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# Multiple community energy storage planning in distribution networks using a cost-benefit analysis

Junainah Sardi [a,b], N. Mithulananthan [a,*], M. Gallagher [a], Duong Quoc Hung [c]

[a] School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, Australia
[b] Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[c] School of Engineering, Deakin University, Geelong, Australia

## HIGHLIGHTS

- Optimal site and size of multiple CES for maximizing total NPV.
- Optimal planning approach for multiple CES based on a cost-benefit analysis.
- Impact of CES unit numbers, PV penetration and load models on CES planning.
- Optimal CES operational characteristic to enhance load factors and voltage profiles.
- Comprehensive cost-benefit analysis that includes all possible CES benefits and costs.

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## ABSTRACT

This paper proposes a strategy for optimal allocation of multiple Community Energy Storage (CES) units in a distribution system with photovoltaic (PV) generation. The main contribution of this strategy is it considers all possible benefits accrued from and costs incurred by CES deployment to a utility. The benefits are gained from energy arbitrage, peaking power generation, energy loss reduction, system upgrade deferral, emission reduction and VAr support. A cost-benefit analysis is also conducted to identify the optimal Net Present Value (NPV), Discounted Payback Period (DPP) and Benefit-Cost ratio (BCR). Moreover, an optimal power factor approach is included in the analysis to dispatch CES units to improve load factors and voltage profiles. The probabilistic distribution of solar irradiance is also incorporated in the proposed strategy to consider the uncertainty of PV generation. Several sensitivity analyses are carried out to investigate the effects of PV penetration, load models and the number of CES units deployed on the profitability of CES investment. Numerical results show that the proposed strategy enables a power utility to identify the location, size and operational characteristic of CES units for maximizing the total NPV and enhancing load factors and voltage profiles.



## 1. Introduction

In recent decades, several revolutionary developments in power distribution systems have taken place around the world. One of them is minimizing the carbon footprint through large-scale integration of renewable energy such as hydro, wind, biomass and solar resources. Recently, 175 countries all over the world have signed onto a global agreement to significantly reduce carbon emissions in the face of the climate change threat [1]. This agreement may lead to the booming deployment of renewable energy for replacing the fossil fuel-based energy. Although renewable energy resources have a huge potential to reduce carbon emissions, a few of them are highly intermittent. Particularly, solar energy is only available during the day and relies heavily on the variability of solar irradiance, cloud, temperature, etc.

Energy Storage (ES) is regarded as one of the key solutions to facilitating seamless integration of intermittent renewable energy. It can also be used to deliver smarter and more dynamic energy services and address peak demand challenges [2–5]. However, the cost of ES, particularly battery is a major obstacle to its adoption [6]. It is also revealed that the current deployment of ES is still uneconomic as the overall ES installation cost is higher than the total benefit obtained from its deployment [7–9]. It is expected

* Corresponding author.
*E-mail addresses:* j.sardi@uq.edu.au (J. Sardi), mithulan@itee.uq.edu.au (N. Mithulananthan), marcusg@itee.uq.edu.au (M. Gallagher), hung.duong@deakin.edu.au (D.Q. Hung).

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that if all ES benefits and its cost reduction in the future are considered in the analysis, ES will be a profitable solution [10]. In addition, the successful deployment of ES would rely heavily on planning strategies, where the location, size and operational characteristic of ES should be considered to bring maximum techno-economic benefits to utilities and consumers.

The issue of optimal ES planning in distribution networks has attracted great attention in recent years. In [11], a bi-level optimization model was proposed to determine the optimal site and capacity of ES units by minimizing the total NPV of distribution networks. However, only load shaving and loss reduction benefits were considered in that work. The authors in [12] developed a probabilistic sizing and scheduling approach for ES units to mitigate the aggregated impact of both PV and electric vehicles. The authors also suggested that every distribution transformer must be equipped with ES, but this may not be profitable due to its excessive investment cost. Moreover, a study [13] presented a numerical approach to allocating and sizing ES units by minimizing costs through accommodating all spilled wind energy and reducing losses. In addition, several researches employed a wide range of heuristic approaches such as Genetic Algorithm (GA) with Simulated Annealing [14], a hybrid of GA and AC Optimal Power Flow [8], and Fuzzy Particle Swarm Optimization [15] to determine the optimal location and capacity of ES considering different objectives. Overall, the above survey reveals that the optimal ES planning may vary according to ES benefits considered. However, most of the existing studies did not comprehensively consider all benefits brought by ES. This consideration may not result in the most profitable investment. A comprehensive methodology for ES integration that conducts a techno-economic and social analysis was proposed in [16], where a demand analysis was used to determine the power rating and capacity of ES. Nevertheless, this evaluation was limited to ES installed in commercial buildings and did not consider any renewable energy integration. In addition, a comprehensive planning strategy was presented in [17], but limited to single CES deployment.

This paper proposes a comprehensive methodology to determine the optimal site, capacity and operational characteristic of multiple CES allocation by considering all possible benefits and costs incurred. The benefits are obtained from energy arbitrage, peaking power generation, energy loss reduction, system upgrade deferral, a reduction in $CO_2$ emission and VAr support. In order to achieve this, a cost-benefit analysis is conducted to identify the optimal Net Present Value (NPV), Discounted Payback Period (DPP) and Benefit to Cost ratio (BCR) of CES deployment. An optimal power factor approach is also proposed to dispatch the active and reactive power sizes of CES units to enhance load factors and voltage profiles. This paper also provides a quantitative analysis on the effect of the number of CES units deployed in the system, PV penetration and load models on CES planning. The impact of the number of ES units on the total NPV was investigated in [10,18]. However, in these works, only few benefits of ES were considered in the planning formulations.

In addition to the cost-benefit analysis, load modelling is considered as one of the crucial steps in ES planning. Normally, most studies in the literature have adopted a constant power load model in the planning of ES due to its simplicity [8,10–16]. However, there are more accurate load models for the power distribution system study reported in [19], one of which is the voltage dependent load model that represents the values of real and reactive power loads in distribution systems as a function of operating voltages. In the constant load model, it is assumed that the operating voltage at every bus in the system is 1 p.u. [20]. This is usually not the case for the distribution network. Though several works have investigated the impacts of load models on planning of distribution system elements such as capacitors and distributed generation [21,22], few studies on this issue has been found for ES planning. Consequently, a sensitivity analysis on the effect of load models is also useful to understand ES planning in depth.

The remainder of the paper is organized as follows: Section 2 describes various benefits of CES deployment. Section 3 discusses a methodology and mathematical formulation used in the planning strategy. Sections 4 and 5 present a 33-bus system and numerical results, respectively. Finally, Section 6 concludes the paper by highlighting the major conclusions and contributions of the work.

## 2. CES benefits

CES has a capability to shave the peak load by storing energy during the off-peak period and releasing the stored energy back to the grid during the peak time. This application will be the main aim of CES operation in this work. By applying CES for this purpose, demand profiles can be flattened and load factors can be improved. However, the economic feasibility of CES application should be justified by considering all associated investment costs and benefits. Possible benefits that can be achieved from shaving the load demand using CES are listed as follows:

- Peaking power generation - a reduction in gas combustion turbine plant costs due to the unleashed power from CES, during the peak load period for generating the same amount of peaking power [22,23].
- Energy arbitrage - the direct benefit from buying energy with a low price during the off-peak period and selling the stored energy back with a higher price during the on-peak period [24].
- Energy loss reduction - a reduction in the peak demand due to CES discharging some power to the grid that may reduce energy losses [24].
- Transmission and distribution (T&D) system upgrade deferral - which is defined as the annual cost that is avoided if a given T&D system upgrade project is deferred. For utilities, that amount is the annual revenue, which must be collected from utility ratepayers to cover the single-year cost [24].
- Reduction in $CO_2$ emission - peak electricity demand shaving by CES can reduce the $CO_2$ emissions from coal-fired power plants [15].
- Reactive power (VAr) support – that is used to maintain the voltage levels on the distribution and transmission system [25].

In order to capture all the above benefits, a planning methodology is developed in the next section.

## 3. Methodology

This section describes a methodology that is proposed in this work for CES planning. The aim of the problem formulation is to optimally site and size multiple CES units in a system with distributed PV generation by maximizing the total NPV obtained from CES deployment over a specified planning horizon. In the procedure of the proposed methodology, the inputs include distribution system data, the probabilistic generation model of PV, costs associated with CES deployment and the number of CES units. The decision variables used in the procedure are the optimal location and size of CES units in kW h. The GA toolbox in Matlab is used to solve the optimization problem presented due to its capability of handling integer variables and its robustness.

Fig. 1 briefly illustrates the procedure of the proposed methodology for CES planning. At the beginning of the procedure, GA generates an initial population for the optimization problem. The GA individuals for each system are characterized by a vector of the location and pre-assigned size of CES units, which are integer