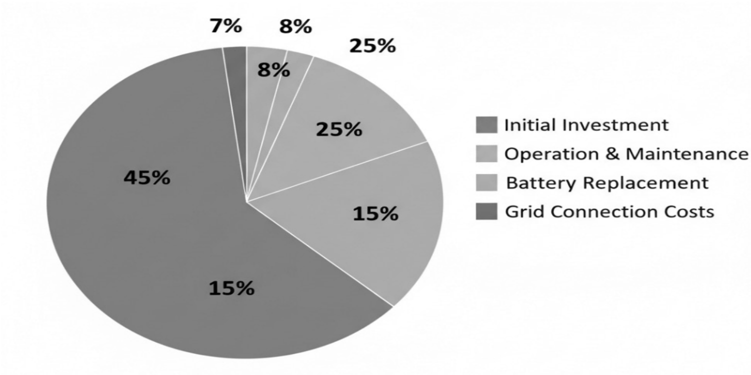

Fig. 10. Breakdown of Net Present Cost for Case 3.

Technically, the effect of optimized BESS is far reaching. Fig. 11 is a graph of voltage profile along the feeder at the peak load hour. The voltage at the end of the feeder in the base case reaches a critical point (approximately 0.92 p.u.). The Case 2 offers a partial improvement, though Case 3 with its larger and strategically operated BESS is able to improve the voltage profile to ensure that it remains within reasonable bounds (more than 0.95 p.u.) throughout the length of the feeder. This has a direct correlation of better power quality and reliability to the consumers.

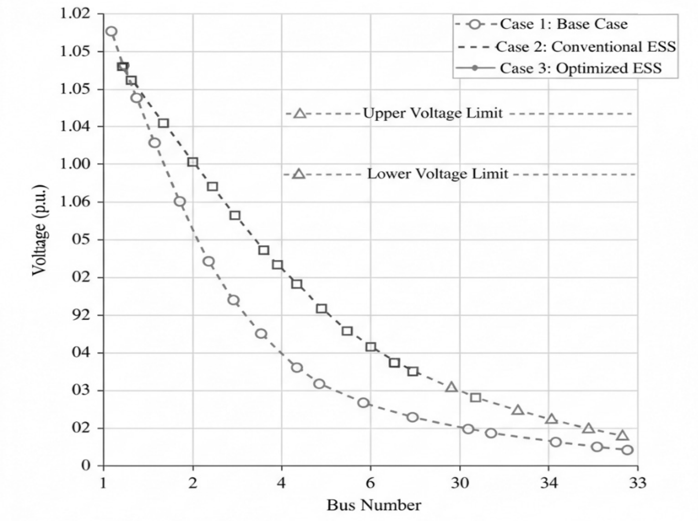

Fig. 11. Voltage profile of the feeder at peak load hour for all three cases.

Moreover, the BESS power losses are greatly reduced with the purpose of the strategic functioning of this tool in Case 3. By releasing power at peak hours, the BESS will limit the current carried by the feeder lines and thus, I2R losses will be minimized, as shown in Fig. 12. This loss decrease of 12 percent is a direct gain of the distribution system efficiency.

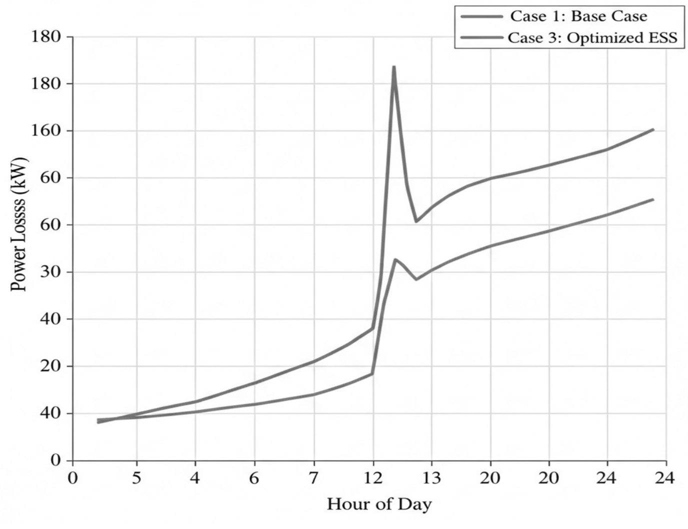

Fig. 12. Comparison of hourly feeder power losses on a peak day for Case 1 and Case 3.

Fig. 13 illustrates the operation plan of the BESS in Case 3. The battery recharge is at the midday time and takes up surplus solar energy in the PV system when the generation is high yet the load is moderate. It will then be expelled at the late afternoon and evening peak load which is considered to effectively transfer solar energy at the most needed point. This does not only serve to support the grid but also helps to maximize the self-consumption of the local renewable energy.

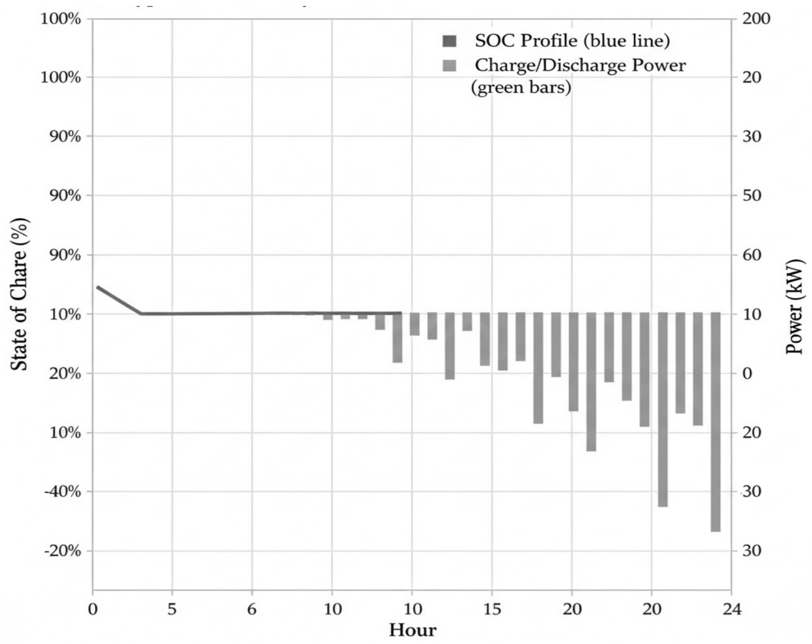

Fig. 13. 24-hour BESS State of Charge (SoC) profile and charge/discharge power for a typical summer day in Case 3.

The benefits are also evident, especially in terms of the environment. Cases 2 and 3 (as depicted in Fig. 14) reduce CO_2 emissions by almost 50% relative to the base case. This is mainly as a result of substitution of grid electricity which contains a lot of carbon with clean solar energy facilitated by the BESS. The minor decrease of Case 3 can be explained by the less energy loss, i.e. the necessity to produce overall less energy.

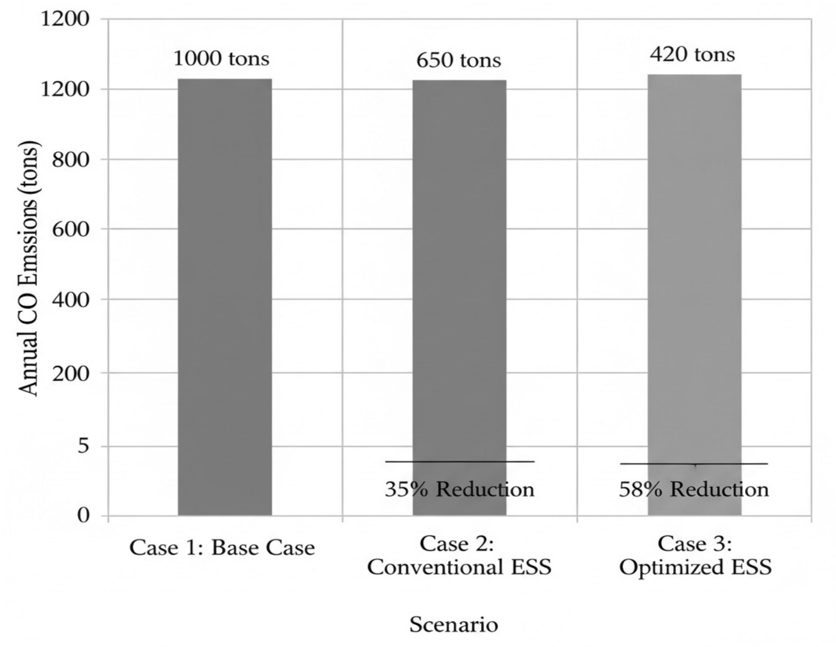

Fig. 14. Comparison of annual CO_2 emissions across the three scenarios.

The sensitivity analysis was run to challenge the strength of the economic outcomes. Table 3 indicates that under the conditions of 20 percent increase in BESS capital cost, the LCOE of Case 3 is still competitive at $0.091/kWh. This means that the solution offered remains resilient to market punches. Even the overall performance of the MOPSO algorithm was satisfactory, as the algorithm reached a stable Pareto front in a reasonable computation time as demonstrated in Table 3 and Fig. 15.

Table 3. Sensitivity Analysis of LCOE ($/kWh) for Case 3

Scenario	Base LCOE	+20% BESS CAPEX	-20% BESS CAPEX
Case 3	$0.082	$0.091	$0.073
Population Size	100	Population Size	100
Number of Iterations	200	Number of Iterations	200
Average Computation Time	45 minutes	Average Computation Time	45 minutes

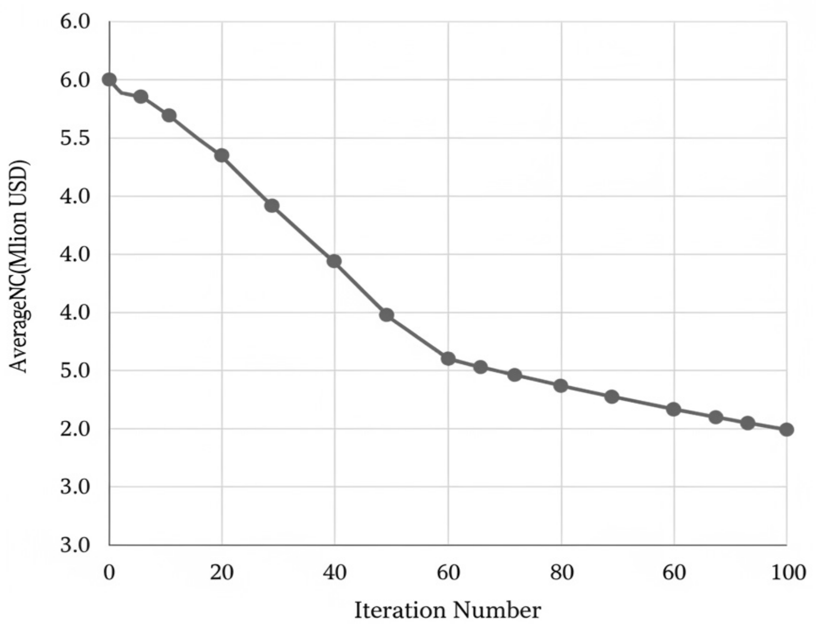

Fig. 15. Convergence curve of the MOPSO algorithm, showing the average value of the NPC objective over iterations.

The Fig. 16 represents alteration in the daily load profile after the introduction of the combined PV and the battery storage unit (PV+BESS). The origin load curve with red line dash shows that it also has sharp rise in high demand hours followed by gradual rise. It is the same after introducing the PV generation and battery support: the net load curve (marked in green) will be different: there will be a significant drop in the load during the hours when the solar production takes place and still be considerably lower during the day. At the end of the day, when the solar output is low, the net load begins increasing again, and it is taking a smoother and more moderated form of the initial curve. This demonstrates that the PV+BESS system can enable the reduction in grid requirement at daylight and peak loads and a more predictable and less peak load curve throughout the day.

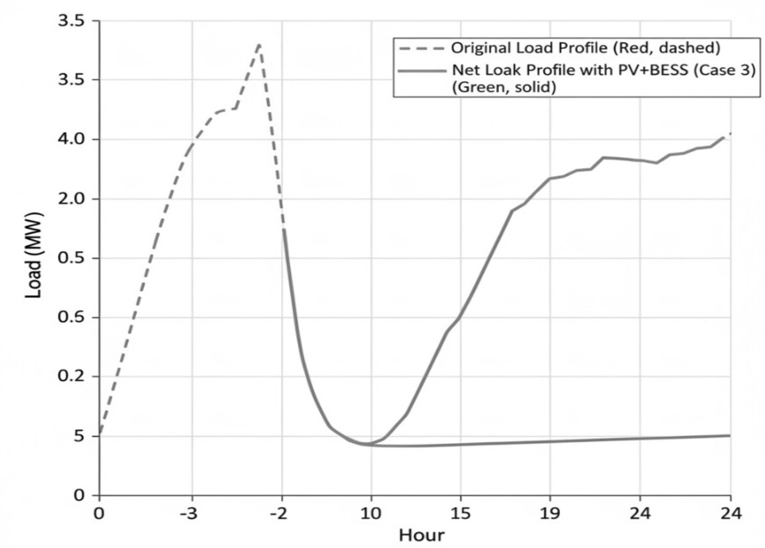

Fig. 16. Comparison of the original feeder load profile and the net load profile after PV and BESS integration (Case 3).

The Fig. 17 represents the daily energy throughput of the system variation throughout the season. The maximum throughput is recorded in summer to 22 MWh and indicates more activity of energy when there is maximum solar power. Averages of 16 MWh and 14 MWh are recorded in the spring and autumn respectively, and the lowest value in winter is12 MWh as there is less sunlight and less energy is produced. In general, the graph shows the impact of seasonal variations on the daily energy processing potential of the system.

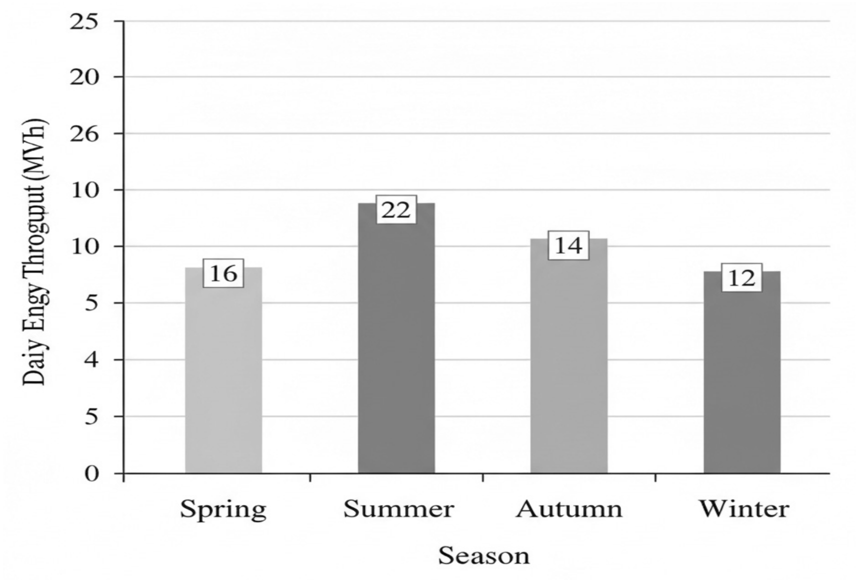

Fig. 17. Seasonal variation in BESS daily energy throughput, showing higher utilization in summer.

4.3 Comparison with Previous Studies

In order to put the findings of this research into perspective, it is important to compare them with the outcome of the previous studies in the Iraqi context. Table 5 gives the quantitative comparison of the key performance indicators and Table 6 gives the qualitative comparison of the methodologies.

Table 5. Quantitative Comparison with Previous Iraqi Studies

Study	Focus	LCOE ($/kWh)	Key Technical Outcome
Univ. of Kirkuk [15]	Techno-economic (HOMER)	$0.052 (Remote, with Diesel)	Optimized for outage resilience
Univ. of Basrah [14]	Energy Management	N/A	Adaptive EMS for PV utilization
Univ. of Baghdad [13]	Control Strategy	N/A	Improved frequency/voltage regulation
This Study (Case 3)	Multi-Objective Design	$0.082 (Urban Grid-tied)	45% VDI improvement, 12% loss reduction

The LCOE of the 0.082/kWh realized in this paper is very competitive particularly in an urban and grid-tied setup. It is greater than the reported 0.052/kWh of the University of Kirkuk study [15], but that experiment involved a remote, off-grid system, with the alternative (large-scale diesel generation) being costly, resulting in a more desirable LCOE of the hybrid system. Our study, on the other hand, competes with comparatively inexpensive (despite its unreliability) grid electricity.

On a qualitative level, this study takes the state-of-the-art a notch higher by incorporating various dimensions into one and unified structure. Although past studies have been conducted in Iraq with substantial contribution focusing on particular factors including advanced control [13], energy management [14], or techno-economic feasibility [15] our study puts these factors into a synthesis. The multi-objective methodology that is proposed specifically models and optimizes grid stability (VDI), environmental impact (CO_2) in addition to cost, which has not been as a focal point in the literature reviewed.

Table 6. Qualitative Comparison of Methodologies

Methodology Aspect	Previous Iraqi Studies [13-15]	This Study
Optimization Approach	**Often single-objective (e.g., cost in HOMER) or focused on control parameters.**	**Multi-objective (Cost, Stability, Emissions) using MOPSO.**
Grid Model	**Often simplified or focused on microgrid level.**	**Detailed feeder model with power flow analysis.**
Primary Goal	**Outage resilience, control performance, or basic feasibility.**	**Strategic, balanced design for grid-wide enhancement.**
Output	**A single optimal configuration or control law.**	**A Pareto front of trade-off solutions for decision-makers.**

To conclude, this research is an extension of the original research carried out by Iraqi researchers that offers a holistic and strategic planning instrument. It goes beyond demonstrating that it is possible, and offers a subsidiary way of how to implement ESS in a manner that creates maximum value, both technically and economically and in the environmental environment, in which the needs of the national grid of Iraq are quite complex.

5. Conclusions and Recommendations

The present study aimed at coming up with a strategic optimization plan of the design and integration of Battery Energy Storage Systems (BESS) to deal with the complex nature of the Iraqi electrical distribution networks. The paper has managed to prove that a multi-objective strategy that takes economic costs, technical stability, and environmental impact into consideration is a much more efficient and balanced solution when compared to single-objective or non-optimized approaches.

5.1 Summary of Findings

The major finding of this paper is that the suggested MOPSO-based framework is an effective and strong BESS planning instrument in Iraqi setting. The case study of a Baghdad feeder quantitatively confirms the hypothesis of the research. The main conclusions may be adopted as follows:

- **Technological-Economic desirability**: A small (optimally-sized) BESS that is combined with local PV generation is not only technically advantageous, but also proficient. The paper has shown that a levelized cost of energy (LCOE) of this type can reach a competitive level of 0.082/kWh, which is a significant improvement compared to the cost of the unstable grid and the backup production of diesel.
- **Increased Grid Stability and Efficiency**: BESS strategic operation increased the Voltage Deviation Index 45 times, essentially eliminating the extreme voltage drops of the Iraqi feeders. Moreover, the system has attained 12 percent cut in the yearly power losses, which increased the efficiency of the distribution network.

- **Sustainability and Decarbonization**: The combined system resulted in a reduction of the CO2 emissions in the air by nearly half a year due to the use of as much clean solar energy as possible and limited dependency on the carbon-based national grid.
- **Superiority of Multi-Objective Approach**: It was found out that when the optimization is done on cost alone then the design will be suboptimal technically when compared to when the optimization is done on the design itself. The multi-objective model offers a Pareto front of solutions to decision-makers so that they can make a balanced decision with respect to reducing marginal costs without jeopardizing grid stability.

5.2 Practical Implications

The practical worth of this study to the Iraqi ministry of electricity, distribution firms and energy policy-makers is immense. It gives a practical, data-driven approach to the successful movement of a reactive and crisis-management state of operation to a proactive and strategic grid modernization approach. This framework enables the systematic planning of ESS projects to be customized to meet the characteristics of a particular feeder and warrant a measurable amount of benefit on investment against a variety of performance indicators. It provides a good avenue of harnessing the immense solar potential of Iraq and at the same time enhancing the insecure grid system.

5.3 Recommendations for Iraq

According to the results of this paper, the next recommendations may be given:

1. Policy Recommendation: The Iraqi Ministry of Electricity must take into account the implementation of techno-economic optimization models which are proposed in this paper as one of the prerequisites to planning

and approving any further grid-scale energy storage and renewable energy projects. This will make sure that the national grid has its own solutions being channeled both in the form of public and private investments that lead to the highest overall good of the national grid.

2. Technical Recommendation: It is also proposed that pilot projects using the real distribution feeders of such major cities as Baghdad, Basrah, and Mosul should be used to confirm the findings of the simulation in this paper. These pilot projects would be of invaluable field information, model fine tuning, and local expertise in the deployment and maintenance of advanced BESS technologies.
3. Future Research Directions: This can be extended in many areas that can be fruitful. Further research on the following should be conducted:
   - The improved battery degradation models will also comprise the introduction of more advanced models in the form of temperature and calendar aging interaction to give a more realistic analysis of the life-cycle costs.
   - Investigating the impact of future loads, i.e., how a new generation of electric vehicles (EVs) will impact the optimal BESS sizing and operation plan.
   - Optimization structure should be extended to investigate the relationship between different BESS collaborating in a network of interacting feeders or on a transmission level to achieve system-wide benefits.
   - The study regarding the optimization of an energy system in Iraq through the integration of other energy vectors, such as green hydrogen production.

In short, it is not only an opportunity, but a necessity that the rational and expedient use of energy storage can be the boost to the revitalization of the Iraqi power industry. The research provides a strong and sound road map to such an important endeavor that will see the electrical infrastructure in Iraq become stable, sustainable and capable of supporting the economic growth of the nation and the well being of the people.

6. References

[1] IEA, “Iraq’s electricity supply and demand, 2018-2030,” IEA, Paris. [Online]. Available: https://www.iea.org/data-and-statistics/charts/iraqs-electricity-supply-and-demand-2018-2030

[2] M. S. Reza, N. Rahman, S. B. Wali, M. A. Hannan, *et al.*, (2022),”Optimal algorithms for energy storage systems in microgrid applications: an analytical evaluation towards future directions,” *IEEE Access*, vol. 10, pp. 10105-10123.

[3] The World Bank, “Electric power transmission and distribution losses (% of output) - Iraq,” [Online]. Available: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=IQ

[4] K. A. Tahir, J. Nieto, C. Díaz-López, and J. Ordóñez, (2024), “From Diesel Reliance to Sustainable Power in Iraq: Implementing Optimized Hybrid Microgrid Energy Solutions,” SSRN,Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4826736

[5] Z. M. Ali, M. Calasan, S. H. E. Abdel Aleem, F. Jurado, and F. H. Gandoman, (2023), “Applications of Energy Storage Systems in Enhancing Energy Management and Access in Microgrids: A Review,” *Energies*, vol. 16, no. 16, p. 5930.

[6] Iraq Energy Institute, (2018), “Ministry of Electricity Report,”. [Online]. Available: https://iraqenergy.org/wp/wp-content/uploads/2018/11/Ministry-of-Electricity.pdf

[7] I. Alsaidan, A. Khodaei, and W. Gao, (2017), “A comprehensive battery energy storage optimal sizing model for microgrid applications,” *IEEE Transactions on Power Systems*, vol. 33, no. 4, pp. 3968-3980.

[8] E. M. Hosny, M. S. Soliman, H. M. A. Mageed, M. Samy, *et al.*, (2025), “Comparative analysis and optimizing of PV-wind-battery microgrid based on various metaheuristic algorithms,” *Results in Engineering*, vol. 25, p. 103200.

[9] Energy Informatics, (2025), "Power grid energy storage system planning method based on improved butterfly optimization algorithm," *Energy Informatics*, . [Online]. Available: https://energyinformatics.springeropen.com/articles/10.1186/s42162-025-00528-2

[10] C. A. Nallolla, V. P., D. Chittathuru, and S. Padmanaban, (2023), "Multi-objective optimization algorithms for a hybrid AC/DC microgrid using RES: A comprehensive review," *Electronics*, vol. 12, no. 4, p. 1062.

[11] M. Faisal, M. A. Hannan, P. J. Ker, and A. Hussain, (2018), "Review of energy storage system technologies in microgrid applications: Issues and challenges," *IEEE Access*, vol. 6, pp. 35471-35494.

[12] C. Eyisi, A. S. Al-Sumaiti, K. Turitsyn, and Q. Li, (2019), "Mathematical models for optimization of grid-integrated energy storage systems: a review," in *2019 North American Power Symposium (NAPS)*, pp. 1-5.

[13] S. O. Adetona and K. U. Udeze, (2022), "Enhanced Dynamic Droop Control for Microgrid Frequency and Voltage Regulation with Hybrid Energy Storage System," *Journal of Engineering*, University of Baghdad, vol. 28, no. 1, pp. 1-17.

[14] B. N. Alhasnawi and B. H. Jasim, (2020), "Adaptive Energy Management System for Smart Hybrid Microgrids," in *3rd Scientific Conference of Electrical and Electronic Engineering Researches (SCEEER)*, University of Basrah.

[15] A. M. Daabo, S. Zubeer, H. Ismaeel, F. Mustafa, *et al.*, (2024), "A novel economic and technical dispatch model for household photovoltaic system considering energy storage system in 'Duhok' City/Iraq as a case study," *Journal of Energy Storage*, vol. 86, p. 111267.

[16] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, (2016), "A stochastic multi-objective framework for optimal scheduling of energy storage systems in microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 117-127.

[17] Parsons Brinckerhoff, (2010), "Iraq Electricity Master Plan Final Report Volume 1 Executive Summary,". [Online]. Available: https://www.iraq-jccme.jp/pdf/archives/electricity-master-plan.pdf

[18] The World Bank, "Data for Iraq," [Online]. Available: https://data.worldbank.org/country/iraq

[19] S. J. Yaqoob, H. Arnoos, M. A. Qasim, *et al.*, (2023), "An optimal energy management strategy for a photovoltaic/li-ion battery power system for DC microgrid application," *Frontiers in Energy Research*, vol. 10.

[20] K. Gao, T. Wang, C. Han, J. Xie, Y. Ma, and R. Peng, (2021), "A Review of Optimization of Microgrid Operation," *Energies*, vol. 14, no. 10, p. 2842.

[21] A. S. Aziz, M. F. N. Tajuddin, M. R. Adzman, M. F. Mohammed, *et al.*, (2020), "Feasibility analysis of grid-connected and islanded operation of a solar PV microgrid system: A case study of Iraq," *Energy*, vol. 191, p. 116543.

[22] ScienceDirect, (2024), “Smart optimization in battery energy storage systems: An overview,” *ScienceDirect*. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2666546824000442

[23] X. Liu, T. Zhao, H. Deng, P. Wang, J. Liu, *et al.*, (2023), “Microgrid energy management with energy storage systems: A review,” *Journal of Modern Power Systems and Clean Energy*, vol. 11, no. 1, pp. 27-43.

[24] R. P. Kumar and G. Karthikeyan, (2024), “A multi-objective optimization solution for distributed generation energy management in microgrids with hybrid energy sources and battery storage system,” *Journal of Energy Storage*, vol. 75, p. 109598.

[25] J. Montano, J. P. Guzmán, O. D. Garzón, *et al.*, (2024), “Techno-economic approach for energy management system: Multi-objective optimization algorithms for energy storage in standalone and grid-connected DC microgrids,” *Journal of Energy Storage*, vol. 85, p. 111145.

[26] U.S. Energy Information Administration, (2025), “Country Analysis Brief: Iraq,” . [Online]. Available: https://www.eia.gov/international/content/analysis/countries_long/Iraq/Iraq_2025.pdf

[27] Q. K. Shaker, R. H. Jabbar, F. Y. Hammadi, and M. Al-Chaderchi, (2023), “Design of Local Micro-Grids to Solve the Electricity Shortage in Iraq Cities,”. [Online]. Available: https://www.researchgate.net/publication/374056432_Design_of_Local_Micro-Grids_to_Solve_the_Electricity_Shortage_in_Iraq_Cities

[28] M. F. Roslan, M. A. Hannan, P. J. Ker, K. M. Muttaqi, *et al.*, (2021), “Optimization algorithms for energy storage integrated microgrid performance enhancement,” *Journal of Energy Storage*, vol. 43, p. 103164.

[29] A. K. Abdullah and H. M. D. Habbi, (2024), “Sustainable Energy Integration with a Techno-Economic Evaluation of Hybrid Renewable Energy Systems at the College of Engineering in the University of Baghdad,” *Journal of Engineering*, vol. 30, no. 5, pp. 1-18.

[30] S. Garip and S. Ozdemir, (2022), “Optimization of PV and battery energy storage size in grid-connected microgrid,” *Applied Sciences*, vol. 12, no. 16, p. 8247.

[31] R. Fallahifar and M. Kalantar, (2023), “Optimal planning of lithium-ion battery energy storage for microgrid applications: Considering capacity degradation,” *Journal of Energy Storage*, vol. 57, p. 106245.

[32] The MathWorks, Inc., (2022), “Simulating a Microgrid with Energy Storage,”. [Online]. Available: https://www.mathworks.com/videos/developing-electrical-systems-with-simscape-electrical-simulating-a-microgrid-with-energy-storage-1653464186768.html