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Integrating Wide Bandgap Semiconductor Technologies into Emerging Mobile Energy Supply Systems

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Abstract— Future energy systems are gradually more susceptible to disruptions due to reduced network redundancy. It is urgent to develop additional flexible resources to improve energy network resilience. Mobile energy supply systems (MOES), typically denoted as truck-mounted generators, can play an important role due to its spatial-temporal flexibility compared with their stationary counterparts. This paper assesses the possibility of integrating advanced wide bandgap (WBG) technologies into emerging mobile energy supply systems. The research firstly starts with the typical configuration and functionality analysis of MOES, investigating potential energy solutions, and then proposes several key performance indicators in relation to MOES. Subsequently, the potential of WBG technologies in different configurations of MOES is investigated. The research demonstrates the promising potential of combing WBG with MOES to enhance its functionality in supporting the operation of future energy systems.

Keywords—Mobile energy supply systems, resilience improvement, wide bandgap technologies.

I. INTRODUCTION

Climate change has escalated the frequency and intensity of extreme weather events over the past two decades, posing great threats to existing energy infrastructures [1]. Existing solutions such as upgrading energy networks on a large scale to meet demand increase are often impractical due to substantial technical and economic barriers [2]. Consequently, more flexible resources are needed for providing energy supply to customers to tackle the case when grid support are limited due to emergencies.

One emerging solution for supporting resilient energy system operation is the deployment of mobile energy supply systems (MOES), which can be generally regarded as utility-scale truck-mounted generators [3]. MOES can be rapidly deployed to areas experiencing faults and operated in different emergency cases. Compared to stationary energy supply devices, the great spatial-temporal flexibility of MOES enables rapid emergency response during grid outages, which aligns with the flexibility needs in supporting local customers. MOES have already been applied in various applications, such as off-grid engineering sites [4], and filming industries [5]. To enable the functionality of MOES, its internal design requires the integration of various energy components to ensure efficient operation, which generally demands higher engineering design and safety standards compared to stationary devices.

Wide bandgap (WBG) semiconductor technologies, such as silicon carbide (SiC) and gallium nitride (GaN) devices, represent a significant technological trend in the power electronic field [6]. They offer significant advantages, including higher breakdown voltage, decent thermal conductivity, and faster switching speeds. These advantageous make WBG semiconductors compatible for applications requiring high efficiency, compact sizing, and enhanced thermal management [7]. In the context of MOES, the integration of WBG devices may bring about significant improvements in system functionality. For example, the high efficiency of WBG devices is critical in applications where energy efficiency directly impacts the system's operational performances. Additionally, the higher power density of WBG-based power electronics allows for modular and lightweight designs, making MOES easier to deploy with fast response speed.

Realizing this, this paper aims to assess the potential benefits of integrating WBG devices for MOES under different configurations. The study begins with discussing typical configurations for MOES, such as mobile batteries and fuel cell systems, and identifies corresponding key performance indicators (KPIs) that reflect the essential functionalities of MOES. Subsequently, the paper reviews recent developments in WBG technologies, focusing on SiC and GaN devices. Finally, the research explores the potential benefits of incorporating WBG technologies into emerging MOES applications. By combining WBG with MOES, the study aims to demonstrate the significant potential of WBG technologies to enhance the functionality of MOES in supporting future energy networks.

II. EXISTING INDUSTRIAL APPLICATIONS OF MOES

Numerous industrial applications for MOES have emerged in recent years. The earliest application is mobile diesel generators [8]. Companies, such as ADE and Cummins [9][10], offer a wide selection of mobile diesel generator products with different power ratings (from tens of kW to more than 1MW). Later, mobile battery storage systems (MBESS) typically use lithium-ion battery technology to deliver electricity. For example, Edison Company has developed the world's largest utility-scale mobile battery storage systems (3MW/12MWh) in 2021 [11]. Moxion Power has developed the MBSS in all-terrain trailers, being to be towed by a standard truck [12]. Meanwhile, hydrogen solutions exhibit both low emissions and greater storage capacity. The H2Rescue hydrogen fuel cell truck has been developed to provide emergency response services to local communities [13]. As an alternative to diesel generators with zero emission, it can drive up to 180 miles and supply for 72 hours without refueling. In the heating sector, mobile thermal storage systems (M-TES) transfer waste heat from industrial plants to local district heating networks, such as that used in the City of Surrey in British Columbia, Canada [14]. Other

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mobile heating units such as gas boilers have long been used to provide heating supply to open terrain or other flexible installation options, most of which rely on gas or oil, such as the Rapid Response Trailer Mounted Boiler [15]. These examples demonstrate that MOES systems exist in various physical forms and represent the integration of multiple energy conversion technologies.

III. CONFIGURATION OF MOES AND KEY PERFORMANCE INDICATORS

Fig. 1 presents a macroscopic conceptual framework for MOES. It is seen that the technology required for MOES is not fundamentally different from their stationary counterparts. The mobility of the MOES is enabled through the integrated installation of energy modules on a vehicle base, such as a container-equipped trailer. In addition to the vehicle base, the MOES typically consists of an energy storage module and an energy generation module. The generation module accommodates components such as batteries, fuel cells, generators, boilers, or combined heat and power units, while the storage module refers to components such as batteries and fuel tanks. Additionally, energy conversion equipment is also essential to facilitate the integration of MOES into broader energy systems. This includes components such as power electronic converters and heat exchangers, as MOES may also function as specific heating supply systems.

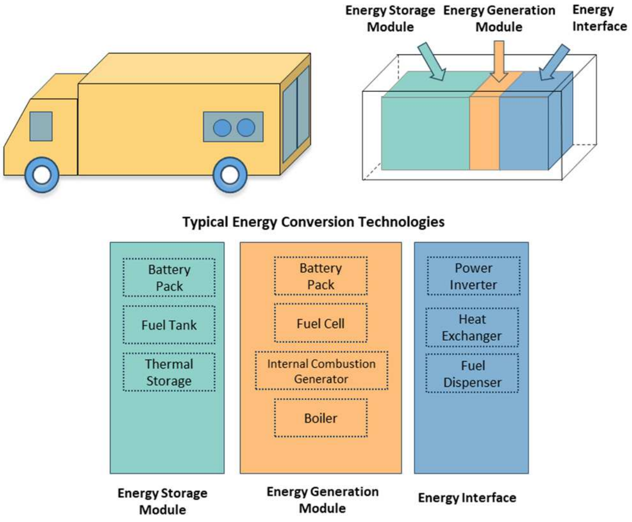

Fig. 1. Configurations and energy conversion technologies of MOES

Several key performance indicators can be used to reflect the physical properties of MOES, such as energy and power rating, efficiency, voltage level, start-up time, costs and so on. Among these indicators, the most critical metrics are the energy rating and power rating. For typical MOES, its power range spans from tens to hundreds of kilowatts, with a maximum capacity of up to 1 MW. The voltage levels typically fall within the low-voltage range, allowing connection to the low-voltage side of transformers (400V). The energy rating of MOES depends on the capacity of the storage module, which is designed to support operation for several hours to several days. Meanwhile, the energy rating can be potentially supplemented by supporting infrastructure such as high-power chargers. It is seen that the design process of MOES should be closely centered around balancing the performance of different indicators.

Similar to the range limitations of electric and hydrogen vehicles, the energy and power ratings of MOES are naturally constrained by physical limitations of the vehicle platform. Increasing the energy and power ratings inevitably results in higher system mass, which can create engineering design challenges. Therefore, optimizing the system design while staying within the vehicle's payload capacity is crucial.

The relationship between system mass and its components can be expressed by (1). For sustaining a duration of T (hour) with the power rating P (kW), the total system mass is determined by the storage module (determined by efficiency η and specific energy SE), generator module (determined by specific power SP), and auxiliary components (M_{aux}), such as power electronics interfaces. The total mass should be lower than the payload of the vehicle. Additionally, the energy conversion efficiency can have a direct impact on the system performance, which is because higher efficiency directly reduces energy losses, allowing for the reduction in system mass and improving the overall functionality of the MOES.

$$\frac{P\cdot T}{\eta\cdot SE_{\text{Stor}}}+\frac{P}{SP_{\text{Gen}}}+M_{\text{aux}}\leq M_{\text{Payload}} \quad (1)$$

IV. BRIEF INTRODUCTION OF WIDE BANDGAP DEVICES

The development of WBG based semiconductor materials has become the direction to solve the bottleneck in the development of traditional silicon-based power devices. Among many WBG semiconductor materials, SiC and GaN are the most ideal compromises, considering the theoretical properties (such as high blocking voltage, high operating temperature and high switching frequency), the actual commercialization possibilities and the level of existing technological development. A comparison of some key parameters of these two WBG materials and conventional Si materials is given in Fig. 2.

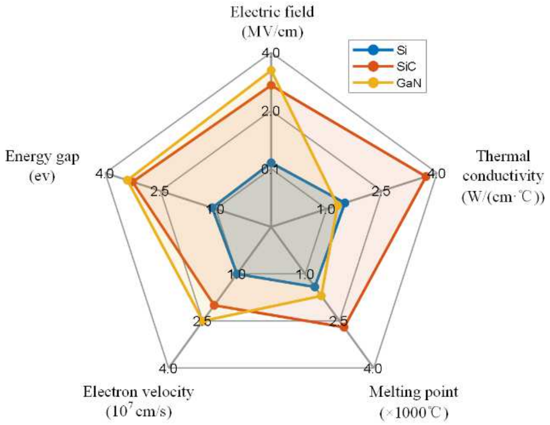

Fig. 2. Comparison of key parameters of several semiconductor materials

As shown in Fig.2, the advantages of WBG semiconductors are more obvious in high power and high switching frequency scenarios, which can overcome the limitations of silicon materials. Among them, SiC material has the best high-temperature resistance (thermal conductivity and melting point), while GaN material has the largest critical breakdown field, and the rest of the characteristics are more or less the same. Overall, SiC is more suitable for high power, high voltage and high temperature application scenarios, and is mainly used in electric vehicles, power grids and other industrial applications, while GaN has an advantage in high frequency and high efficiency applications, and is particularly suitable for radio frequency (RF) and fast switching power supplies.

Considering the current development level of existing materials and manufacturing process, SiC materials, particularly 4H-SiC with higher carrier mobility are mature and reliable solutions in the high-voltage and high-power application scenarios [16]. As a result, they are becoming a major focus of research in both academia and industry. Current research, on SiC devices primarily focuses on three areas: enhancing the channel mobility of 4H-SiC, addressing threshold voltage instability, and optimizing ohmic contacts [17]. Nowadays, SiC devices with voltage ratings ranging from 600 to 3300V are available on the market and have significantly reduced energy consumption in various power conversion systems, such as solar inverters [18], uninterruptible power supplies [19], and solid-state transformers [20]. For example, using SiC JFETs and SiC diodes can lower the cost of a 17-kW solar inverter by 20% [21]. Additionally, engineering samples with voltages of 10 kV or higher have also been produced for research purposes [22]. For instance, reference [23] presents a 10 kV-rated SiC MOSFET module, while references [24] propose modules rated at 10 kV and 15 kV for energy conversion and transmission systems.

GaN and SiC have similar material properties and GaN exhibit high electron velocity. However, due to current manufacturing limitations, most GaN devices available on the market are rated at 600-650V [25]. Nevertheless, it has recently emerged as the most cost-competitive alternative to Gallium Arsenide and LDMOS for most RF applications, thanks to outstanding advances in Gallium Nitride-on-Silicon (GaN-on-Si) technology, supply-chain optimization, device packaging technology, and fabrication efficiencies [26].

V. INTEGRATION OF WBG TECHNOLOGIES INTO MOES

In MOES systems, various power electronic devices employing semiconductor components are used for energy conversion, control and distribution, such as converters (AC/DC, DC/DC and DC/AC, etc.) [27][28], charging modules [29], and power conditioning systems [30]. These elements are potentially suitable for adopting WBG devices. When semiconductor devices based on WBG materials are used, the low switching and conduction losses of the devices increase the power conversion efficiency and reduce the heat generation, lowering the heat dissipation requirements and thus improving the thermal performance of the system. In addition, WBG devices allow for higher switching frequencies, which reduces the size of inductors and capacitors, thereby reducing the overall size, weight, and cost of the system. Furthermore, equipping WBG-based battery chargers enable high power battery chargers, and potentially reduce the battery charging duration. WBG devices are also stable at high temperatures for harsh environmental conditions, simplifying cooling design. Finally, WBG devices provide higher power density, allowing the entire system to handle more power in less space, which is critical for the compact design of MOES with higher power rating.

If MOES system is equipped with heating devices for heating supply purposes, such as combined heat and power (CHP) applications, the heat exchanger equipment can also benefit from the use of SiC devices. SiC materials can resists high temperature up to 1000°C and has high durability in harsh working conditions, which can enhance the mechanical strength of the heat exchanger and extend the equipment's lifespan [31]. Meanwhile, the high thermal conductivity materials enable more efficient heat transfer, significantly improving the heat exchange efficiency and the overall thermal rating of the whole system [32].

From the perspective of key performance indicators, the benefits of integrating WBG technologies are diverse. For instance, SiC devices can enable MOES systems with higher power rating without significantly impacting the mass of auxiliary components. Additionally, as demonstrated in (1), if higher energy efficiency is enabled, MOES can accommodate larger energy generation modules under the same vehicle payload, thus leading to higher energy rating. The integration of WBG also leads to economic benefits, as significant enhancement across multiple indicators is seen. Although the capital costs of WBG devices is higher than traditional Si devices, the overall system technical and economic performance is superior.

In summary, as technology advances, WBG devices possess significant potential to be applied in MOES for various power and thermal applications. Further specifically considering the application scenarios of MOES, its input side tends to use high voltage and high current devices to improve the energy conversion efficiency, and energy and power rating. Given these requirements, it is suggested that SiC devices are currently more suited for improving the overall performance of MOES across multiple applications.

VI. CONCLUSION

This research investigates the potential of integrating WBG semiconductor devices into MOES. It begins by emphasizing the need for developing MOES for future energy systems, explaining its concept and development trend. Then the research discusses the typical configurations of MOES, highlighting several key performance indicators to maintain decent supply performances during emergencies. Finally, WBG semiconductor devices are introduced and an outlook on the advantages of using WBG semiconductor devices for MOES is provided.

This research provides insights that SiC devices currently have more potential for applications within MOES, due to their suitability and higher technological maturity. As GaN technology advances, its future application prospect in MOES should not be ruled out. Importantly, MOES comprises various solutions, such as batteries and fuel cells, and serves multiple functions, including electricity and heat supply, thus, future research should focus on the specific engineering design required to integrate WBG devices into MOES effectively. Special consideration should be given to how WBG devices can be comprehensively designed to accommodate these diverse configurations of MOES and achieve a good trade-off between key performance indicators in future studies.

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