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Review

On Hybrid Nanogrids Energy Management Systems—An Insight into Embedded Systems

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Abstract: In recent years, the growing demand for efficient and sustainable energy management has led to the development of innovative solutions for embedded systems. One such solution is the integration of hybrid nanogrid energy management systems into various applications. There are currently many energy management systems in different domains, such as buildings, electric vehicles, or even naval transport. However, an embedded nanogrid management system is subject to several constraints that are not sufficiently studied in the literature. Indeed, such a system often has a limited energy reserve and is isolated from any energy supply for a long time. This paper aims to provide a comprehensive overview of the current state of research, advancements, and challenges in the field of hybrid nanogrid energy management systems. Furthermore, it offers a comparative analysis between hybrid nanogrids and microgrids and the implications of their integration in embedded systems. This paper also discusses the key components, operation principles, optimization strategies, real-world implementations, challenges, and future prospects of hybrid nanogrid energy management systems. Moreover, it highlights the significance of such systems in enhancing energy efficiency, reducing carbon footprints, and ensuring reliable power supply.

Keywords: nanogrid; energy management system; power management system; optimization; hybrid system; embedded system; isolated nanogrids; renewable energy sources

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Citation: Bitar, M.; El Tawil, T.; Benbouzid, M.; Dinh, V.B.; Benaouicha, M. On Hybrid Nanogrids Energy Management Systems—An Insight into Embedded Systems. *Appl. Sci.* **2024**, *14*, 1563. https://doi.org/10.3390/app14041563

Academic Editor: Antonio Ficarella

Received: 20 November 2023
Revised: 20 January 2024
Accepted: 2 February 2024
Published: 15 February 2024

1. Introduction

Between 2009 and 2019, global energy consumption witnessed a 21% increase and is expected to grow by over 50% by 2050 [1]. To meet this escalating demand, the world's energy production in 2018 reached 14,421 million tons of oil equivalent (Mtoe), with fossil fuels accounting for more than 81% of the total production [2]. However, the adverse environmental impacts, including greenhouse gas emissions, have led the international community to address climate change, resulting in the signing of the Paris Agreement in 2016. The objective of this agreement is to significantly reduce global warming and the associated risks of climate change. In this context, renewable energy sources are expected to play an important role in achieving the objectives outlined in the COP21 agreement for a sustainable and decarbonized future [3].

To ensure a consistent power supply, it is essential to manage energy flows (including production, consumption, and storage) in an optimal manner. An energy management system (EMS) is necessary to effectively manage the distribution of energy to different loads and storage systems. This is especially important for renewable energy sources, as their intermittency requires advanced prediction of production, storage capacity, and consumption needs. By integrating these various constraints, an EMS can help minimize energy losses and ensure efficient energy usage. In the context of modern energy management, a nanogrid emerges as a small-scale power grid that can operate independently or in parallel with a larger grid. Hybrid nanogrids particularly highlight the incorporation of various energy sources, enhancing the adaptability and robustness of the energy management system. In the context of applications of nanogrids, an embedded context refers to situations where nanogrids are integrated into or used as part of other systems or devices to enhance local power distribution and management.

A nanogrid is similar to a microgrid, but it is a scaled-down version of it and often has lower power and less complexity than microgrids [1–5]. According to [6], a distributed island resource system (considered a microgrid) meets four requirements: (i) integrate DERs and loads; (ii) have the capability of being disconnected (in parallel) from the electric power system; (iii) contain the local electric power system; and (iv) be purposely planned [7]. While microgrids have undergone significant standardization efforts due to their relatively large size and impact on the overall grid, nanogrids, despite their popularity, lack a clearly defined standard to the same extent [8]. Some references provided a definition for the term nanogrid using the following statements:

- "a single domain for voltage, price, reliability, quality, and administration" [9].
- "a small power system that uses a combination of renewable and non-renewable energy sources to supply power to small local loads" [10].

Additional definitions are cited in [11].

Nanogrids are characterized by their compact size and flexible functionality. This complex system includes diverse types of electrical equipment, along with a combination of renewable and non-renewable energy production sources. Additionally, nanogrids are integrated with energy storage systems, further enhancing their capacity to deliver reliable and sustainable power solutions [11–22]. Despite being a relatively new area of research in the field of power systems, nanogrids are gaining interest from both small and large research groups worldwide [23]. This is evident from the keyword searches for "microgrid" or "nanogrid" and "energy management" in the Elsevier and IEEE databases shown in Figure 1.

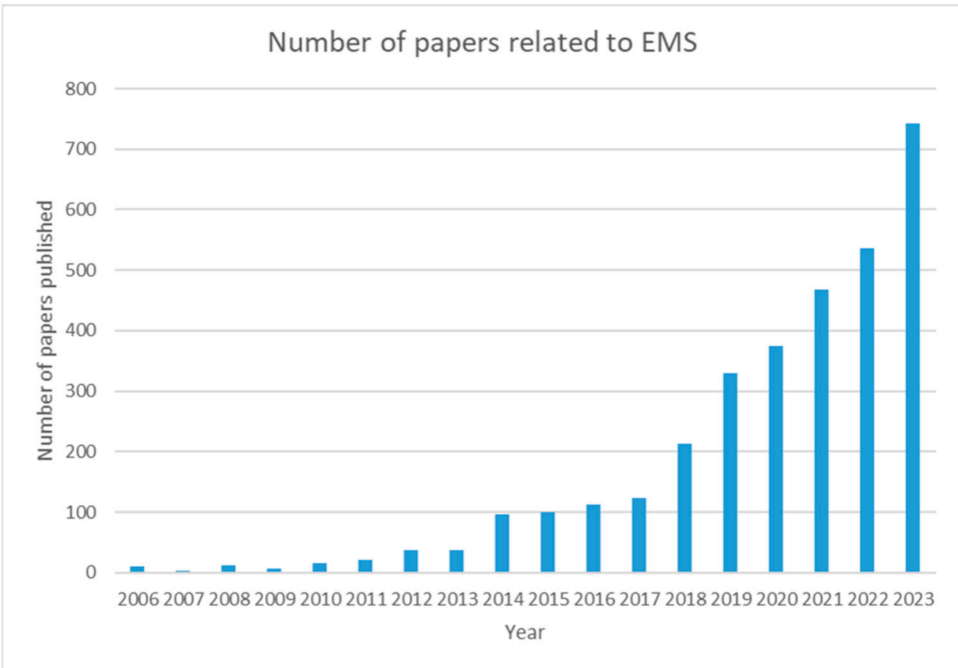

Figure 1. Number of published papers on EMS for microgrids and nanogrids.

Despite the promising potential of renewable energy sources such as solar, wind, and tidal power, their intermittent nature presents many challenges. As a result, energy storage systems (ESS) have emerged as an essential component of renewable power plants, improving their reliability and dispatchability. Moreover, the integration of ESSs brings additional economic benefits by storing excess power during periods of low demand or low generation costs, which can be utilized during peak periods with higher electricity prices [24]. This facilitates the transition towards a more flexible, cost-effective, and electrified future [7–10]. Over the past few decades, various types of ESSs have been developed and classified based on their specific storage mechanisms.

This paper addresses the case of hybrid nanogrid energy management systems used in an embedded context. The system contains a variety of energy production sources, including wind turbines, solar panels, and tidal turbines, as well as fossil fuel-based sources. The production sources must generate enough energy to ensure the power needed for all the loads. Additionally, the system is equipped with energy storage systems such as batteries and fuel cells. An embedded system is a specialized computer system designed to perform specific functions within a larger device or system. It is distinct from general-purpose computers and is typically integrated into a host device to execute dedicated tasks or control functions. Embedded systems are characterized by their compact size, efficiency, and real-time processing capabilities. They often interact with the physical world through sensors, actuators, and communication interfaces, enabling them to monitor and control devices, machinery, appliances, vehicles, and various other applications [25]. An ongoing evolution in embedded systems is to achieve optimal system performance in response to changing factors such as environmental conditions and user requirements. In printing systems, for example, customers are increasingly looking to achieve higher productivity while also aiming to reduce the energy consumed. One approach to achieving these desired outcomes involves two key steps: first, ensuring system adaptability to enable the adjustment of system characteristics; and second, using this adaptability to effectively manage the operation of the system within the existing conditions in order to ultimately optimize its performance [26]. The appropriate value for the control parameters (decision variables) must be chosen to optimize the system's characteristics (objectives). The power applied to a component and the speed of the system are two examples of parameters. The range of possible values is often constrained. For example, a component requires a certain amount of power at a given speed. This is an optimization problem known as multiobjective optimization. In this context, this paper provides a review of the EMS used for a hybrid nanogrid in an embedded context.

Several review studies have covered various microgrid topics, including interconnecting multiple microgrids [27], a survey of experimental microgrid systems implemented in Europe, North America, and Asia [28], microgrid protection and control schemes [29], and microgrid reactive power compensation methods [30]. They also discussed droop control methods [31], control strategies for voltage and frequency regulation of microgrids [32], and control methods for inverter-based microgrids [33]. They considered the modeling, design, planning, and architectures of hybrid renewable microgrids and nanogrids [34], control strategies for distributed energy resources in microgrids [35], and an analysis of AC and DC microgrids [36]. Reviews of homeostatic control-based energy-efficient microgeneration systems [37], microgrid uncertainty quantification techniques [38], and a review of network-based energy efficiency in buildings and microgrids [39] were also included in the literature.

The state of the art in the field of EMS is large, but it has been developed for applications that do not directly address the problem considered in this study. EMS for buildings describes some techniques for modeling occupant comfort as well as for load management, especially those that are modifiable over time or over the duration of use [40,41]. Other work aims to increase the energy efficiency of a building by satisfying the needs of the occupants [42]. A rule-based, real-time EMS for the development of integrated microgrids has been proposed by Sechilariu et al. [43]. They describe a rule-based power control algorithm that can switch between grid supply, load shedding, battery charging and discharging, and PV limit modes. The choice of procedures is based on battery SOC, time-of-use tariff, and load generation imbalance. PV power, load demand, and the reference DC bus voltage are used as inputs in the PI controller to determine the load generation imbalance, which stabilizes the DC bus voltage. Battery backup and the main grid compensate for this imbalance. Mendes et al. [44] suggested a hierarchical framework for a grid-connected microgrid with optimal energy management and vehicle-to-grid operation in order to guarantee its stability at the first level and its profitable operation at the second level. Energy trading with the main grid, maximizing the use of renewable energy, and managing the operation of electric vehicles and batteries are all part of the economic operation of the microgrid. Experimental verification of the performance of the proposed method is also provided. To achieve efficient energy management within residential microgrids, Igualada et al. [45] proposed a model that aims to minimize operating costs. This model takes into account energy trading expenses, penalties associated with adjustable load shedding, battery wear costs for electric vehicles, and a notion related to electric vehicle range anxiety. The loads considered include critical, adjustable, and shiftable categories. Range anxiety in the context of electrical vehicles is defined as the fear of running out of battery charge before reaching the intended destination. The study explores three scenarios based on risk levels within the range anxiety concept to assess the trade-off between microgrid operating costs and the average state of charge (SOC) of EV batteries. In the field of electric vehicles, EMS is mainly used to reduce energy consumption, and the only performance criterion is the gain in autonomy [46]. For the maritime sector, many studies address dedicated EMS for ships [47]. Many constraints related to the stand-alone maritime environment and the management of renewable energy are often implemented (such as the balance between energy production and demand, hardware limitations of the generators and storage systems used, voltage and frequency balance of the grid, environmental limitations, and navigation constraints).

The literature on EMS for buildings primarily focuses on devices connected to an electrical grid [48]. The combination of multiple sources and loads in buildings is similar to the constraints found in stand-alone systems. However, there is limited research on stand-alone systems, particularly in the context of embedded systems. Factors such as uncertainties and risk assessment, operational flexibility and reliability, comfort level monitoring, and user behavior are not typically developed for an embedded system. As such, this paper presents an assessment of the advancements and challenges in the field of hybrid nanogrid EMS. Section 2 provides an overview of nanogrid architectures and technologies. Section 3 provides a review of different nanogrid EMS strategies based on the various solution approaches used by the authors and their main limitations. Energy storage systems are discussed in Section 4, followed by future directions.

2. Nanogrids Technologies and Architecture

2.1. Nanogrids versus Microgrids

Renewable energy resources are being deployed on a large scale to meet the demands of increasing energy consumption, reduce environmental pollution, and provide socio-economic benefits for sustainable development [49]. Microgrids are enabled by the integration of such distributed energy resources into the utility grid. The idea of a microgrid has been developed to create a self-sufficient system of distributed energy resources that can operate in island mode during grid outages. In a microgrid, an energy management system is required for the intelligent, safe, reliable, and coordinated use of these distributed energy resources.

A nanogrid is a single-distribution power system that can operate in stand-alone or grid-connected mode. It consists of local power production, providing local loads with power when needed. It can be used for a single house, a small building, or a small-scale site with the ability to connect or disconnect from other power entities like ESS and/or a control system via controllers and converters [11]. The nanogrid must have at least one local power production unit (renewable sources or fossil fuel-based sources). To ensure the stability of the system, energy storage devices can be used, and they are selected based on many parameters like cost and life cycle. The presence of a controller is also necessary for a nanogrid to coordinate the essential operational strategies [15].

The majority of the world's power transmission is based on AC technology, which has historically replaced DC transmission due to the convenience of transformer-based voltage boosting for long-distance transmission [50,51]. The choice of AC or DC nanogrids is influenced by several factors, such as the type of energy sources, the type of load, energy storage technology, and regulations. AC nanogrids are more commonly used due to compatibility with the traditional grid and the widespread use of AC appliances, but DC nanogrids are gaining popularity for their simplicity and efficiency in certain applications. DC/AC converters can be used when energy sources and loads generate or require different types of electrical current. They ensure that the electrical energy generated or stored in a nanogrid can be used to provide power for the loads effectively and efficiently. The major benefit of a DC microgrid is the favorable integration of power electronics, as shown in Figure 2, but AC microgrids are still the main architecture in the field. When various sources and loads, whether AC or DC-based, are connected to the AC grid, a two-stage energy conversion process is typically required. This includes transformations such as AC–DC–AC for sources and AC–DC–DC or AC–DC–AC for loads. Hybrid AC/DC microgrids, which combine AC and DC microgrids, can further reduce the number of conversions within microgrids, thereby maximizing investment costs and efficiency [52,53]. Hybrid AC/DC microgrids have been the core architecture for land-based distribution systems, including zero and net-zero buildings [54], transport, and energy integration [55,56], ranging from utility and municipality to military applications. In hybrid AC/DC microgrids, ESSs are essential to achieve both AC and DC sub-grid forming capacity to support AC bus voltage/frequency and DC bus voltage. Multiple hybrid AC/DC microgrid connections can be easily expanded using a modularized design. Compared to traditional AC grids, a hybrid grid system is more efficient. This is particularly important in remote and emergency applications where energy needs to be used as efficiently as possible [57].

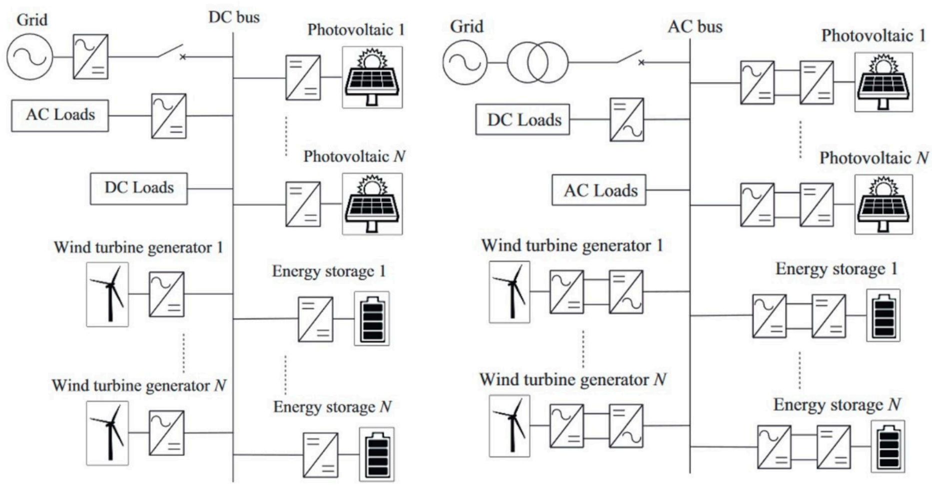

Figure 2. General DC and AC architectures. Reproduced from [57].

The existing research in the nanogrid field can be divided into the following groups: concept, control, hardware, and software. It has received the attention of many researchers in the fields of energy/power management for its important perspectives in power system engineering [12,58]. According to Energizing Development [59], nanogrids are generally considered to be in the power range of 500 Wp to 10 kWp. Microgrids are generally used for managing multiple buildings or a small town, whereas nanogrids are usually used for one system (a single house/building, a vehicle, an airplane, a sailboat, or a small community) [11]. Nanogrids can operate in islanded or grid-connected mode, which is a characteristic also found in microgrids [60–62]. Nanogrids are generally less expensive to install and maintain than microgrids because they are smaller and require fewer components. On the other hand, microgrids require larger and more complex infrastructure, which can result in higher initial costs. The main difference between microgrids and nanogrids is based on some factors like system size, power rating, load size, complexity, hardware configuration, and control strategy. The margin of these factors between nanogrids and other grids is still debated and is presented in [11]. Table 1 summarizes the comparison between a nanogrid and a microgrid.

Table 1. Comparison between nanogrids and microgrids based on different features.

Feature	Nanogrid	Microgrid
Size	Small, serving a single house/building or small community	Larger, serving multiple houses/buildings or a larger community
Power Generation	Includes renewable energy sources and energy storage, relying on local resources for power generation	Includes renewable energy sources, energy storage, and is connected to traditional power sources
Control	Usually operates independently. Requires simpler regulations.	Can operate in grid-connected or island mode. Requires more complex regulations.
Complexity	Simpler in design and operation	More complex due to the larger scale and integration of multiple power sources and energy storage options
Flexibility	Designed for specific applications, with limited flexibility to adapt to changes	More flexible in terms of integrating different energy sources and adjusting to changes in demand

Nanogrids are typically smaller in size and can be designed to match the specific energy demand of an embedded system, which can result in lower capital costs and operating expenses compared to larger microgrids. Nanogrids also have the ability to incorporate energy storage solutions, such as batteries or flywheels, which can help to further improve the reliability and stability of the energy supply. Nanogrids may be more resilient and secure than microgrids, particularly if the system is designed to operate in island mode. This can be important for embedded systems that require a high level of security and resilience.

Nanogrid technology is still relatively new and, as such, may have a higher level of risk and uncertainty compared to more established microgrid technology due to the complexity of the technology and the potential for unexpected failures or downtime. While designed for smaller-scale applications, nanogrids present complex challenges due to the integration of diverse energy sources, such as solar panels, wind turbines and energy storage systems, into localized networks. This complexity can lead to unexpected failures or downtime, a notable vulnerability of nanogrids. Unlike microgrids, which often have redundancy and backup generation, nanogrids may lack such resilience. A single component failure in a nanogrid can disrupt the entire energy supply, raising reliability concerns. In addition, nanogrids may be more vulnerable to cyberattacks and security breaches due to their complex and interconnected nature. This could result in increased maintenance and support costs, more robust security and privacy measures, and a high level of operational flexibility and reliability. However, as the technology becomes more mature and widely adopted, these costs may decrease. While making the distinction between a nanogrid and a microgrid, it is important to note that the two are not always mutually exclusive. The modular design of the nanogrid allows several nanogrids to be grouped together to form a microgrid [63].

2.2. Structure and Components of a Nanogrid

The basic composition of a hybrid nanogrid, as shown in Figure 3, includes many components. Energy sources (solar panels, wind turbines, battery storage, or diesel generators) are present to provide energy supply. Energy storage systems (ESSs) are used to store excess energy generated by energy sources and provide it during periods of low energy production. The loads are the end-use devices or systems that consume energy in the nanogrid, such as lighting, appliances, and communication systems. Power electronics and converters are used to convert and manage the flow of electrical energy within the nanogrid, ensuring that the energy is properly distributed to the loads. They also provide real-time visibility into the performance of the system. The energy management system (EMS) is responsible for controlling and regulating the flow of energy between the energy sources, energy storage, and loads. It consists of a control system responsible for coordinating the operational strategies of the nanogrid, such as load management and energy balancing, to ensure its stability and reliability.

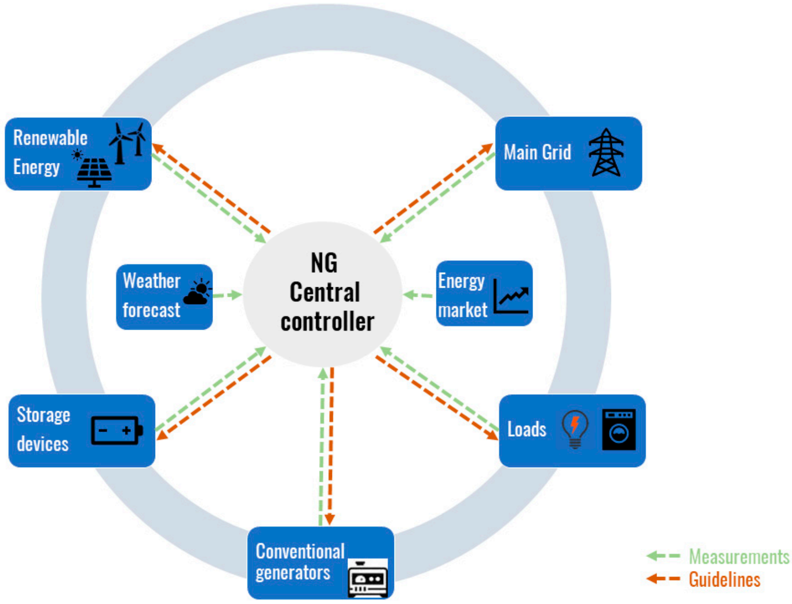

Figure 3. Structure of a hybrid nanogrid.

Microgrids are generally used for managing multiple homes or buildings, whereas nanogrids are usually used for one system (a single house/building or a small-scale load) [8]. Nanogrids and microgrids have separate functions in the power hierarchy. For instance, by linking multiple nanogrids, a microgrid can be established [11]. There are two categories of centralized and decentralized EMSs in the supervisory control architecture of the EMS. In the centralized EMS, the central controller collects all the data, including energy resource generation, cost function, weather information, customer energy consumption patterns, etc. The centralized EMS then decides on the best energy planning and informs all the local controllers of its findings. In the decentralized EMS architecture, however, the central controller sends and receives all data to the local controllers in real-time. Each local controller sends a demand or generation request to the central controller for both the present and the future. The best scheduling is decided by the central controller and sent back to the local controller. The latter can disagree with the way things are going and keep negotiating until both global and local targets are met [49].

3. Nanogrid EMS

3.1. Overview of EMSs

The International Electrotechnical Commission, in its IEC 61970 standard on the application program interface of EMSs in power system management (version 1.1 or later), defines EMSs as follows: "a computer system comprising a software platform providing basic support services and a set of applications providing the functionality needed for the effective operation of electrical generation and transmission facilities so as to assure adequate security of energy supply at minimum cost" [64]. A nanogrid EMS consists of software and hardware systems used to monitor, control, and optimize the generation, storage, and distribution of energy within the nanogrid. It ensures efficient and reliable energy flow, maximizes energy utilization, and reduces energy waste. The EMS is responsible for real-time energy monitoring, load forecasting, and energy scheduling to minimize energy costs and improve overall grid stability. An EMS also includes communication protocols for exchanging data with other components of the nanogrid. Many studies have been conducted in this emerging field, and some research shows the use of hybrid energy in embedded systems. As shown in Figure 4, a nanogrid EMS performs a number of tasks, including the monitoring, analysis, and forecasting of power generation and load consumption, taking into account energy market pricing, ancillary market prices, and meteorological data. These features support EMS in maximizing MG performance while respecting the technical limitations.

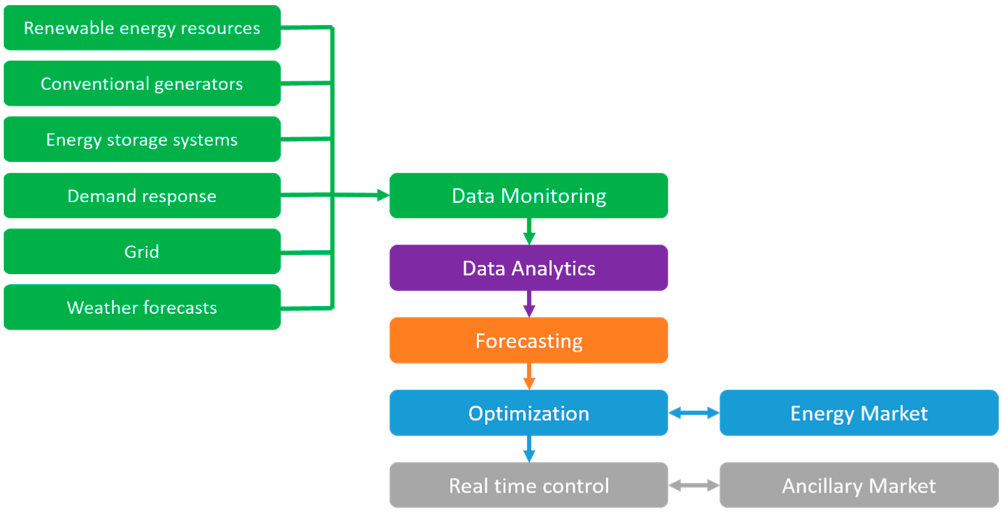

Figure 4. Nanogrid EMS functions.

A building energy management system has been developed with the objective of adjusting consumption to the available energy resources while maximizing the comfort of the inhabitants. It is modeled as an integer mixed linear problem model consisting of several binary and continuous variables, constraints, and an objective function to be minimized [65]. A comparison is made between several solution approaches for the optimization of multi-source and multi-client power flows. This study is directed towards a hybrid centralized solution: a central system receives information from all the equipment and controls it [66]. This approach is further studied, where the optimization is based on the different operating modes of the electrical equipment, the preferences of the users, and also the electricity prices. The electrical equipment is thus divided into three categories: permanent, which runs over the whole horizon, like the freezer; temporary, which needs a specific request to run; and unsupervised, which is not managed by the EMS. In this study, two different approaches are proposed to design the energy management system: the non-centralized approach (multi-agent systems), adopting a distributed architecture and resolution through cooperation between the different agents of the system and the exchange of information between them, and the centralized approach, which is a linear formulation of the problem to be optimized [40]. A human–machine interface with an EMS has been designed in G-homeTech and aims to make substantial savings by avoiding consumption during peak prices for buildings [67]. A study is carried out to identify energy efficiency measures and innovative technologies to ensure that the energy efficiency of buildings is maximized while meeting the needs of the occupants [68]. A linear system for building energy management has been designed with the aim of minimizing the cost of electricity while satisfying the thermal comfort constraint [69].

A farm design consisting of a combination of wind turbines, tidal turbines, diesel generators, and pumped hydro storage was developed while compromising the overall cost of the system for a 15-year period and the minimization of CO_2 emissions. This renewable energy farm is dedicated to energy production in a self-sufficient marine context [70]. In another study, an optimization algorithm for a microgrid system is proposed, containing a wind turbine, a micro-turbine, a diesel generator, a photovoltaic generator, a fuel cell, and a storage battery [71].

Some studies have considered a sailing boat based on hybrid sources, designed to carry out trips for 6 months [72]. The aim of this project was to study the relevance of coupling renewable energy sources with hydrogen storage. In other studies, an electric boat based on hybrid sources and storage systems such as batteries and fuel cells was developed to replace the diesel generator [73,74].

In the field of electric vehicles, EMS is mainly used to reduce energy and fuel consumption. In a study [46], a non-linear optimization algorithm was applied to minimize the fuel consumption of an electric vehicle powered by dihydrogen. The constraints used in this study are limited to the equilibrium of the electric microgrid, which allows the use of a non-linear solving method. It is more accurate but slower than other methods. The optimization parameters are also optimized via neural networks to improve the solution obtained over predefined driving cycles.

3.2. Comparative Analyses of Nanogrid EMSs

The case of a stand-alone network with the same performance and constraints as a building has not been extensively studied in the literature. In fact, EMS in buildings is considered a device connected to an electrical grid [16]. The combination of multiple sources and multiple loads is very similar to the constraints mentioned in the problem of this study. However, comfort level monitoring, long-term planning, uncertainties in weather data, and user behavior are not present in the context of an embedded system.

Ban et al. [75] proposed a comprehensive cyber–physical energy management system (CPEMS) that optimizes the operation of networked nanogrids with battery swapping stations. The main focus of the article is to optimize not only the reliability of the energy supply system but also its economy and resilience. The use of a mixed-integer linear programming (MILP) approach allows for robust decision-making that efficiently addresses the challenges of networked nanogrids. However, drawbacks include the complexity of implementing this system and the computational resources required for real-time optimization.

Salazar et al. [76] proposed an EMS for islanded nanogrids, emphasizing the use of stochastic dynamic programming techniques for optimization. They focused on improving energy consumption and generation within islanded nanogrids, thereby increasing their overall efficiency and reliability. However, the computational requirements of stochastic dynamic programming can be resource-intensive.

Sheng et al. [77] focused on optimizing power flow management in photovoltaic nanogrids with battery storage. Their work contributes to the efficient use of energy resources within the nanogrid, ensuring that surplus energy is stored and used effectively. However, real-world implementation requires compatible hardware and control systems.

Ding et al. [78] proposed an energy management strategy specifically tailored for grid-connected PV household nanogrid systems. Their contribution focuses on maximizing energy use while minimizing grid dependency, a critical aspect of sustainable and efficient energy management in residential contexts. However, the effectiveness of this strategy depends on regional solar conditions and household energy patterns.

Bruno et al. [79] proposed a predictive control-based energy management system for hybrid AC–DC residential nanogrids. The main contribution is the implementation of predictive control strategies that enable real-time adjustments to energy flows, thereby improving energy efficiency and grid integration in residential nanogrids. However, the need for real-time data and control systems may not be readily available in all residential environments.

Farzaneh et al. [80] proposed a decentralized mean field control approach to ensure the robustness and reliability of energy management in residential nanogrids. Their approach contributes to the resilience of these nanogrids by optimizing energy distribution and consumption. However, there is a need for an advanced control infrastructure.

Salazar et al. [81] proposed a non-linear stochastic dynamic programming approach to the optimization of islanded nanogrids. Their contribution lies in providing advanced optimization techniques for islanded nanogrids, which offer effective solutions to energy management challenges. However, this strategy has potential complexity and computational requirements.

Sandgani et al. [82] proposed a compromise programming approach for coordinating energy resources in a network of grid-connected microgrids and nanogrids. Their contribution lies in achieving a balance in resource allocation, leading to efficient energy management in interconnected systems. However, it faces implementation challenges in interconnected systems.

Table 2 summarizes the above contributions and limitations of the nanogrid EMSs with strategic, tactical, and economic objectives.

Table 2. Contributions and limitations of the nanogrid EMS.

References	Techniques	Objectives	Contributions	Limitations
[75]	MILP	maximization of battery life and minimization of operational costs	optimize the sizing and operation of networked nanogrids, offering economic benefits, improved reliability, and efficient battery storage solutions.	model dependencies, complexity in implementation, scalability challenges, and the need for cost considerations.
[81]	Stochastic Dynamic Programming	minimization of the overall operational cost	optimized nanogrid operation under uncertainty, enhancing its reliability and performance.	computational complexity in large-scale systems, reliance on accurate modeling and forecast data, and the need for practical validation.
[77]	Dynamic Programming	increasing PV energy utilization and reducing fuel consumption	optimizing power flow and enhancing the efficient use of renewable energy resources and battery systems	specific applicability to PV NGs and potential challenges in real-world implementation
[78]	Rolling Optimization	enhancing battery charging and discharging activities and minimizing power oscillations between the nanogrid and main grid	optimizes the utilization of PV-generated energy within the household nanogrid.	focus on specific PV grid-connected systems and potential challenges related to system scalability and adaptability.
[79]	MILP	maximize energy self-consumption and reduce the overall energy cost.	efficient energy utilization and integration of renewable energy sources.	need for specific hardware and sensor configurations to implement predictive control and real-time prediction accuracy.
[80]	Decentralized Mean Field control	minimizing user discomfort, energy consumption, and battery degradation costs	enhancing the reliability and resilience of the nanogrid.	complexities associated with decentralized control implementations and challenges in scalability
[76]	Stochastic Dynamic Programming	maximize the use of PV and optimize the battery state of charge	enhancing the efficiency and performance of the nanogrid.	computational complexities associated with stochastic programming and the need for accurate stochastic models
[82]	Rolling Horizon, Compromise Programming	minimize the net cost of electricity	effective coordination and optimization of energy resources	need for compromising programming expertise, computational resources, and integrating diverse microgrid/nanogrid components into a coordinated network.

4. Energy Storage Systems

While EMSs are proving to be the key to intelligent energy management in nanogrids, they are closely linked to energy storage solutions. EMSs have the ability to anticipate energy demand in real-time and monitor the status of power generation resources, especially renewables that are intermittent. When the EMS detects excess energy being generated, it can direct it to an ESS like lithium-ion batteries, thermal storage, or supercapacitors. This exchange of information between EMSs and ESS optimizes the use of resources and ensures a constant supply of energy, even during fluctuations in production or peaks in demand. As a result, nanogrids equipped with these advanced EMSs are able to maximize their energy efficiency while offering greater reliability in power distribution.

Electrical energy storage involves various technologies, including electrostatic energy storage such as capacitors and supercapacitors, as well as magnetic/current energy storage like superconducting magnetic energy storage (SMES) [25]. Thermal energy storage involves different methods, such as sensible heat storage, latent heat storage, and thermochemical heat storage [83–86]. Mechanical energy storage involves storing kinetic energy through mechanisms like flywheels and potential energy through systems like pumped-storage hydropower (PSH) and compressed air energy storage (CAES) [87]. Chemical energy storage includes options such as hydrogen and methane [25]. Lastly, electrochemical energy storage encompasses batteries such as lead–acid, lithium-ion, and nickel–cadmium, as well as fuel cells [88].

Among all these energy storage technologies, batteries have been proven to be the most adapted for energy storage in embedded systems. In common with solar PV and wind technologies, battery storage has shown rapid declines in cost in recent years, which are expected to continue decreasing in the future. By 2030, the total installed cost of lithium-ion batteries in stationary applications has the potential to decrease by at least 54%, creating new economic opportunities for electricity storage and expanding their role in offering grid flexibility services [89].

Additionally, other battery storage technologies show significant potential for cost reduction. "Flow batteries" could experience a two-thirds decrease in total installed cost by 2030. High-temperature sodium sulfur (NaS) and sodium nickel chloride batteries are also expected to become more affordable, with projected cost reductions of 56–60% by 2033 and improved performance. Flywheels could have a 35% reduction in installed costs by 2030. Furthermore, compressed air energy storage (CAES), leveraging mature technologies, could witness a 17% cost decline by the same timeframe [89]. Therefore, by utilizing battery storage, the need to rely on diesel generators as a backup or supplementary power source can be reduced or eliminated, thereby reducing carbon emissions and dependence on fossil fuels. The proposed storage technologies are listed in Figure 5 based on the values of various technical and commercial parameters of different energy storage technologies with data from [90]. Each parameter can be given a competitive score from 1 to 5, with 5 being the best and 1 being the worst.

Energy storage systems have the potential to improve the performance of various applications, with particular emphasis on their suitability for transport and utility-scale applications. In some cases, ESSs play a key role in determining the adoption of certain technologies, such as electric vehicles. For transport applications, the time and power ranges are from seconds to hundreds of minutes and from tens of kilowatts to tens of megawatts [91]. For utility applications, the time and power ranges are from tens of minutes to hours and from MW to GW. In the context of utility or renewable energy integration, key performance criteria include energy storage capacity, power output, and the overall life cycle of the system. The emphasis on extended lifecycles has driven the exploration of storage solutions based on reversible physical processes, such as compressed air energy storage or pumped hydro, as alternatives to electrochemical batteries. This shift is driven by the challenges associated with battery aging and recycling. In transportation applications, the key performance factors revolve around portability, scalability, energy, and power density. As a result, despite various challenges, including limited lifetime, batteries continue to be seen as the most practical choice for transportation applications due to their modular nature and portability.

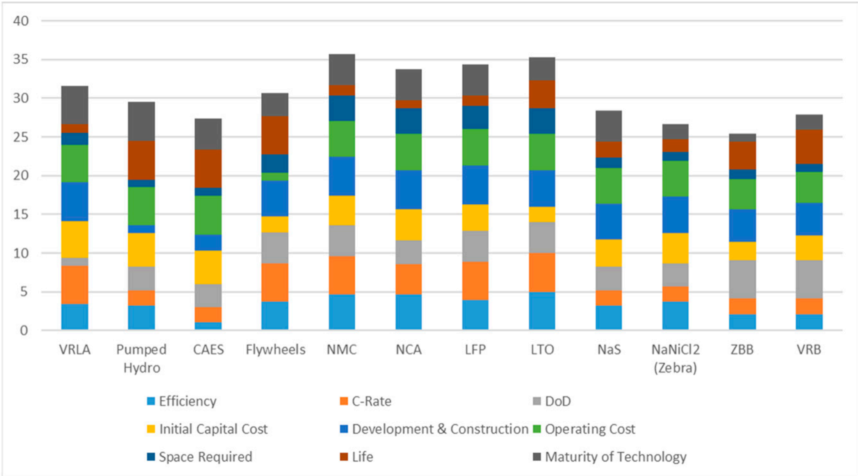

Figure 5. Example of competitive scores for storage technologies.

5. Limitations and Challenges

In the utility, industrial, commercial, and residential sectors, an EMS is essential for optimal operations. Its objectives are to limit greenhouse gas emissions, optimize the scheduling of energy resources, and reduce energy consumption. Monitoring and data analysis are facilitated by the integration of supervisory control and data acquisition (SCADA) and human–machine interface (HMI) in an EMS. This involves energy production from generation sources, weather forecasts, load demand, and the latest energy prices. This information is used by the EMS to improve system performance at the generation, transmission, and distribution levels.

Careful selection of an EMS method is essential to maintaining stable and reliable operation for nanogrids. The choice of a specific EMS should take into account the characteristics of the deployed system, such as operating modes, topologies, and structure. However, the choice of one approach does not necessarily imply the unreliability of the other. The main challenge is to match the chosen method with the studied constraints and the fixed objective related to the control strategy, aiming to identify its utility in the deployed system.

Nanogrids' EMS operation is mainly divided into two layers: the day-ahead layer and the real-time layer. In order to account for forecast errors, the day-ahead layer is further divided into smaller time segments. Reference values are sent to LCs in real-time using communication links. Implementation and validation for EMSs are conducted using diverse solution methodologies, applied in different domains, using simulation validation [92–95] and experimental validation [96–107].

There have been efforts to establish standards and guidelines for the development of both AC and DC microgrids. The standards framework for AC microgrids is at a more advanced stage of development than that for DC microgrids. However, research is still being developed to address the standards and guidelines for DC microgrids, indicating continued progress in this area.

While significant progress has been made in the field of hybrid nanogrids for embedded systems, there are still challenges to address. Designing an EMS for hybrid nanogrids that is scalable and adaptable to different scales of embedded systems needs further research and development efforts to optimize system designs, improve component efficiency, enhance integration and interoperability techniques, and achieve cost-effective solutions. Moreover, the need for real-time decision-making poses a challenge, especially in embedded systems where rapid adjustments are required. Developing algorithms that can make quick and accurate decisions to respond to changing conditions while ensuring secure and reliable communication within the hybrid nanogrid is essential.

6. Conclusions and Perspectives

In conclusion, hybrid nanogrids offer promising solutions for the efficient and sustainable power supply of embedded systems. By seamlessly combining renewable energy sources, energy storage systems, and advanced energy management techniques, these systems enhance energy reliability, reduce dependence on traditional grids, and minimize environmental impact. This review article has provided a comprehensive overview of the current state of research and advances in hybrid nanogrid EMS. It has covered key components, operating principles, optimization strategies, and challenges.

The objectives of nanogrid EMSs are shaped by various factors, including their mode of operation (centralized or decentralized), economic considerations, and the inherent unpredictability of renewable energy sources. They also take into account environmental concerns associated with conventional energy sources, the health of energy storage systems, system losses, reliability, and customer privacy. While significant progress has been made in addressing some of these objectives, there is an urgent need for further research. In particular, there is a need for robust strategies to address customer privacy issues and to establish secure and reliable communication systems. In addition, a thorough investigation of the reliability of microgrid systems, especially in islanding and remote scenarios, remains an unexplored area.

The use of hybrid nanogrids in embedded systems brings several benefits, including improved energy efficiency, reduced operating costs, and increased resilience to power outages. By harnessing the potential of renewable energy sources such as solar and wind, coupled with energy storage systems, embedded systems can operate autonomously while minimizing carbon emissions. In addition, the incorporation of advanced energy management algorithms facilitates the optimal utilization of available energy resources and efficient load management. Exploring these areas of research is essential to achieving optimal and energy-efficient operation of nanogrids.

Author Contributions: Conceptualization, M.B. (Maria Bitar), T.E.T., M.B. (Mohamed Benbouzid), V.B.D. and M.B. (Mustapha Benaouicha); methodology, M.B. (Maria Bitar), T.E.T., M.B. (Mohamed Benbouzid), V.B.D. and M.B. (Mustapha Benaouicha); formal analysis, M.B. (Maria Bitar), T.E.T., M.B. (Mohamed Benbouzid), V.B.D. and M.B. (Mustapha Benaouicha); investigation, M.B. (Maria Bitar); writing—original draft preparation, M.B. (Maria Bitar); writing—review and editing, M.B. (Maria Bitar), T.E.T., M.B. (Mohamed Benbouzid), V.B.D. and M.B. (Mustapha Benaouicha). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statements: Not applicable.

Conflicts of Interest: Authors Maria Bitar, Tony El Tawil, Van Binh Dinh, and Mustapha Benaouicha were employed by the company Segula Technologies. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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