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Perspective

New Horizons for Microgrids: From Rural Electrification to Space Applications

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Abstract: The microgrid concept has evolved from the humble origins of simple remote electrification applications in rural environments to complex architectures. Microgrids are key enablers to the integration of higher penetrations of renewables in the energy sector (including electricity, heating, cooling, transport and industry). In addition to the local energy sources, energy storage systems and loads, the modern microgrid encompasses sophisticated energy and power management systems, peer-to-peer energy markets and digital technologies to support this energy transition. The microgrid concept has recently been applied to all energy sectors, in order to develop solutions that address pressing issues related to climate change and the decarbonization of these important sectors. This paper initially reviews novel applications in which the microgrid concept is being applied, from a detailed analysis of recent literature. This consists of a comprehensive analysis of the state of the art in shipboard microgrids, port microgrids, aircraft microgrids, airport microgrids and space microgrids. Future research directions are then presented, based on the authors' perspectives on pushing the boundaries of microgrids further.

Keywords: microgrids; maritime microgrids; space microgrids; aircraft microgrids

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1. Introduction

The European Green Deal, recently adopted by the European Commission (EC), has set ambitious goals for the decarbonization of the European economy by 2050 and potentially start reversing the effects of climate change. The EC has adopted a set of measures in the energy and transportation sectors to reduce the net greenhouse gas emissions by 55% by 2030. However, significant research and innovations are required to achieve these aims. While the adoption of renewable energy sources (RESs) is essential to reach the key objectives of the green deal, energy storage is the enabler that facilitates the integration of RESs in a cost-effective and flexible manner. The diversification of RES generation and integration of energy storage in modern power systems are also leading to the formation of microgrids and microgrid clusters/communities for more reliable and sustainable electricity networks.

Microgrids can become key enablers to achieve the ambitious aims set by the EC within the expected time frame. Microgrids can accelerate the decarbonization and decentralization of the utility grid while providing excellent opportunities for sector coupling, market integration, consumer empowerment and technical innovations. However, while in the US, microgrid adoption is facilitated by polices in specific states (e.g., bill SB 1339 enacted in 2018 by the California Public Utilities Commission (San Francisco, CA, USA)), this is still not the case for Europe. The revised Renewable Energy Directive (2018/2001/EU) moved a step towards this direction through the introduction of provisions on renewable energy communities. However, the timeline for adoption by the individual EU member states is still uncertain.

In the literature, microgrids were initially considered to be small-scale energy networks for rural electrification that include local loads, energy storage systems and local energy sources. These microgrids operate in grid-connected mode and can transition to islanded operation during faults or planned disconnection events. Since then, microgrids have evolved into complex distribution networks and have been applied extensively in literature at the low-voltage levels in residential and industrial applications. Microgrids can improve the flexibility, reliability and energy security of the local energy network. Hence, microgrids are considered one of the most promising solutions for achieving high penetrations of distributed renewable energy sources in the modern distribution networks. In addition, microgrids can also push forward new technologies by coupling the electricity, transport, buildings and industrial sectors into the electrical grid. In recent decades, microgrid technologies, architectures and control strategies have been extensively researched to increase their reliability and scalability. These ongoing research efforts can be grouped into the following categories: hierarchical control loops and architectures [1–6], microgrid clusters and multi-microgrids [7–9], integration and management of energy storage systems [10–15] and peer-to-peer energy trading and new roles for prosumers [16,17].

This review is aimed at setting future directions for microgrid research that can be used to push further the boundaries of microgrid applications. The methodology considered in this study is summarized in Figure 1. A systematic review of recent literature was performed to showcase the novel applications in which the microgrid concept has been applied to solve pressing issues related to decarbonization and climate change. Due to the vast number of publications in the field of microgrids, this review only considers relevant journal articles published in the past four years. Review papers summarizing the previous state of the art were taken as the starting point for the studies, and novel contributions from newly published research articles were then analyzed. Future research directions were then defined based on the identified research gaps and the personal assessment of the authors.

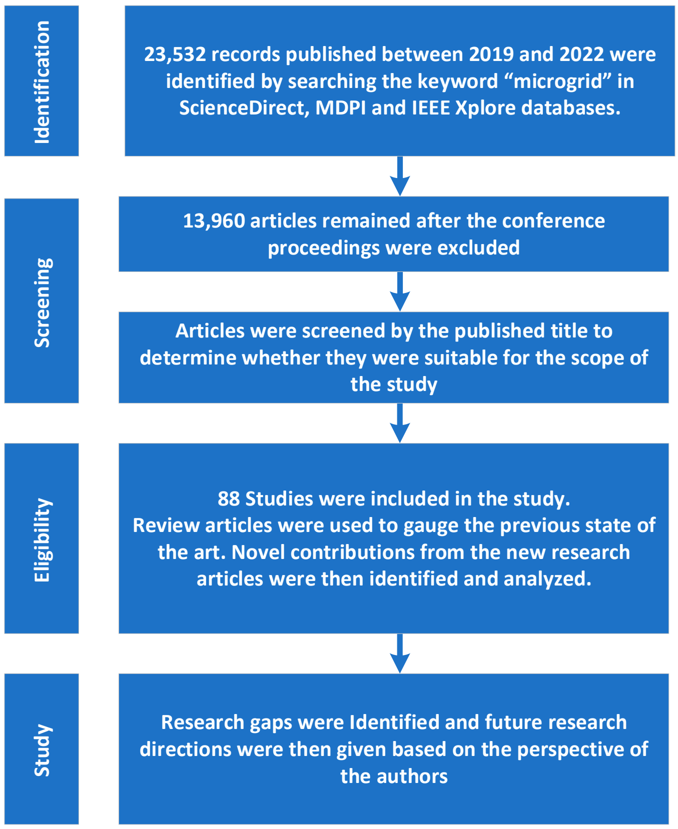


Figure 1. Methodology adopted in this review article.

The rest of the paper is organized as follows. Section 2 gives a very brief overview of the microgrid concept. (A detailed account is beyond the scope of this article.) Section 3 contains a description of how microgrids are being applied in the transportation sector to accelerate the electrification of transportation (Land, Maritime and Aerospace). Section 4 describes recent research activities that are extending the microgrid concept into space applications such as Nanosats, Islanded Ecosystems and Microgrids in Future Moon Bases. Section 5 describes current research gaps and possible future directions based on the personal assessment of the authors. Section 6 concludes this review paper.

2. The Microgrid Concept

The microgrid concept can be simply defined as the coordinated operation and management of local energy sources, energy storage systems (ESS) and loads. The microgrid appears as a single controlled entity to the main grid which enables bidirectional power transfer between the two networks via the PCC. This section summarizes the general research directions related to the traditional class of microgrids. A detailed account of the research efforts in these topics is beyond the scope of this paper.

2.1. Hierarchical Control

Coordination within the microgrids is required to achieve the envisaged reliability and performance that cannot be achieved only using decentralized control techniques that consider only the local variables. Coordination can be achieved by adopting the microgrid hierarchical control architecture microgrids, a widely accepted structure that consists of four distinct layers. The control loop bandwidths are the highest at the physical level and decrease as the levels increase. These layers are shown in Figure 2 and the distinct roles for each layer can be defined as:

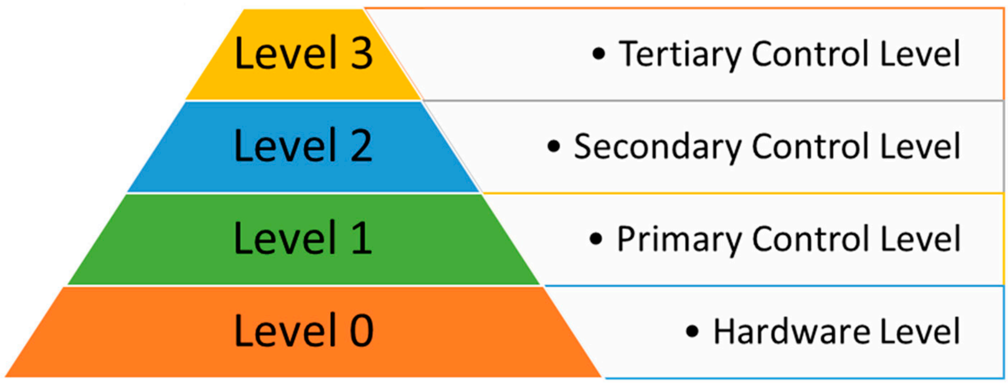


Figure 2. Representation of the microgrid hierarchical architecture.

1. Hardware layer: The power electronic converters (PECs) are the building blocks that enable the formation of the microgrid. The PECs enable the formation of AC, DC and hybrid (AC/DC) microgrids by connecting RES, ESS and loads according to the selected network architecture.
2. Primary Control Layer: The primary layer is implemented within the PEC. This uses local information to impart basic microgrid functionality. PECs that are deployed in AC, DC or hybrid microgrids typically use droop control for distributed power sharing. This layer also includes virtual impedance loops that emulate various complex impedance behaviors to improve the power sharing.
3. Secondary Control Layer: The secondary control layer implements the control and management algorithms for the optimal operation of the microgrid. Control strategies in this layer are concerned with energy balancing of ESSs, power quality improvement, voltage and frequency restoration, transition from grid-connected to islanded operation and vice-versa. The secondary control functionality can be implemented either as centralized, decentralized (or quasi-centralized) or distributed.
4. Tertiary Layer: The tertiary control layer is the highest level of the hierarchy that implements energy management and power flow control strategies. The tertiary layer supervises the operation of the microgrid, regulates the power import/export from

the microgrid, coordinates the operation of microgrid clusters, implements energy management strategies that optimize single or multiple variables.

2.2. Integration and Management of Energy Storage Systems in Microgrids

Energy storage systems (ESS) are critical elements in microgrids. Consequently, the integration and management of energy storage systems in microgrids is a heavily researched topic. Various types of ESS technologies have been considered in the literature to date that can be categorized into mechanical, electrical, battery, thermal, electrochemical and chemical [10]. Recently, there has also been a shift towards hybrid energy storage systems that typically consist of battery energy storage systems coupled with another storage element [15]. ESS can be deployed into three possible configurations: centralized, decentralized and distributed.

As a result, there are many known sizing and dispatch strategies for ESS in microgrids [11–14]. ESS sizing and dispatch strategies are typically required to address multiple optimization problems that can include minimization of cost, minimization of emissions, minimization of battery degradation and/or maximization of system reliability, amongst others. These approaches can be divided into numerical optimization based and heuristics. Multi-objective optimization is concerned with the simultaneous optimization of the mathematical models of more than one objective function. However, the traditional numerical optimization methods are computationally intensive and in complex multi-objective scenarios may not converge to a global optimum solution. In these scenarios, relaxation of constraints can improve the convergence of the algorithms. Heuristic tools are iterative computational procedures that attempt to determine an optimal solution (which might not be the best solution) with a few or no assumptions about the problem being optimized. Several heuristic tools have been employed in microgrid-related literature to date that attempt to solve ESS sizing problems. Recently, heuristic tools are also being combined with traditional approaches or even with other heuristics to solve complex optimization problems within reasonable timeframes.

2.3. Microgrid Clusters and Multi-Microgrids

Microgrid clusters, also referred to as multi-microgrids in the literature, refer to distribution networks that contain two or more interconnected microgrids. The transition from large, centralized distribution networks into interconnected microgrid clusters with distributed generation can result in significant benefits to the reliability, resilience and energy security of the local energy networks. The literature to date has focused on multiple aspects related to microgrid clusters including possible architectures, communication frameworks, energy management strategies, operation, protection, and resilience strategies [7–9]. Typically, the hierarchical control architectures defined in Section 2.1 are employed by all the microgrids forming the clusters. The tertiary layer algorithms respond to dispatch commands to regulate the energy flows amongst the interconnected microgrids. However, due to the complexities involved in setting up and coordinating the operation of the microgrid clusters, there are still significant challenges that arise from uncertainties (such as the randomness of the load demand, energy market fluctuations and intermittency of the renewable power generation) [7].

2.4. Peer-To-Peer Energy Trading

Demand response strategies in microgrids mainly consist of active control and management of the local distributed generation, energy storage systems and loads by the microgrid operator. These strategies may cause security and privacy concerns that could result in a trade-off with the optimal operation scenarios. Transactive and peer-to-peer energy sharing are energy trading platforms for demand-response applications at the distribution level [16,17]. Small-scale consumers and prosumers can participate in the local energy markets, thereby contributing to the demand-supply balance of the microgrid via energy trading [17]. A detailed classification of transactive energy systems was presented in [17] that considers the participating objects, market structure, clearing method, solution algorithm and trading commodities. Architectures are categorized as provider-dominant transactive control, consumer-dominant transactive control and provider-consumer interactive energy trading. Transactive energy systems are mostly considered at theoretical development stages with only a few demonstration projects evaluating the technical and operational feasibility.

3. Electrification of Transportation

The European Environment Agency (EEA) recently published national projections for greenhouse gas emissions from the EU's transport sector [18]. The projections show that emissions from domestic transportation will only drop below the 1990 level in 2029, while international transport emissions (aviation and maritime) are projected to continue to increase. Microgrids can become key enablers for the electrification of the transportation sectors and the achievement of net-zero emissions. Existing methods reported in the literature can be transferred to the transportation sectors, however there are specific challenges that must be addressed before microgrids can realize their true potential. The following is a summary of the latest research activities concerned with applying microgrids into the transportation sector.

3.1. Vehicle-To-Microgrids (V2M)

Electric vehicles (EVs) were extensively considered in microgrid-related literature simply as controllable loads in the energy management systems of residential or industrial environments that can be used in demand-response strategies. Recently, this trend has shifted towards considering EVs as energy storage systems that could also provide additional flexibility in microgrid control and management. The provision of operational flexibility is countered by the concerns of battery lifetime degradation that can affect the performance of the EVs. This gave rise to significant research efforts on vehicle-to-grid (V2G) and vehicle-to-microgrid (V2M) applications. A basic representation of the V2G and V2M applications is shown in Figure 3. The goals of V2M depend on whether the microgrid considered is islanded or grid-connected [19]. For grid-connected operation, V2M functionality typically includes the provision of ancillary services and optimization of the local microgrid distribution network. In islanded operation, V2M can contribute to the frequency and voltage regulation of the local microgrid, thus improving its stability.

Table 1 gives a summary of the recent literature focusing on the integration of EVs in microgrids and V2M. Yu et al. in [20] provide a comprehensive survey on EV literature and V2G technologies, with topics ranging from EV charger topologies to V2G auxiliary services and application challenges, amongst others. The authors also provide a comprehensive assessment of EV-grid integration and V2G operation performance in nanogrids, microgrids and microgrid clusters. The assessment includes the charging demand compatibility, V2G availability, architecture scalability, impacts on the power quality, and technology maturity. The authors in [21] review the main technical issues related to the EV hosting capacity in real-case scenarios. Identified issues include distribution transformers overload, feeder overload, and other power quality phenomena. In addition, the authors also describe how charging stations with V2G capabilities can improve the hosting capacity and power quality. The authors in [22] analyze the different EV charging architectures for V2M applications. A comparison of the microgrid-based charging station architectures is given in terms of the energy management strategies, control architectures, and charging converter control algorithms. While the literature to date appears to suitably analyze the control methodologies necessary for the provision of V2M functionality by EV charging stations, there are still knowledge gaps as to how the full potential of V2M can be unlocked to benefit the end-user as well as the microgrid. As the behavior of the end-user significantly affects the availability of the EVs for the provision of V2M services, detailed frameworks should be established to define how EV user patterns can be integrated into the real world V2M wide-scale deployment scenarios.

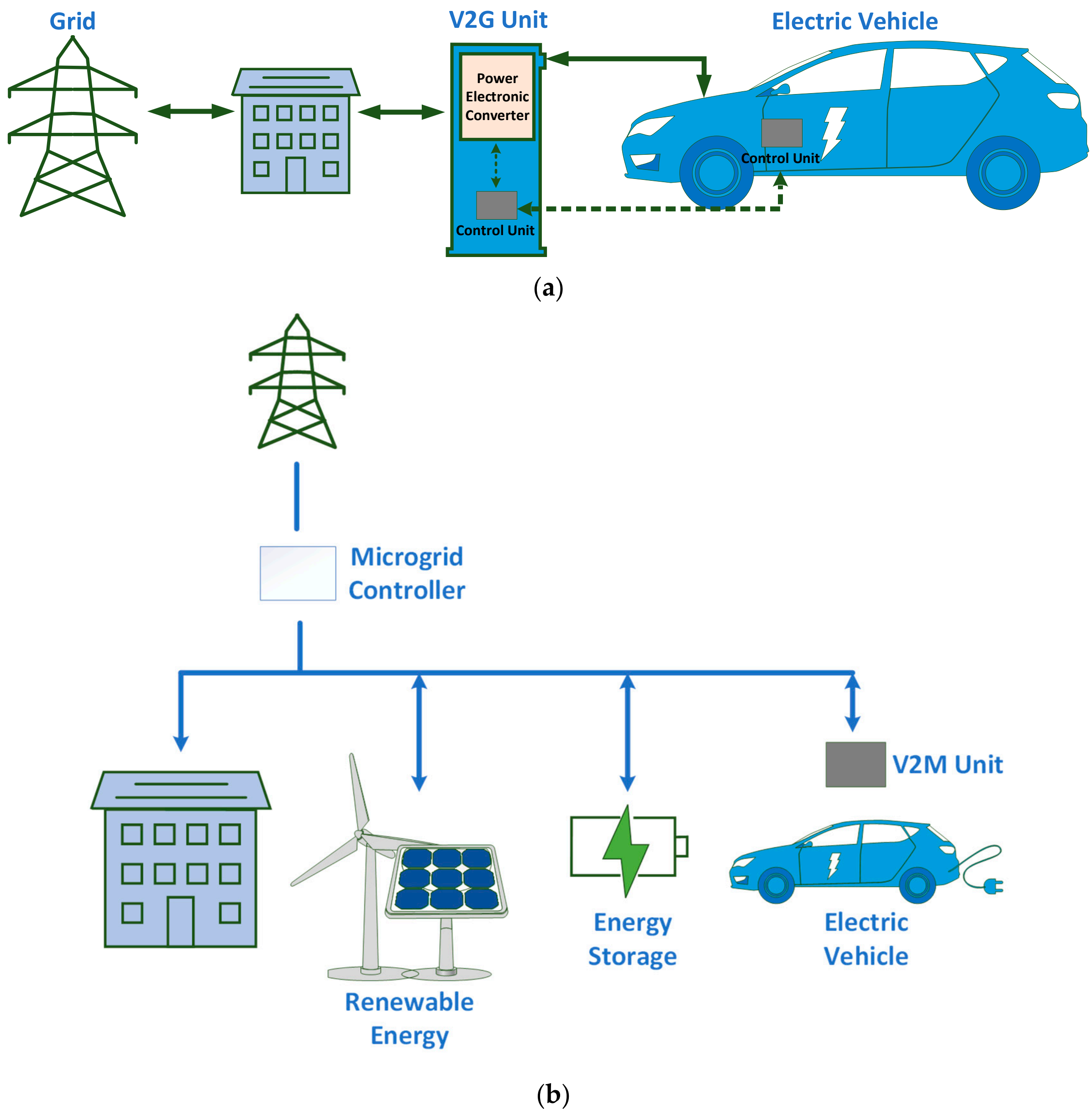


Figure 3. Simplified representation of the V2G and V2M applications. (**a**) Representation of the V2G application. (**b**) Representation of the V2M application.

Table 1. Main contributions in recent literature focusing on V2M.

Reference	Contribution	Limitations
[20]	State-of the art on EV literature and V2G technologies. Comprehensive assessment of EV-grid integration and V2G operation.	The assessment for EV-grid interaction does not consider the EV user behavior.
[21]	Review the main technical issues related to the EV hosting capacity. Proposed a mixed deterministic and probabilistic method to pre-evaluate harmonic disturbances.	Limited dataset for EV power quality data. Accuracy of estimation procedure was not quantified.
[22]	Analysis of different EV charging architectures for V2M applications.	Mainly focuses on PV-powered EV-charging stations.
[23]	Two-stage optimization framework for EVs providing ancillary services to DC microgrids.	Iterations of the interior-point method tend to be computationally expensive.

Table 1. *Cont.*

Reference	Contribution	Limitations
[24]	Bi-level scheduling model that coordinates the energy scheduling between an islanded microgrid and battery swapping stations.	JAYA can get trapped in a local optimum when solving complex problems.
[25]	A multi-objective optimization model for V2M aimed at minimizing the microgrid load fluctuations, maximizing the renewable energy utilization, and the benefits to the EV users.	Simplistic EV parameters and basic EV user behavioral patterns.
[26]	A multi-objective optimization strategy to minimize the operational cost, the pollutant treatment cost and the carbon emission cost in V2M applications.	Traditional ABC algorithm is prone to convergence in local minima and slow global convergence.
[27]	A two-step optimization model to manage the large-scale EV fleet integration in microgrids.	The scoring mechanism can lead to bias in favor of the highly ranked drivers.
[28]	Online model predictive controller for real time V2M applications.	Reliance on the reliable prediction of uncertain system parameters.
[29]	Analysis of the impact of EV uncertainties in V2M frequency stabilizing applications.	As the number of parameters increase, GSA methods can become hindered by impractically large sample sizes.
[30]	An MPC-based methodology for the real-time energy dispatch in microgrids.	Necessity of estimating the prosumers' net demand with day-ahead accuracy.
[31]	An optimization strategy for the large-scale integration and management of EVs in microgrids.	The proposed GSA-RFR algorithm shows significantly high computational requirements.
[32]	A multi-objective real-time energy management strategy for a microgrid with V2M capabilities.	The use of ANFIS for the EV prioritization presents limitations including high computational expense and training complexity.
[33]	An optimization approach with a Monte Carlo simulation to estimate the hosting capacity of isolated DC microgrids with DG and EVs.	A genetic algorithm was used to determine the optimal solution to the total distributed generation problem. However, it is well known that genetic algorithms do not scale well with more complex scenarios.

Recent studies focused on the scheduling/frameworks for V2M providing ancillary services to AC or DC microgrids. The main complexity in scheduling of EVs lies in the uncertainties in the behavior of the EV users that can affect the charging/discharging behavior in V2M applications. Yu et al. in [23] propose a two-stage optimization framework for EVs providing ancillary services to DC microgrids. The provision of ancillary services by EVs results in a trade-off between benefits to the microgrid owner due to the reduction in network losses and the EV charging functionality. Yu et al. formulated a multi-objective OPF as a shortest path problem, which was solved by a modified Dijkstra's method. Li et al. proposed a bi-level scheduling model in [24] that coordinates the energy scheduling between an islanded microgrid and battery-swapping stations. The optimal day-ahead scheduling model promotes the participation of battery-swapping stations in multi-stakeholder microgrid scenarios, while optimizing the energy management and minimizing the operational costs. A multi-objective optimization model for V2M was developed in [25] aimed at minimizing the microgrid load fluctuations, maximizing the renewable energy utilization, and the benefits to the EV users. The multi-objective strategy coordinates the energy exchange between the EVs and the microgrid strategy and consists of three sequential stages: a searching valley scheduling algorithm, a variable threshold optimization algorithm and a variable charge/discharge rate optimization algorithm. The authors in [26] consider EVs as dynamic load in V2M applications for both islanded and grid-connected operation. A multi-objective optimization strategy was developed to minimize the operational cost, the pollutant treatment cost and the carbon emission cost. The authors applied the Artificial Bee Colony optimization algorithm to determine the best global optimal solution. The authors in [27] propose a two-step optimization model to manage the large-scale EV fleet integration in microgrids. The microgrid dispatching center formulates a cluster-based day-ahead optimal EV charging/discharging characteristics that minimize the costs for both microgrid operators and EV owners. Instead of resorting to a dynamic energy pricing scheme, a real-time scoring-based coordination was used to motivate the EV owners to follow the cluster-based day-ahead optimal charging/discharging characteristic. However, these studies do not consider the real-world operating conditions for both microgrids as well as the end-user behaviors. In addition, the coordination with stationary energy storage systems (utility/community/behind-the-meter) as well as the impact of V2M service aggregation on the microgrid operation have not yet been fully explored.

Other studies also consider the challenges for real-time management of the EV integration and V2M services. The authors in [28] propose an online model predictive controller over a future rolling time horizon which takes new decisions at hourly time steps in microgrids with available V2M services for EVs. Stochastic optimization techniques were used, together with the rolling horizon control, to overcome modelling uncertainties. The authors in [29] analyze the impact of EV uncertainties in V2M applications that contribute to stabilizing the frequency deviations in a microgrid. The analysis was conducted from the perspectives of both system operators (available power for frequency stabilization) and the EV owners (available SoC after participating in frequency stabilization services). In [30], Garcia-Torres et al. develop an MPC-based methodology for the real-time energy dispatch in microgrids with external agents such as EVs or other microgrids. The methodology constrains the energy exchange with the external agent to maximize the economic benefits of the microgrid based on day-ahead market decisions. Nazir et al. in [31] propose an optimization strategy for the large-scale integration and management of EVs in microgrids. The multi-objective optimization model considers the system's operational costs, EV user participation in V2M, and environmental pollution control cost. The authors in [32] propose a multi-objective, real-time energy management strategy for a microgrid with V2M capabilities. The objectives consist of peak shaving, minimizing the microgrid operational costs and an EV prioritization strategy that extends the battery lifetime, while utilizing the resources fully. The authors in [33] combined an optimization approach with a Monte Carlo simulation to estimate the hosting capacity of isolated DC microgrids with DG and EVs. However, the proposed hybrid methodology is computationally expensive when increasing the number of nodes of the grid and the number of EVs. Most studies consider the approach of day-ahead scheduling, possibly optimizing even at an hour-ahead level. However, in microgrids dominated by power electronic converters, uncertainties resulting from large numbers of EVs during hour-ahead scheduling could still result in stability issues, especially in networks without stationary storage systems. A framework for the actual real-time management and coordination strategies still need to be developed and validated.

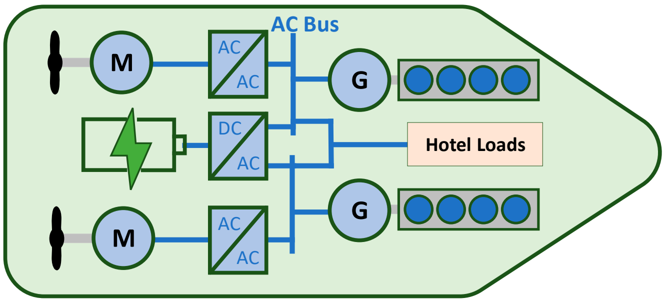
3.2. Shipboard Microgrids

Shipboard power systems (SPSs) are evolving to minimize their environmental impacts by optimally using the onboard energy sources, through the integration of energy storage systems and by transitioning towards the all-electric ships. Presently, approximately 80% of ships use a diesel electric transmission system in their onboard SPS. The integration of BESSs and alternative power sources are transforming SPS into highly dynamic shipboard microgrids (SMGs). While SMGs have many similarities with the terrestrial microgrids, there are also many differences [34]. These include:

1. In SMGs, power generation is provided by the diesel gensets, while the load is mainly the dynamic propulsion. Variations in the propulsion demand can significantly affect the power system stability.

2. The volume and weight of its onboard equipment is an important factor due to spatial limitations onboard the ships.
3. Wind and ocean current will impact the stability, reliability and survivability of the SPS.

Similar to land-based microgrids, SMGs can also be categorized as either AC, DC or hybrid AC/DC. Modern vessels adopt integrated power systems architectures, connecting the generators, propulsion and other loads to a common AC or DC bus. Simplified representations for the three types of SMG are given in Figure 4. While a detailed review of the possible power system architectures is beyond the scope of this paper, a brief description of their characteristics is given below.



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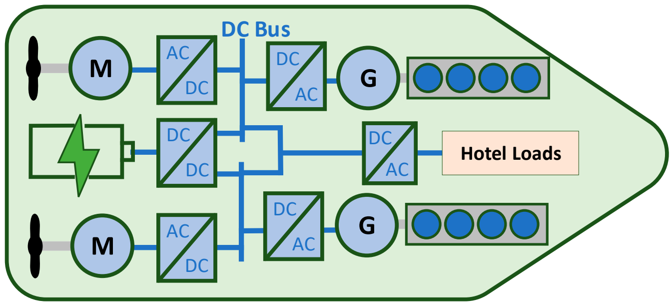

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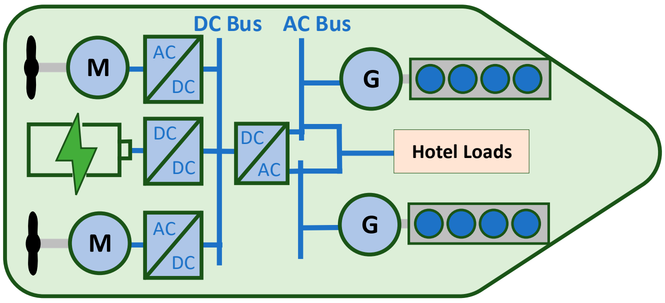

(**c**)

Figure 4. Simplified representation of shipboard microgrid architectures. (**a**) AC shipboard microgrids. (**b**) DC shipboard microgrids. (**c**) Hybrid shipboard microgrids. (Adapted from [35]).

- AC shipboard microgrids (ac-SMGs) are based on the traditional integrated power systems (IPS) that have been employed in the marine industry since the 1980s. Multiple parallel generators are connected to main switchboards that are physically separated from each other to improve the survivability and redundancy. Table 2 summarizes the main contributions in recent literature focusing on ac-SMGs. As the ac-SMGs are based on traditional IPS, present research efforts are being focused on the integration of onboard energy storage devices, as well as power quality mitigation strategies. The presence of high-power and/or propulsion loads on the common AC bus cause significant power quality issues such as voltage/current unbalance, frequency deviations, and voltage/current harmonics. The shift towards higher penetrations of power electronic converters has increased the concerns on power quality phenomena onboard ships. However, an additional topic of interest for ac-SMGs that has yet to be considered in detail is how autonomous ships can optimize the onboard energy and power management in real navigation conditions.

Table 2. Main contributions in recent literature focusing on ac-SMGs.

Reference	Contribution	Limitations
[36]	Review of PMS and EMS for SMGs with a specific focus on the optimization-based strategies.	The suitability of the considered optimization-based strategies for distributed architectures was not assessed.
[37]	A review of the energy storage devices that have been extensively used in SMGs (Batteries, ultra-capacitors, flywheels and HESS).	Ambiguities concerning the selection of the appropriate storage technology for the possible applications have not been addressed. Does not include an analysis of the control and management strategies used for the integration of the different storage devices.
[38]	A hierarchical architecture was proposed for a HESS (battery and ultracapacitor) connected to the dc bus of the bow thruster drive.	Sizing strategy for the HESS (battery and ultracapacitor) was not defined.
[39]	An optimization framework that determines the optimal ESS size while considering the navigation route schedule.	Does not consider the port operations in the optimization strategy. This could include berth allocation to calling ships and berth occupancy ratios.
[40]	A two-step multi-objective optimization method to simultaneously optimize the economic and environmental objectives of the diesel generators by HESSs.	Pareto-optimality of solutions for NBI decomposition method is not guaranteed. This can limit the generalizability of the proposed strategy.
[41]	Review the main power quality issues in ship microgrids.	Only focuses on AC maritime microgrids. Mitigation measures are also not considered.
[42]	An estimation method based on GPOFM with virtual exponentials inside the least-square approach of the harmonics and interharmonics.	DC offsets and voltage unbalance could have an impact on the estimation strategy.
[43]	An assessment and prediction method of the expected severity of voltage dips under unbalanced conditions due to the onboard motor startups.	The accuracy of the Riemann method for estimating the voltage dips is dependent on the gradient of the measured waveforms.
[44]	Static VAR compensators applied to improve the onboard power quality.	Proposed controller only verified by Software in the Loop testing.

- The dc shipboard microgrid (dc-SMG) has a dc bus to which all the onboard power components are interfaced through power converters. The main advantage of the dc bus architecture is that high-speed turbines and generators can be used. This reduces the volume and size of SPS equipment as well as the fuel consumption. The additional advantages of dc-SMGs are well defined in the literature [35,36,45,46], and there is already uptake by commercial maritime power and propulsion companies. Table 3 summarizes the main contributions in recent literature focusing on dc-SMGs. Xu et al. in [45] provide a summary of the state of the art in DC shipboard microgrids, including the available bus architectures, voltage levels, functional blocks, power electronic converters and their applications. The discussion on the functional blocks covers the conventional diesel generators and propulsion, with an introduction on the integration of energy storage systems and hydrogen fuel cells. The authors in [46] give a review of the coordinated control strategies, stability analysis, and fault management applied to dc-SMGs. Even though there were significant efforts in recent years on the coordinated control strategies for DC microgrids, the frequent variable load demands in dc-SMGs highlight the need for specific research efforts on this topic. As the number of dc-SMG applications is on the rise, power quality phenomena and mitigation strategies should also be given due attention. The impact of such phenomena on the operation of new alternative fuel systems (e.g., hydrogen fuel cells) also needs due consideration to ensure that adequate mitigation efforts are put in place.

Table 3. Main contributions in recent literature focusing on dc-SMGs.

Reference	Contribution	Limitations
[36]	Review of PMS and EMS for SMGs with a specific focus on the optimization-based strategies.	The suitability of the considered optimization-based strategies for distributed architectures was not assessed.
[37]	A review of the energy storage devices that have been extensively used in SMGs (batteries, ultra-capacitors, flywheels and HESS).	Ambiguities concerning the selection of the appropriate storage technology for the possible applications have not been addressed.
[45]	Review of state of the art on the available bus architectures, voltage levels, functional blocks, power electronic converters and their applications.	Selection criteria for the available dc-SMG architectures are missing.
[46]	Review of the coordinated control strategies, stability analysis, and fault management.	The challenges of real-time control on the stability of dc-SMGs have not been fully explored.
[47]	A hierarchical coordinated control architecture for the operation of the diesel generators.	Simplistic ship model that does not account for real navigation conditions.
[48]	A coordinated control strategy for an SMG with two diesel generators and two BESSs aimed at operating the diesel generators efficiently and balancing the SoC of the BESSs.	Simplistic ship model that does not account for real navigation conditions.
[49]	A data-driven robust generation and demand-side management to address uncertainties in the PV generation onboard all-electric SMGs.	Uncertainties resulting from degradation rates of BESS and PVs can have an impact on the management strategy.
[50]	A two-stage optimal SMG strategy to mitigate the pre-voyage and intra-voyage navigation uncertainties.	The limited capacities of fuel tanks as well as the fuel prices are not part of the constraints. These add to the operational costs of the SMGs.
[51]	A design methodology for the onboard battery energy storage system (BESS).	Considers the DC bus configuration for an assumed vessel with simplistic characteristics.
[52]	A two-step sizing and siting strategy for distributed cloud ESS (DCESS) that minimizes the total cost while enhancing the resilience of the SMG.	The navigation uncertainties can have a significant impact on the performance of the proposed strategy.
[53,54]	Review of the state of the art in fault protection and management of dc-SMGs.	Fault recovery strategies were not considered.
[55]	A modified directional strategy to identify faults by combining directional zonal interlocking (DZI) with the short-time Fourier transform (STFT).	Experimental testing is a necessary step to validate the proposed strategy.
[56]	A three-level protection coordination scheme with time-based discrimination.	Network reconfiguration during faults can limit the effectiveness of the coordination scheme.
[57]	A review on advanced nonlinear control strategies to stabilize and control the CPLs.	Selection criteria and methodologies for applicable nonlinear control strategies were not explored.
[58]	A framework to identify and investigate the stability issues during operation.	Simplistic ship model that does not account for real navigation conditions.

- Hybrid Shipboard Microgrids (hybrid-SMGs) in the literature of SMGs can refer to two possible categories. The first interpretation follows from the previous paragraphs and consists of a SMG having both AC and DC buses interconnected via a power electronic converter. This configuration enables the integration of AC generators, AC and DC energy storage systems, and AC/DC loads. A second interpretation consists of diesel-electric-driven SMGs that are complemented by onboard BESS. In this manuscript, hybrid-SMGs shall only be used in the context of the first interpretation. Table 4 summarizes the main contributions in recent literature focusing on hybrid-SMGs. Hybrid-SMGs are the latest evolution of SMGs that benefit from the advantages of both ac-SMGs and dc-SMGs, however there is significant research that needs to be carried out before they can achieve their full potential.

Table 4. Main contributions in recent literature focusing on hybrid-SMGs.

Reference	Contribution	Limitations
[34]	A coordinated control strategy for hybrid-electric SMGs that improves the fuel consumption efficiency and the power quality.	The coordinated architecture was only implemented for range extended mode.
[35,59]	A modified, hierarchical control structure with multi-mode control.	A dedicated hierarchical control architecture for each ship to shore connection could limit the scalability.
[37]	A review of the energy storage devices that have been extensively used in SMGs (batteries, ultra-capacitors, flywheels and HESS).	Ambiguities concerning the selection of the appropriate storage technology for the possible applications have not been addressed.
[60]	An optimization methodology that coordinates the voyage scheduling and the energy dispatch including uncertainties from the onboard power service loads, outdoor temperature variations and onboard solar PV generation.	The two-stage optimization with the multiple "min-max" constraints could result in computational difficulties.

3.2.1. Control and Power Management

Control and power management strategies play a vital role in the operation of SMGs. Zhaoxia et al. in [34] propose a coordinated control strategy for hybrid-electric SMGs that improves the fuel consumption efficiency and the power quality. BESSs are connected to the dc bus that supplies the main loads of the SMG, while the generators and shore power are connected to the ac bus. The coordinated strategy enables the SMGs to operate in pure electric mode, range-extended mode, and shore power mode. The authors in [35,59] proposed a modified, hierarchical control structure with multi-mode control for a hybrid SMG. The multi-mode adaptive power management strategy achieves autonomous operation during the ship's islanded and grid-connected operation. The hierarchical control strategy enables ship-to-shore (S2S) or ship-to-everything (S2X), that charges/discharges the onboard battery energy storage systems to/from the grid. However, the wide scale deployment of S2S/S2X to support future port microgrids still requires significant research efforts to overcome the present challenges. Zhaoxia et al. in [47] propose a hierarchical coordinated control architecture for power sources in dc-SMGs. The primary control level regulates the DC bus voltage and the power output by the diesel generators. On the other hand, the power management system (PMS) provides the optimal speed reference setting and the secondary voltage recovery control loops. Xu et al. in [48] considered the possible operational modes of dc-SMGs and proposed a coordinated control strategy for a SMG with two diesel generators and two BESSs. The control strategy was aimed at operating the diesel generators efficiently and balancing the SoC of the BESSs.

While there are significant efforts in the development of power management systems (PMS) and energy management systems (EMS) for shipboard microgrids, there are still significant challenges that need to be addressed. Xie et al. in [36] provide an extensive review of PMS and EMS for SMGs with a specific focus on the optimization-based strategies. These strategies rely on optimization algorithms that can give optimal/suboptimal solutions. The authors in [60] propose an optimization methodology that coordinates the voyage scheduling and the energy dispatch for a hybrid SMG of a cruise liner. The complexities that result in scheduling the resources of a multi-energy ship are due to uncertainties from the onboard power service loads, outdoor temperature variations and onboard solar PV generation. The authors in [49] propose a data-driven robust generation and demand-side management to address uncertainties in the PV generation onboard all electric SMGs. An extreme learning machine (ELM)based forecasting method was used to predict the worst-case PV generation due to the real conditions of the vessel (speed, rolling, etc.), while the second stage corrects the uncertainty predictions during operational use. The authors in [50] proposed a two-stage optimal SMG strategy to mitigate the pre-voyage and intra-voyage navigation uncertainties (i.e., water waves, wind direction and speed). The first stage addresses the worst pre-voyage navigation uncertainties while the second stage is an on-line recourse action which acts on intra-voyage uncertainty based on real-time decisions. Most of these studies focus on the power management strategies of pure-electric (battery only) as well as plug-in hybrid ships. However, one of the most critical trends in shipping is the transition towards other green technologies, for example in long-distance shipping. The control and power management strategies to optimally integrate alternative fuel systems powered by LNG, hydrogen or ammonia in SMGs have yet to be considered. In addition, the integration of wind-assisted propulsion to the multi-energy optimization problem in SMGs also deserves significant attention.

3.2.2. Integration of Energy Storage Systems

ESS sizing strategies for SMGs depend on the power management strategy, ship operating conditions and optimal route planning. Generalized approaches applicable to land-based power systems can also be adapted to derive solutions specific to each vessel. Hence, there are also significant research efforts that are ongoing in this respect. Mutarraf et al. in [37] reviewed the energy storage devices that have been extensively used in SMGs. Batteries, ultra-capacitors, flywheels and HESS are the identified storage technologies that were mainly used to improve the reliability, minimize the fuel consumption and for frequency transient mitigation. However, the authors do not explain contradictions concerning the selection of the appropriate storage technology for the possible applications. The authors in [51] describe a design methodology for the battery energy storage system (BESS) of an all-electric DC-SMG. The proposed methodology, however, only optimizes the DC bus configuration for an assumed vessel with simplistic characteristics. In [52], Lai and Illindala proposed a two-step sizing and siting strategy for distributed cloud ESS (DCESS) in dc zonal SMGs. The DCESS sizing step is concerned with minimizing the total cost while the DCESS siting enhances the resilience of the SMG. The optimal solution was obtained by stochastic programming for representative operating conditions.

While the previous studies are mainly focused on the integration of battery energy storage systems, one can observe a transition towards hybrid energy storage systems (batteries and ultracapacitors, or batteries and flywheels) for improved transient performance. Zhaoxia et al. in [38] proposed a HESS (batteries and ultracapacitors) connected to the dc bus of the bow thruster drive. A hierarchical architecture was proposed for the bidirectional dc/dc converters that control the response of the ultracapacitors and batteries. However, having dedicated storage simply to mitigate the impact of the bow thrusters on the DC grid would result in non-optimal use of the onboard resources. The authors in [39] proposed an optimization framework for all electric SMGs that determines the optimal ESS size while considering the navigation route schedule. The main aims of this optimization strategy were the minimization of the costs (CAPEX and OPEX) and reduction of the greenhouse gas emissions by minimizing the navigation time. The authors in [40] propose replacing the onboard battery storage for all electric ships by HESSs. A two-step multi-objective optimization method to simultaneously optimize the economic and environmental objectives of the diesel generators is then proposed. The second step of the optimization method minimizes the battery life degradation by splitting the storage requirements between BESS and a high-power density storage device. However, battery life degradation can be reduced through effective control and management of the HESS, while the analysis focused only on the scheduling of the resources.

3.2.3. Dynamic Stability, Fault Identification and Management in dc-SMGs

Fault identification and management are vital topics for the wide-scale adoption of dc-SMGs. There is a lack of standardization in the methods that the dc-SMGs identify and use to respond to the faults during both islanded and grid-connected operation.

Reconfiguration after a fault occurs is also critical to continue supplying power to the associated loads. The authors in [53,54] reviewed the state of the art in fault protection and management of dc-SMGs. These studies provide a summary of research activities in areas related to fault management of dc-SMGs, including fault detection, location, identification, isolation, and reconfiguration. The authors in [55] propose a modified directional strategy to identify faults in dc-SMGs that works by combining directional zonal interlocking (DZI) with the short-time Fourier transform (STFT). The advantage of the proposed system is that both the DZI and STFT require current signals. Kim et al. in [56] define a three-level protection coordination scheme for dc-SMGs that is presently used by industrial manufacturers. The three layers are as follows: The first level consists of actions that should occur for up to several tens of microseconds, such as bus separation by solid-state bus-tie switches. The second level consists of feeder protection actions that take up to a few milliseconds, such as high-speed fuses or solid-state circuit breakers. The third level consists of actions that take up to several seconds, such as power supply protection by generator de-excitation and fold-back protection control. The authors also demonstrated the system protection and coordination of a two-bus DC PDN, including the device setting, protection scheme integration, and the system-level verification. While the three-level strategy provides a good framework for protection coordination in dc-SMGs, there are still significant challenges that need to be overcome prior to standardization.

The dynamic stability of dc-SMGs is affected by constant power loads (CPLs) and pulsed loads. Propulsion motors and hotel loads in dc-SMGs behave as CPLs to the common DC bus, since these are supplied through power electronic converters. As CPL's exhibit negative incremental impedance, the stability of the bus voltage in dc-SMGs can become compromised. Hassan et al. in [57] present a systematic review on advanced nonlinear control strategies to stabilize and control the CPLs in dc-SMGs. Techniques that were covered in this review include the sliding mode control, model predictive control, and passivity-based control, amongst others. Park and Zadeh in [58] proposed a framework to identify and investigate the stability issues in the operation of dc-SMGs with CPLs. Averaged models were used for the power electronic converters since the investigations were concerned with the system dynamics and interactions of the low-level controllers with the PMS. The authors also proposed a model predictive controller instead of the conventional direct power control of the AFE rectifiers to improve the voltage regulation. However, without the description of the design procedure for both controllers, it may be difficult to replicate the results.

3.2.4. Power Quality Assessment and Mitigation in ac-SMGs

Power quality assessment and mitigation strategies in ac-SMGs have also attracted attention due to the increased applications of power electronic converters onboard ships. Tarasiuk et al. in [41] discuss the main power quality issues in ac-SMGs, starting from phenomena such as voltage and frequency variations to waveform distortions. The authors show that standard power quality measurement methods are not suitable in SMG applications and that current power quality rules by ship classification societies are insufficient to ensure ship safety. In [42], Terriche et al. proposed a method based on virtual exponentials inside the least-square approach to estimate the harmonics and interharmonics of modern maritime microgrids systems. This method is proposed as an improvement over the generalized pencil-of-function method. The harmonics and interharmonics can be determined with shorter window lengths even under larger frequency drifts, while retaining the frequency independent property. Liu et al. in [43] proposed a method to assess and predict the expected severity of voltage dips under unbalanced conditions due to the onboard motor startups. The proposed method was validated by experiments in a real SMG for a ballast pump motor startup showed a maximum error of less than 4.9%. However, as the assessment method is based on the motor capacity and fixed SMG parameters, only an average estimate of the voltage dip severity can be obtained. Terriche et al. in [44] demonstrate how static VAR compensators such as the fixed capacitor-thyristor controlled reactor (FC-TCR) can be used to improve the power quality in SMGs. FC-TCRs were used to reduce the harmonics distortion to meet the IEC 61000-4-7/30 standards, as well as to shift the power factor toward unity.

3.3. Port Microgrids

Ports can be broadly categorized as either as inland ports (dry/wet) or as seaports. An inland port is a port on an inland waterway (river, lake or canal) and supplies regions with an intermodal/multimodal terminal (rail, air and road). Seaports are the most common types of ports worldwide and are used for commercial shipping activities. These can be categorized as either cargo ports (loading and unloading of cargo) or cruise ports (passenger terminals, onboard provisions, etc.). Port microgrids refer to electricity distribution networks in ports that use the microgrid concept to support its operations. In ports, microgrids can improve the operational efficiency, increase the renewable energy penetration, and provide flexibility by installing energy storage systems. The literature on port microgrids is mainly concerned with the challenges of seaport microgrids. The authors in [61,62] perform a review of the main characteristics of port microgrids and SMGs. While the general framework of port microgrids is identical to those of terrestrial microgrids, the significant difference arises from the application. Port microgrids must also consider the logistics elements (such as berth allocation and crane scheduling) in addition to the load electrical demand profile and characteristics.

A number of authors have focused on the optimal planning and scheduling of the microgrid resources for cost minimization and increased reliability. The authors in [63] consider a hypothetical port microgrid with onboard PV panels, fuel cell stacks and BESS on several ships. This port architecture is only possible due to the bidirectional ship-to-shore functionality, where the ships are interconnected via the DC bus of the onshore charging stations. However, the architecture is based on a fictitious port and only considers the ship-to-shore functionality for multiple vessels without any consideration of the additional port infrastructure. Kermani et al. in [64] investigate the integration of single and hybrid ESSs in port applications for peak reduction, energy management, and economic aspects. Techno-economic analysis was performed by the authors for the integration of ESS with ship to shore, cranes and rubber-tired gantries. The authors in [65] propose a distributed cooperative control framework for a hypothetical DC port microgrid that achieves current sharing and voltage regulation. A droop-free cooperative controller was employed to regulate the average bus voltage and to share the load current. In addition, a discrete dynamic consensus algorithm (DCA) was used to achieve global consensus by neighboring DGs exchanging virtual average state variables. However, the uncoordinated scheduling and control of the SMGs can have a significant impact on the node voltages of port microgrids. In addition, methodologies for the generalized application of the strategy to real-world applications have not been fully elaborated.

Sun and Qiu in [66] propose a three-stage coordinated voltage control strategy for port microgrids. The first stage consists of a time-of-arrival estimation method for ships to minimize the node voltages variations in port microgrids by using optimal power flow scheduling of the available resources. During the second stage, optimal route planning for the ships is carried out using the Dijkstra algorithm to minimize the propulsion power consumption. In the final stage, a rule-based local voltage control strategy was proposed that uses the BESSs of the berthed SMGs to provide voltage support. The strategy was evaluated for a cruise vessel visiting three hypothetical island microgrids. Thus, the feasibility of the strategy still has to be evaluated in real-world shipping scenarios. The authors in [67] propose a two-stage day-ahead scheduling algorithm that optimizes the port operations and the port microgrid within one framework. In the first stage, the port authority determines the optimal berth allocation for the incoming vessels, while in the second stage, the optimal day-ahead scheduling allocates the port microgrid assets for each time slot. The optimization procedure minimizes the total cost of a vessel when berthed as well as the operational costs of the port microgrid. Uncertainties due to the local renewable energy generation and port load forecast are also incorporated in the problem formulation. Sun et al. in [68] propose a distributed optimal voltage control and berth allocation strategy that regulates the voltage within the port microgrid. The voltage control problem was formulated as a second-order cone program (SOCP) while the berth allocation problem was formulated as a mixed-integer linear program (MILP). The authors in [69] developed a simulation-based method to determine the best configuration and overall sizing for a hybrid generation system in a port microgrids. A case study for the Port of Aalborg (Denmark) was given for a grid-connected port microgrid with renewable energy sources, energy storage systems, and cold ironing facilities. The optimal configuration for the port microgrid was performed in HOMER with an analysis of economic feasibility, energy reliability, and environmental impact.

3.4. Aircraft Microgrids

In recent years, there have been significant efforts towards the decarbonization of aviation through research and development activities on the more-electric aircraft (MEA). The electrical power systems of the MEAs are transitioning towards aircraft microgrids because of the electrification of the onboard components. While aircraft microgrids share similarities with ground-based microgrids, the main differences that distinguish these special microgrid applications include the high reliability requirements for the power supply, high power densities (since weight is a critical issue onboard aircraft) and load prioritization during each mission. However, high power density and resilient operation are conflicting requirements [70]. There are also unsolved challenges that still need to be addressed such as electrifying the propulsion system possibly through the use of alternative (green) fuels. The authors [70,71] review the key aspects of the aircraft microgrids for the more-electric aircraft (MEA), including the power system architectures, power electronic converters, energy management and control requirements. Special focus was also given to the specific requirements of aircraft microgrids.

Figure 5 shows a simplified representation of half of the hybrid microgrid architecture studied within the More Open Electrical Technologies (MOET) FP6 project in [70]. The hybrid power system architecture of the MOET strongly focuses on maximizing reliability, whereby each generator has dedicated loads that can be connected to other buses only in case of faults. This topology relies completely on power electronic converters, however the additional redundancy results in many power electronic converters having a low utilization rate. Improving the utilization rate and/or decreasing the number of converters can significantly improve the onboard power densities, resulting in significant fuel savings.

Current research activities on aircraft microgrids have shifted towards DC architectures in aircraft microgrids in order to decrease the number of onboard power electronic converters. Wang et al. in [72] propose an online centralized battery scheduling strategy for aircraft microgrids based on model predictive control (MPC). The DC aircraft microgrid is divided into high voltage (HVDC) and low voltage (LVDC) buses. A case study for the LVDC bus was considered that focuses on the load and BESS management. The MPC-based control strategy was determined to prolong the battery lifetime, while minimizing load shedding and switching transients. Fang and Xu in [73] propose a two-stage coordinated scheduling strategy to minimize the costs and the environmental impact of hybrid electric unmanned aircraft microgrids. In the first stage, the energy consumption of the aircraft is scheduled through an optimization model to minimize the fuel consumption and emissions. In the second stage, a decomposition-based method converts the nonlinear multi-objective optimization model into a bi-level model that is solved through iterations. The authors in [74] propose to modify the HVDC and LVDC bus voltages of aircraft DC microgrids to satisfy the peak power demand and overload conditions. An online load identification algorithm for dc aircrafts was proposed to assess the load dependence on the bus voltage. This information was used to modify the power consumption, while avoiding load shedding. The authors in [75] propose a mixed integrated linear programming (MILP) methodology to define the supervisory control of the aircraft DC microgrid. The linear regression approximation and Branch and Bound methods were evaluated for optimal energy management onboard the aircraft. The authors in [76] propose a sizing and control strategy for supercapacitors interfaced with a bidirectional DC/DC converter for aircraft DC microgrids. The supercapacitor mitigates the voltage transients during dynamic conditions. Most authors have focused on the management and optimal use of the onboard resources, however there are significant research questions that need to be addressed in order to reduce the dependence on conventional fuels.

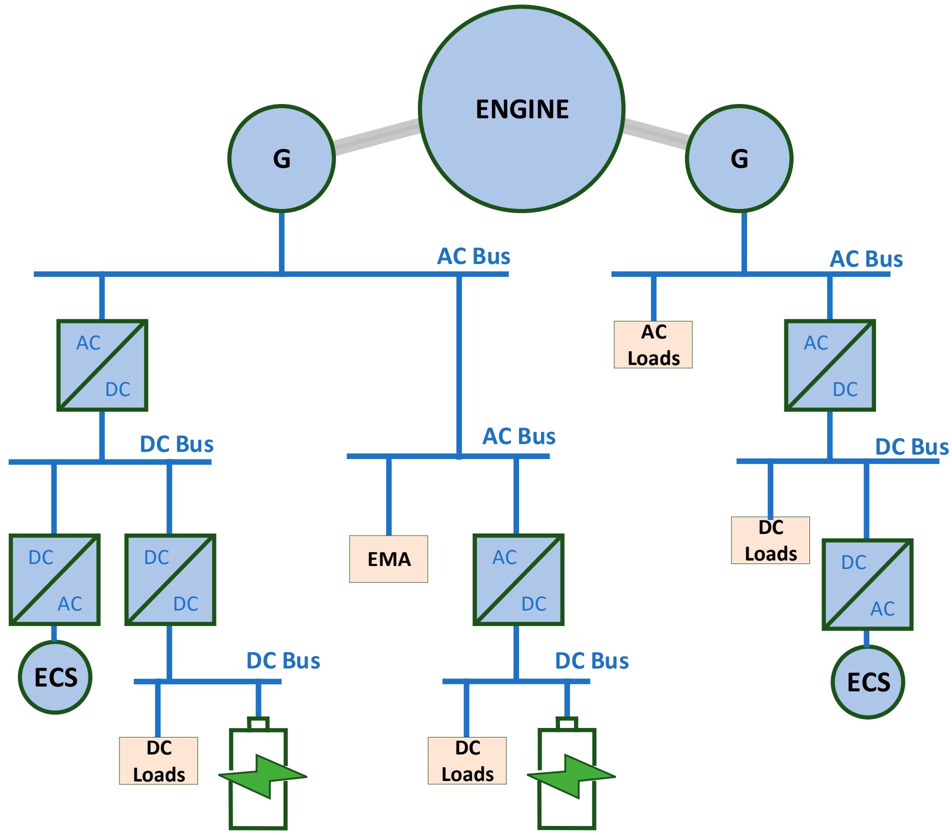

Figure 5. Simplified representation of the hybrid aircraft microgrid in the MOET project derived from [70].

3.5. Airport Microgrids

Airports can also achieve low-carbon operation or carbon neutrality by integrating microgrids into their energy systems. Similar to ports, airports are hubs for multimodal transportation and other economic activities that enable cross-sector coupling. However, research in this sector is the least explored of all the transportation-related sectors, with only a few journal articles exploring the electrification challenges in airports.

Alruwaili and Cipcigan in [77] perform a techno-economic assessment of an airport microgrid that includes of solar photovoltaic (PV), energy storage system and diesel generator. A modified mixed-integer linear programming scheme was used to enhance airport power resilience under different power interruption scenarios and minimize the total annual operating costs. Xiang et al. in [78] propose a hydrogen-solar-storage airport DC microgrid for the energy system outside the airport terminal. Aircraft auxiliary power units (APUs) and EVs were integrated into the DC microgrid for energy dispatch strategies based on airport flight schedules. A mixed integer linear programming (MILP) optimization method based on lifetime cycle theory was proposed to size each energy source, which aims at minimizing the total costs and maximizing the environmental benefits. Zhao et al. in [79] perform a techno-economic assessment for an airport microgrid integrating hydrogen energy systems, photovoltaics, BESS, APUs and Evs. A mixed integer linear programming

(MILP) optimization method based on lifetime cycle theory was also used in this case to minimize the total costs of hydrogen-integrated airport microgrid.

4. Space Microgrids

Recently, the microgrid concept has been proposed for space applications (nanosats, islanded ecosystems, and manned moon base camps) since these have the same characteristics as the land-based microgrids applied to remote electrification, albeit with important differences. There are only a few authors who have applied microgrid concepts to space applications such as nanosats, islanded ecosystems, and manned moon base camps. The main findings from these published articles are summarized below, however there is clearly significant work that can still be done in this research field.

4.1. Lunar Habitats and Manned Base Camps

Space organizations are scheduling lunar missions to build Moon bases such as the Artemis base camp by the National Aeronautics and Space Administration (NASA). The base camp consists of a habitation unit, and a mining and processing facility. Hence, the lunar base camp requires a reliable, resilient, robust, optimal and stabile electrical system infrastructure [80]. This implies setting up local power generation and distribution infrastructure as well as ESSs and energy management strategies. While solar energy is available on the surface of the Moon, there are also extended night hours and extreme environmental temperature changes from day to night. In addition, while sunlight is available at the poles, there are irregular periods of darkness and other environmental conditions such as dust and radiation that complicate matters. The authors propose harvesting PV solar energy from multiple sites on the Moon south pole. Locations for possible PV harvesting sites were identified through a Sun location tracing methodology implemented for the lunar sky.

Saha et al. in [81] explore technologies that are presently available for power generation, storage and distribution for space microgrids applications. Lunar microgrids have several important design elements for the correct functioning of the microgrid as their terrestrial counterparts, including the local power generation, distribution network, local energy storage, electrical loads and power/energy management systems. Solar photovoltaics and small-scale nuclear reactors (Kilopower reactor using Stirling technology) are the available lunar power generation technologies to date. Multijunction solar photovoltaics are a highly reliable, resilient and stable source of electricity that can be installed to the lunar bases, minimizing losses and without environmental/safety issues. The location of the lunar base is a key element in this respect, to minimize the exposure to the PV systems to extreme temperature variations as well as performance degradation due to space debris and cosmic radiation. Electrical loads in lunar habitat enable the astronauts to carry out their mission, from periods lasting up to a couple of months, while ensuring their safety and comfort during their stay. These loads vary from essential equipment such as life support systems (LSSs), communication systems, and laboratories to charging stations for exploration vehicles and rovers. Future electrical loads include facilities to produce the required resources locally, which can have significant impacts on the electrical energy demand. The authors also present the control system requirements for the reliable operation of space microgrids. Kaczmarzyk and Musiał in [82] evaluate the effect of technical and environmental parameters of nine different power systems for lunar base power systems. Multiparametric studies were performed for the site illumination conditions, power management strategies, photovoltaic source parameters, nuclear power source parameters and three alternative energy storage systems. For the considered scenarios, hybrid power systems (solar PVs during lunar days and nuclear reactors during lunar nights) were found to be the most reliable and the most advantageous solution. The authors in [83] propose a hierarchical architecture for space closed ecosystems that is based on the well-known hierarchical architecture of microgrids. However, the main challenge of the three-level hierarchical architecture for ecosystems is the management of multiple producers and consumers of oxygen without violating the critical boundaries for carbon dioxide. The hierarchical architecture can also be scaled up to include the interconnection of several ecosystems.

4.2. Satellites

Small satellites, known as CubeSats, have been proposed to carry out basic missions. CubeSats are modular and scalable, with a basic unit weighing around 1.33 kg and occupying volumes of 10 cm × 10 cm × 10 cm. In [84], Lashab et al. review satellite-based microgrids with specific focus on the energy generation and storage as well as the protection schemes of CubeSats. CubeSats have the same main components as the traditional microgrids, i.e., energy generation, storage and loads as well as an energy management system, albeit at significantly lower power levels. Although there have been developments in this respect, CubeSats are mainly powered by multijunction PV cells. The onboard batteries are charged when there is excess generation, during periods of high solar irradiance. The batteries are used as the main source of power when the satellite is eclipsed by Earth or to supply peak loads during periods of low solar irradiance. In addition, sizing guidelines are also given for the energy generation and storage devices. Yaqoob et al. in [85] also review and explore SmallSat microgrid research developments, energy transfer and architectures, converter topologies, latest technologies and main challenges. Two SmallSat electrical power system topologies were defined by the authors. The direct energy transfer architecture operates at a fixed point of the I-V characteristic curve of the PV cells. The power is the distributed to the loads and any excess power is then curtailed. The maximum power point tracking architectures regulates the output voltage to match the maximum output power depending on the environmental conditions, thus exploiting the full potential of the PV cells.

5. Discussion and Perspectives

While the application of the microgrid concept has significantly evolved in the past decades, giving rise to new cross-sectoral opportunities, there are still various topics that have yet to be fully exploited. Possible future research directions that build on the work currently being carried out by the microgrid research community are given below.

5.1. Alternative Fuel Integration in Shipboard Microgrids

The optimal integration of battery storage systems, hydrogen, ammonia and other alternative fuels in shipboard microgrids offers significant engineering challenges that are yet to be overcome. Future research directions in this field should leverage the sector coupling potential of microgrids to maximize any synergies. Two main research areas have been identified in this category.

5.1.1. Ship-To-Microgrids for Battery-Powered Ships

The uptake of BESSs on ships that are currently in operation (hybrid/plug-in hybrid/electric) is on the increase, albeit mainly in the short-distance shipping sector. While there has been reported effort on the BESS sizing strategies, the integration of shore-to-ship infrastructure (charging stations) for battery-powered vessels in microgrids has not yet been given the due attention by the research community. While the concepts are similar to the charging infrastructure for Evs (both wired and wireless infrastructure), the power requirements in marine vessels are significantly higher. This important difference becomes even more significant when considering fast charging requirements in shipping applications that also require quick turnaround times (e.g., passenger ferries). Fast charging infrastructure can significantly increase the electrical load demand of the ports, may affect the stability of the local microgrid, and/or affect the power quality, thus having negative repercussions on the port microgrid or other nearby customers. Automatic charging systems that combine marine wireless charging and automatic mooring applications, can also significantly further reduce the turnaround times in short-distance shipping applications. Technical, economic and environmental impact assessments that consider the integration of these technologies in the port microgrids could be the drivers towards their widescale adoption/implementation. While ship-to-shore applications have also been explored in a few of the reported studies, the ships in these studies were mainly considered to be fixed energy storage systems (i.e., stationary assets). While this assumption is valid for ships that are kept berthed for long periods of time (e.g., superyachts), other vessels with short berthing times could still contribute to the dynamic stability. In the latter, the uncertainties in SoC availability are significantly higher due to the dynamic use of the vessel and its onboard resources. Therefore, ship-to-microgrid (S2M) applications that provide ancillary services to the local port AC/DC/hybrid microgrids and additional flexibility to the microgrid control and management need to be explored further.

5.1.2. Alternative Fuel Integration

The uptake of BESSs on long-distance shipping can also provide advantages with respect to optimization for the onboard power/energy flows. However, battery electric vessels for long-distance shipping are still not feasible based on present BESS technologies. The integration of hydrogen, ammonia and other alternative fuels in shipboard microgrids can provide significant advantages to the decarbonization of long-distance shipping. These alternative fuels can be integrated in shipboard microgrids through either fuel cells or combustion engines. Hydrogen proton-exchange membrane (PEM) fuel cells are finding new applications in the shipping industry since these are compatible with modern electric and hybrid SMG architectures. Onshore hydrogen PEM fuel cell power has also been proposed as an alternative to present cold ironing technologies, especially in places the utility grid can only reach with significant investments. Ammonia is considered to be a promising fuel in the transition to green transportation due to the higher energy densities when compared with other proposed fuels. While dual fuel naval engines have recently become available that can also work using ammonia, dual fuel alkaline fuel cells powered directly by ammonia and solid oxide fuel cells (SOFCs), on the other hand, still have very low TRL levels [86].

5.2. Power-To-X in Microgrids

Traditionally, the electricity supply, heat supply, transport and industry, function independently from one another. A conceptual framework, termed sector coupling, has recently emerged which envisages the integration of these sectors within the electricity sector. The integration of Power-to-X (P2X or PtX) technologies in microgrids can open pathways to convert excess renewable energy generation into thermal energy (heat/cold), hydrogen, methane or other liquid fuels, instead of resorting to power curtailment strategies.

Palys and Daoutidis, in [87], review the state of the art for power-to-hydrogen (PtH), power-to-methanol (PtM), and power-to-ammonia (PtA) technologies applied to the energy and transportation sectors. Hydrogen and ammonia are viewed as the future of long-distance road transportation and long-distance shipping. However, their integration within microgrids is also filled with techno-economic challenges. Ports and airports are multi-modal transportation hubs upon which people, cargo and services rely on. As the strategies for decarbonization of transportation need to be put in place swiftly, ports and airports can become energy hubs in an all-electric future scenario. Port and airport microgrids are natural sector coupling hotspots that can integrate multi-modal transportation and industry (i.e., the interconnection of the main energy consumers) to a renewable powered electricity grid. Future port and airports can facilitate the green transition of the maritime and aviation industries by producing local green electricity (from local RES or other green fuels), producing green fuels from excess RES generation by P2X plants and by bunkering of green fuels. However, the frameworks by which microgrids can achieve these long-term objectives, or at least how these technologies can be optimally integrated into the operations of these future microgrids, is still unknown.

Thermal (heat/cold) energy storage can provide significant opportunities for sector coupling in residential and industrial settings. Settino et al. in [88] provide a detailed review of the available technologies that convert solar energy into electrical and thermal energy. In this review, the authors highlight that thermal energy storage systems should be located as close to the end-user as possible to minimize thermal energy losses. In countries where district heating is already present, the integration of heat energy storage in microgrids provides an excellent opportunity to couple the thermal and energy sectors. However, in cases where no district heating is present or where cooling has a higher impact on the energy demand (e.g., Mediterranean countries), the integration of these technologies in microgrids still proves to be complex.

5.3. Microgrid Digital Twins

While the concept of digital twinning has been successfully applied in the aerospace, manufacturing and automotive industries for many years, its application to microgrids has yet to be fully explored. Bazmohammadi et al. in [89] introduce the concept of digital twins for terrestrial microgrid applications and present methods to establish microgrid digital twins. Microgrid digital twins can bridge the barrier between the simulation models and the physical electricity network. Data from the physical system and relevant external sources can be acquired, processed and manipulated by the digital twin. These real-time digital data streams and historical data can be employed by the digital twin to determine possible outcomes in real time. The digital twin presents many advantages in all the microgrid applications presented in this review paper. However, its implementation still carries significant risks and uncertainties that can affect its reliability. One main area that requires attention arises from ensuring the reliability of the data from the various sensors and measurement equipment deployed to relay data to the microgrid digital twin. Additional concerns arise from the real-time processing of the data in the digital twin, especially when processing large amounts of data and decisions need to be taken in very short time frames. Combining the microgrid digital twins with machine learning algorithms, artificial intelligence and big data results in probabilistic digital twins. This will extend the applications of the microgrid digital twins for risk assessment and decision support through the use of forecasting strategies and probabilistic models.

6. Conclusions

This paper provided a review and additional perspectives for novel applications in which the microgrid concept is being applied. These can be broadly categorized either as part of the electrification of transportation research efforts or in space microgrid applications. In the transportation electrification category, the state of the art for the literature identified consists in novel technologies, architectures, algorithms and strategies for shipboard microgrids, port microgrids, aircraft microgrids and airport microgrids. For space applications, microgrid concepts have been recently introduced as possible technologies that can lead to the formation of lunar habitats and as possible architectures that can power SmallSats. Future directions for microgrid research in these fields were also given based on the authors' personal perspectives that are aimed at pushing further the state of the art in the field of microgrids. The advancement of research activities in these areas should also go hand in hand with the development of policies and standards to support the ambitious decarbonization aims for 2050.

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