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A Review of Energy Management Strategies with A Focus on Hosting Capacity in Modern Energy Systems

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Abstract

Renewable energy sources (RES) power output is variable and intermittent consisting of predictable and unpredictable fluctuations. Large-scale integration of RES requires solutions like energy storages to manage the increased intermittency. Management of energy flow among various generation and storage systems becomes crucial when multiple sources are integrated to the power system. To optimize power system performance and minimize negative impacts of RES, sizing of the storage components and energy management strategies and solutions become essential. The energy management, often using some optimization techniques, aims to ensure reliable and cost-efficient electricity supply and distribution. The details of energy management strategy depend on the type of network, its components and connected controllable energy resources. This review focuses on energy management strategies with a primary interest on hosting capacity (HC). Widespread adoption of distributed generation (DG) in distribution networks has increased different challenges and violations of operational limits. These issues include overvoltage, undervoltage, excessive line losses, transformer and feeder overloads, protection failures, and elevated harmonic distortion levels. Such problems arise when the distribution network exceeds its HC limit. This review includes an examination of HC's evolution, methodologies, and implications for grid resilience and sustainability.

1. Introduction

Over recent decades, there has been an intensive global push towards the development and utilization of renewable energy sources. These sustainable alternatives are now recognized as essential components of our energy sector. Governments worldwide have responded by implementing new regulations and policies that encourage the adoption of renewable technologies [1].

Key efforts include promoting renewable energy solutions, enhancing energy efficiency, and establishing conservation plans alongside legislative actions. The scope of development includes diverse renewable sources, backup systems, and energy storage technologies. Integrating these with conventional energy sources becomes crucial, especially for supplying isolated loads or microgrids placed far from the main power grid. Such hybrid energy systems ensure electricity supply continuity and quality despite the intermittent nature of renewables [2].

By strategically selecting appropriate renewable energy sources for specific geographical locations, we can significantly reduce our reliance on fossil fuels. This can occur through implementing a proper energy management strategy. Several strategies and techniques for employing energy management are depicted in Fig. 1. Through utilization of these management methods, we can enhance sustainability of the energy system. Optimal utilization of renewable resources while maintaining battery state-of-charge (SOC) has been proposed in [3]. The minimum power exchange rate between AC/DC microgrids was defined by the proposed system, which leveraged photovoltaic and wind energy. System consistency was enhanced through storage banks, and the fuel cell served as the hold-up resource to maximize generation system consistency. Power exchange management based on SOC was overseen by a supervisory controller. The multi-objective particle swarm optimization algorithm was employed for system optimization. Where a novel energy management system (EMS) for networked microgrids has been introduced. The interconnected microgrids facilitate information and power exchange. The proposed bi-level EMS handles information and power exchange between microgrids and schedules energy for individual microgrids during separation. A step-wise demand response program has been incorporated for cost-effective operation. Additionally, a new pricing model based on microgrid marginal pricing has been introduced in [4].

The stochastic energy management in a microgrid has been investigated in [5], considering RESs like solar, wind, and tidal power. The presence of demand response programs and storage devices has also been accounted for. Uncertainties related to RESs, demand, and electricity prices were addressed using Monte Carlo simulation. The model, a linear multi-objective optimization, aimed to minimize costs and emissions. Additionally, interactive fuzzy decision-making guides the selection of the best solution from the Pareto set based on planner criteria.

A unified approach to constructing and optimally managing community microgrids has been presented in [6]. These microgrids feature an internal market, considering social, environmental, and economic benefits. A novel modeling framework based on bilevel programming and reinforcement learning for structuring and solving the internal local market has been introduced. Entities within the community microgrids can exchange energy and services. proposed approach enabled interaction between local control systems and the community microgrid operator.

Furthermore, the integration of conventional and renewable energy systems enhances overall grid reliability, even in challenging environmental conditions. This synergy not only mitigates the limitations of renewables but also creates new investment opportunities. Therefore, the global transition toward renewable energy is reshaping our energy landscape, fostering sustainability, and opening doors to innovative solutions [7].

The adoption of distributed generation technologies like photovoltaic (PV) and wind energy has transformed the traditional flow of power in electrical systems. The development of renewable DG technologies has been motivated by various factors, including political, social, economic, technical, and environmental considerations. However, it's crucial to recognize that an excessive influx of DG can have adverse effects on system performance [8]. Issues such as overvoltage, thermal strain on network equipment, and potential protection equipment malfunctions need careful evaluation. System capacity must be assessed to accommodate these new DG sources without compromising operational limits. In deregulated energy markets, a tension exists between DG investors, who advocate for greater DG integration, and distribution system operators (DSOs), who are cautious about managing excessive DG penetration.

To address this conflict, a transparent and equitable solution was necessary to determine when to accept or reject requests for integrating new DG sources. Here is where the concept of hosting capacity (HC) enters. This concept was initially proposed by André Even, the HC idea was further refined by Math Bollen and colleagues in 2011 [9]. While the term "hosting capacity" wasn't commonly used in electrical applications, it had been employed in other fields, such as computer science, where it defines a web server's ability to handle incoming access requests. In the context of electric power systems, similar terms like "absorption capacity" were suggested—referring to the maximum PV capacity that could be added without requiring reinforcement of any distribution system segment. The key advantage of HC lies in its straightforward use of clear performance indicators and limits as criteria for assessing DG penetration, making it a practical and measurable approach.

This paper aims to review several works in energy management strategies. Additionally, the concept of hosting capacity—a critical parameter in assessing the integration potential of distributed energy resources within power grids is

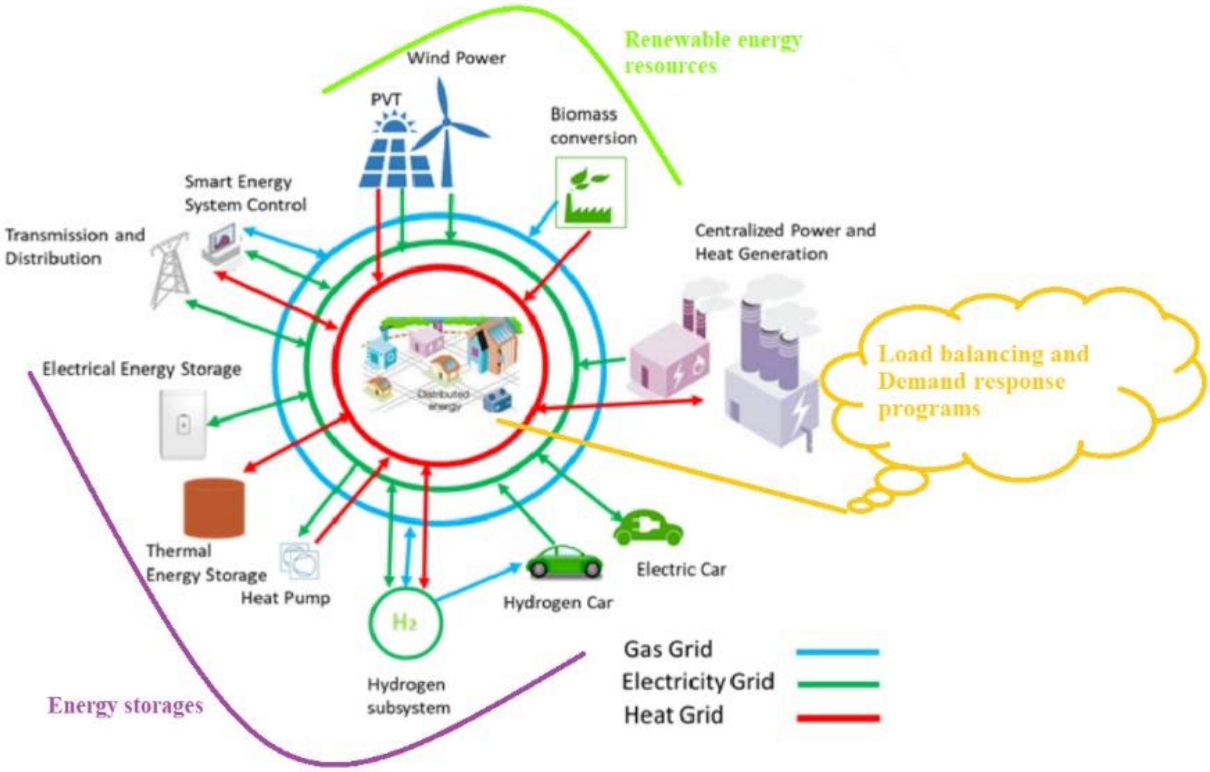

Figure 1. Different types of energy management

explained. This exploration includes an examination of hosting capacity's evolution, methodologies, and implications for grid resilience and sustainability.

2. Hosting Capacity Estimation

The concept of hosting capacity, primarily comprehended in 2004, was further developed by Math Bollen and his team in 2005 [10]. They proposed the HC approach to evaluate the effects of escalating DER integration on power systems. This method aimed to compile the technical constraints set by both system operators and consumers. They characterized the HC as the peak DER penetration level at which the power system can function effectively. The computation of HC is not a static process with a singular outcome. Instead, it should be determined for different performance indicators such as variations in voltage and frequency, thermal overload, issues related to power quality, and protection challenges. Deuse and his team outlined the methodology used in the European Distributed Energy Partnership project to evaluate the incorporation of DERs into European distribution systems over a decade (2010–2020) [11]. The project emphasized DERs connected to MV or LV distribution networks with a rating of 10 MW or less, and the HC concept was further developed during this project. In the work of Bollen and Hassan, the HC is described as the maximum number of DG units that can be incorporated into the power system, beyond which the system performance deteriorates. The criterion for calculating HC is explained with a focus on the performance index used for its calculation, demonstrated through representative power system models [9]. The concept of HC is becoming important among the European countries as it is recommended by the European energy regulators and by the European network operators as a way to quantify the performance of the future electricity network. The latter additionally highlighted the advancement of techniques for computing renewable hosting capacity within distribution networks as a key focus in their strategic plan for Europe's future power grid. The influence of extra DER on a network can be assessed through various performance indicators, including measurements related to power quality such as voltage magnitude, voltage dips, and the risk of overload.

Fig. 2 introduces the concept of HC in relation to various limiting factors. In this Fig. 2, the original performance cure and the performance curve after implementation of HC enhancement are indicated through solid line and dashed line, respectively. When we focus on the overvoltage in our energy system. When incorporating PV systems into the grid, there exists a limit beyond which the system's voltage constraint will be breached. Further increases in PV integration can disrupt the system's steady operation. Consequently, studies on HC prevent the network from entering an unacceptable operational region beyond the defined limit line [12].

It is worthwhile to mention that HC can be assessed based on several parameters such as thermal HC, current HC, and voltage HC. While the specific criteria may vary across studies and grids, power quality standards are commonly used and predefined by network operators. If any of the evaluating constraints exceed their predefined limits, the DG connected at that point in time will define the HC of that network. To establish the HC limit, certain performance indices of a grid are selected, and an acceptability limit for those indices is defined. The limiting constraints for a network depend on the nature of the network and the type of grid selected. For instance, in rural networks (typically radial and long), voltage level violation is the primary concern, while in urban regions, current/thermal limit violation of the equipment becomes the defining constraint due to large loads [13].

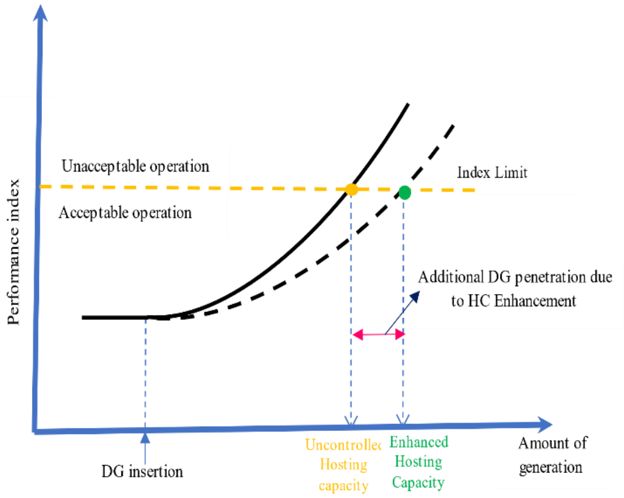

Figure 2. The definition of the hosting capacity

In [14], four distinct methods - deterministic, stochastic, optimization-based, and streamlined - are introduced for the computation of HC in distribution networks. Each method is shown to have its unique strengths and weaknesses. The deterministic method is found most appropriate for sizing a single RES at a specific location if the generation profile is known or can be predicted. On the other hand, the stochastic method is suitable for sensitivity analysis and forecasting.

Enock Mulenga et al. presented three different methods - deterministic, stochastic, and time series - for determining the solar PV HC of low voltage distribution grids [15]. The authors discuss the advantages and disadvantages of all three methods. The deterministic method is noted for its speed, with its accuracy depending on the model and method used to calculate voltage rise. In contrast, the stochastic and time series methods require a large number of simulations and computational time, which is a significant concern.

3. Effect of Energy Management System on HC improvements

Energy management systems are crucial for optimizing HCs within distribution networks. One such system is the distributed energy resources management system (DERMS), as discussed in [16]. DERMS is designed to synchronize the flexibility of DERs with the goal of maximizing HC.

DERMS operates both individually and in an aggregated manner, integrating all DERs across a distribution network. When aggregated, it allows the DSO to manage DERMS, aiming to incorporate the maximum amount of renewable-based DGs while ensuring power system security.

For instance, [17] proposes an energy management strategy based on model predictive control. This strategy targets enhancing the hosting capacity of PVs and EVs. The control algorithm leverages a storage unit located at the end of the feeder in an islanded microgrid. Results indicate a significant increase in HC for the stand-alone microgrid, meeting all operational constraints of the network.

In the study [18], a demand-side energy management system is introduced to enhance the HC of the distribution network. The research presents a distributed control strategy that regulates the operation cycles of thermal loads, such as domestic electric water heaters and heating, ventilation, and air conditioning (HVAC) systems. The primary objective is to adhere to the operational constraints of the network while maximizing the PV hosting capacity in the LV feeders under investigation. Additionally, the model prioritizes users' thermal comfort by ensuring temperatures remain within predefined minimum and maximum limits. The simulation results demonstrate that, the overvoltage caused by PVs was alleviated which causes less PV curtailments and thus higher HC.

In another study introduced by [19] a management system is designed to synchronize the operation of the onload tap changer (OLTC) transformer, EV charging/discharging, and reactive power support from PV inverters to optimize the HC of photovoltaics in the local network. The proposed two-layer optimizer focuses on optimizing the charging/discharging power of EVs, OLTC taps adjustments, and reactive power support in the inner layer, while the outer layer aims to maximize the size of PV systems, thereby enhancing the PV hosting capacity of the network.

The summary of the main novelties of some of the studied works has been provided in Table 1.

Table 1: The summary of the studied works.

	Ref.	The main contributions of each study
Energy Management	[1]	The impact of economic policy uncertainty and financial development on renewable energy consumption
	[2]	Hybrid whale optimization algorithm and pattern search algorithm optimizes operations of mixed power units and energy storage to minimize operating costs.
	[3]	Uses multi-objective particle swarm optimization algorithm to enhance generation consistency and minimize power exchange between AC/DC micro-grids utilizing photovoltaic, wind energy, storage banks, and fuel cells.
	[4]	Implementing a bi-level energy management system (EMS) for isolated MGs, incorporating cyber-physical connections for data and power exchange within microgrids. The outer-level EMS facilitated information and power exchange between interconnected microgrids, while the inner-level EMS managed energy scheduling for individual microgrids in case of disconnection. Interconnected microgrids were radially linked via tie lines.
	[5]	Studying a stochastic energy management within a microgrid, integrating RESs like solar, wind, and tidal, alongside demand response programs and storage devices to address the uncertainties in RES output, demand, and electricity prices using Monte Carlo simulation. The approach is based on linear multi-objective optimization, aiming to minimize both cost and emissions.
	[6]	Utilized Monte Carlo tree search algorithm to enhance bi-level optimization for maximizing public welfare via a marginal pricing scheme, ensuring beneficial energy exchange within the community.
	[7]	A quantitative review of research themes in smart homes and cities, identifying barriers to smart home progression into sustainable smart cities via qualitative review. It suggests innovative solutions for advanced energy conservation systems in sustainable smart cities, including infrastructure construction and new energy trading strategies. Proposed responses to future research challenges include real-time energy monitoring, intelligent energy management, and integrated energy network technologies, applying a "bottom-up approach" from smart home to smart city levels.
	[8]	This review categorizes methods for reducing excess electricity in stand-alone hybrid renewable energy systems (HRESs) into four categories: direct use, storage, indirect use, and production decrease. It highlights deferrable loads, power-to-heat, storage banks, power-to-hydrogen, power-to-gas cycles, multiple generators, and loss of power supply as prevalent methods, discussing their impacts on energy cost, renewable fraction, and excess electricity reduction potential in HRESs.
Hosting capacity	[9]	Studying the design and operational challenges in distribution and transmission systems arising from distributed generation integration. It introduces the HC approach, which quantitatively measures the allowable generation connection without system performance degradation. This approach necessitates well-defined performance indices and acceptable limits.
	[10]	Reviewing the developments, assessment techniques, and enhancement technologies related to HC. It is organized into four main sections: historical developments, performance limits, perceptions, and enhancement techniques. Additionally, it includes practical experiences

		from system operators and energy markets, as well as insights from real case studies.
	[11]	Providing insights into the potential impacts of EU policies regarding integrating electricity markets on market efficiency and on different market players with the aim of supporting policy makers to increase the penetration of renewables in a cost-efficient manner.
	[12]	Proposing a stochastic multi-objective optimization model to maximize the distribution network's HC for wind power and minimize the energy procurement costs in a wind integrated power system.
	[13]	Using a stochastic time-series method to investigate the impacts of EV penetration levels and EV charging forms on the HC of a local residential electricity network.
	[14]	Methods for quantifying PV HC in low voltage distribution grids are categorized into three: deterministic, stochastic, and time series. They vary in input data, accuracy, computation time, consideration of uncertainties, time-related influences, and models used. Uncertainties, both certain and uncertain, need consideration, with the latter addressed in some stochastic methods.
Energy management and Hosting capacity	[17]	The improvements of the HC of PVs and EVs in a stand-alone MG with an energy storage by considering a model predictive control-based energy management system.
	[18]	Proposed a distributed scheme to boost PV HC in LV feeders by adjusting domestic load profiles without compromising consumer comfort. The scheme optimally manages HVAC and EWH systems based on a linear model decomposed into a master problem (SwM) and sub-problems (HwM) using the Dantzig–Wolfe method. Each sub-problem corresponds to an HwM, and data exchange between HwMs and SwM occurs iteratively, ensuring consumer privacy and avoiding congestion in control centers and communication systems.
	[19]	Proposes a novel stochastic approach to maximize photovoltaic hosting capacity in distribution systems. It coordinates control devices like transformer taps and VAr sources while considering the stochastic nature of electrical vehicles. The model accounts for variables such as arrival/departure times and battery state of charge conditions.

4 Conclusions

In conclusion, the inherent variability and unpredictability of renewable energy sources necessitate smart design strategies to mitigate their intermittent nature. While these strategies may incur higher costs, they are vital for the efficient management of energy across diverse supply and storage systems. Proper sizing of components and the implementation of a robust energy management strategy, often reinforced by optimization techniques, are critical for ensuring uninterrupted power supply and cost-effectiveness. This research has been conducted to explore energy management approaches. However, the proliferation of DGs poses significant challenges, potentially leading to operational breaches such as voltage irregularities, increased line losses, and equipment overloads, which can compromise system protection and induce unacceptable levels of harmonic distortion. These complications typically emerge when the system's hosting capacity is exceeded. Where HC serves as a pivotal concept that facilitates a transactional framework for assimilating a multitude of energy systems into the distribution network, thereby enhancing grid resilience and promoting sustainability. Hence, the definition, methodologies, and broader implications of hosting capacity, underscoring its role in the evolution of modern electrical networks. In summary, DER energy management systems and control strategies are vital for maximizing HC. Coordinated management strategies incorporating active and reactive power management of DERs, along with onload tap changer adjustments, empower DSOs to efficiently manage their networks, thereby augmenting the hosting capacity of renewable DGs. However, additional future studies are needed to analyze how different types of energy management systems, implemented at various levels of distribution networks (including individual customer, community, and city-wide levels), affect the HC of distribution networks.

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