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Malmö, Sweden, Sept. 18-21, 2024

- The Proceedings –

Volume II:

PROJECTS, IMPLEMENTATIONS, SUSTAINABILITY AND SOCIETAL IMPACTS

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II. PROJECTS, IMPLEMENTATIONS, SUSTAINABILITY AND SOCIETAL IMPACTS

40. Applications of Maglev Derived Systems into European Interoperable Railway Network

COMPATIBILITY CHALLENGES, REQUIRED INTERFACES, POTENTIAL BENEFITS

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ABSTRACT

The paper is describing research activities carried out within the MaDe4Rail projects, funded by EU- Rail Joint Undertaking. The project purpose is to investigate Maglev-Derived Systems (MDS) and assess the feasibility of their implementation in the conventional lines of the European interoperable network. Based on the extended analyses on the Maglev systems developed and operated worldwide, the following groups of MDS have been identified: Full MDS, Hybrid MDS and Conventional system Upgraded with MDS technologies. The implementation of the MDS is evaluated according to cost, compatibility, energy efficiency, safety criteria and related benefits focused on performance enhancement, reduced maintenance, increased capacity, financial viability. The primary benefit of MDS systems over conventional rail systems is the decrease in friction, which can lead to faster speeds on traditional lines, greater energy efficiency and less maintenance expenses. In the paper are addressed the advantages of each subsystem and the achievable Technology Readiness Level.

Keywords: Maglev, Maglev-Derived Systems, Railway, Interoperable Network, Friction

INTRODUCTION

A Full Maglev system generally refers to a transport system that use magnetic technologies for both suspension and propulsion of vehicles. Maglev technology eliminates the need for traditional wheels and tracks, relying instead on magnetic forces to lift and propel the vehicle. This technology is often associated with high-speed trains and urban transit systems.

Having in mind the target to investigate Maglev-Derived Systems (MDS) in view of their potential applications in the conventional lines of the European interoperable network, the following groups of MDS have been identified in the framework of the extended analyses developed within the MaDe4Rail project [1]:

- Full MDS, importing entire subsystems or components, ensuring both suspension and propulsion of the vehicles rely on maglev technology. Generally, Full MDS maglev systems use specific and dedicated infrastructure, not compatible with the existing railway infrastructure,
- Hybrid MDS, coupling maglev derived technologies with traditional wheel-based systems, designed to be compatible with railway infrastructure. They can be based on principle of magnetic induction between materials with different permeability through the interaction of a slider with a ferromagnetic rail or based on air cushion suspension creating a differential pressure between the air inside and outside an air chamber generates enough mechanical force to lift the vehicle, a few millimeters off the ground.
- Conventional systems upgraded with MDS technologies, using the traditional wheel-rail contact as support means, while relying on other forms of propulsion technology; therefore, they can get advantages, such as increase in the allowable track slope, lack limitation of traction due to adhesion between the wheel and the rail, reduction of rotating components, more compact wagon design, allowing smaller cars and smaller tunnels.

The main principle that all MDS have in common is the use of magnetic technologies. Meanwhile, beyond the technical compatibilities, the main criticalities for all MDS are to fulfil the railway regulations and standards.

The paper will be organized according to this structure:

- Section 1 will be dedicated to materials and methods on the vehicles concept, including its functional components and the features of 3 potential MDS configurations (Full, Hybrid and Conventional Upgraded) introduced in [2],
- Section 2 will focus on results and discussion about the systematic comparison with the characteristics of the subsystems as defined in the Technical Specifications for Interoperability (TSI) [3]. Moreover, the interfaces within the MDS and between the MDS and the existing infrastructure are identified, to allow more detailed studies of the technologies' implementation within the existing Common European Network; Full MDS subsystems and Hybrid system interfaces have been there compared for compatibility with the requirements set out in the TSI to move from the potential compatibility to a functional description of the required interfaces with reference to a vehicle breakdown structure,
- Section 3 will provide with closing remarks and a description of ongoing and future research activities.

1 MATERIALS AND METHODS

1.1 Full Maglev-Derived System

A Full Maglev system generally refers to a transport system that uses magnetic technologies for both suspension and propulsion of vehicles. Maglev technology eliminates the need for traditional wheels and tracks, relying instead on magnetic forces to lift and propel the vehicle. This technology is often associated with high-speed trains and urban transit systems. Examples of urban transit systems and high-speed trains linked to this technology can be found around the world, mainly in Asia. Figure 1 represents the functional principle of a Maglev train and the related required forces.

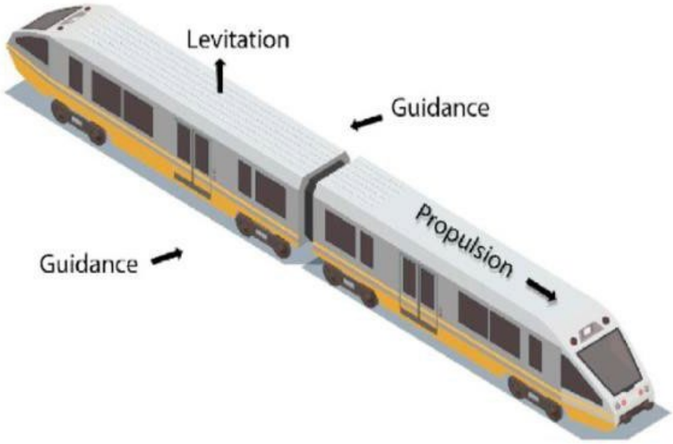

Figure 1: *Functional scheme of a MDS vehicle*

Maglev systems use magnetic fields to overcome gravity by suspending carriages using the principles and techniques of magnetic levitation. The electromagnetic forces required to implement the technology in the transportation sector can be generated in a variety of ways. The different types of maglev systems are discussed below.

1.1.1 Systems based on Electromagnetic suspension (EMS)

The Electromagnetic suspension uses forces produced by electromagnets on a magnetically conductive track. The Transrapid [4] [5], a German-developed high-speed monorail, is a paramount example of this typology, in which both levitation and guidance are provided by electronically controlled support magnets located on both sides along the entire length of the vehicle. The propulsion and the braking systems are guaranteed by a synchronous long-stator linear motor. The Transrapid reached the *Technology Readiness Levels* (TRL) of *prototypal demonstrations in an operational environment* (TRL7). Another EMS in operation in Japan is Linimo. For this system, the suspension and guidance forces are provided by a typical U-core electromagnet. The propulsion is generated by Linear Inductive Motors (LIM). The Linimo system has been *proven in operational environment* (TRL9). ECOBEE is an EMS-based system, developed for a circular line traveling along the coastline of Yeongjongdo Island (South Korea), with U-shaped magnets and LIMs for levitation and propulsion. The guidance forces are provided by the lift magnets. The mechanical brakes, used with the LIMs. ECOBEE too, reached a TRL9. In China, specifically in Changsha and Beijing, two urban MDS were developed, which have reached TRL9. Both are based on normal conducting EMS guiding technology and a Stator Linear Induction Motor (SLIM) as traction technology.

1.1.2 Electrodynamic Suspension (EDS)

In the electrodynamic suspension, the electromagnetic forces are produced by the relative motion between the conductive element and an electromagnetic field source (e.g., permanent magnets with an aluminium track, or permanent magnets' track and superconductive electromagnets).

The first EDS train was the Chuo Shinkansen in Japan, under construction on high-speed railway between Tokyo and Nagoya. Propulsion, levitation, transfer of energy to the vehicle are combined functions. The two magnetic fields from the superconducting magnets and the induced currents in the ground coils generate the magnetic pressure, which provides the vehicle with levitation and guidance forces. The propulsion method is the iron-cored long-stator LSM and the superconducting magnets are also used as the field for LSM. The guideway has a U-shape made of concrete. Each bogie has 8 magnets (2 magnetic poles/side). The 3-phase primary windings of LSM are installed in between inner and outer layers of the side wall, with TRL8. Other systems use superconductive principles *demonstrated in relevant environments* (TRL6), such as Maglev Cobra in Brazil (TRL6) [6] and the Evacuated Tube Transport (ETT). Another approach is the permanent magnetic levitation: in this case repelling magnetic forces are produced by the interaction of a flux-concentrated magnetic field produced by permanent magnets arranged in a *Halbach* array of electromagnets, with an inductively loaded closed electric circuit. This technology was used in the USA by Inductrack (TRL5) and in China with the Maglev train Xingguo (TRL7).

1.1.3 Passive suspension

Passive suspension is provided by alternative methods of force generation produced by passive elements, such as permanent magnets, rather than dynamic effects, such as counteracting magnets. Configuration of magnets that are often referred to as passive systems such as *Halbach* array systems are in fact based on electrodynamic effects. At the present stage there is no evidence of commercial applications of full maglev systems based on passive levitation technology.

1.2 Hybrid Maglev-Derived System

A Hybrid MDS system based on magnetic levitation generally refers to a system that relies both on wheel-based suspension and magnetic levitation suspension in combination or in different operative conditions. As an example, the vehicle can operate on wheels during switch crossing or platform approaching and on magnetic levitation systems on dedicated maglev corridors. The propulsion can be wheel-based during wheeled operation, while different technologies can be adopted during maglev operations. A proper choice of the propulsion technology should be based on a compatibility study and an economic evaluation. The vehicle should be designed to ensure the compatibility with the existing or upgraded railway infrastructure as well as the interoperability of the transportation system.

One example of hybrid MDS system is based on Ironlev technology, which can be applied to standard railway track thanks to the ferromagnetic properties of the iron rail itself. Ironlev technology is based on the principle of magnetic induction between materials with different permeability through the interaction of a slider with a ferromagnetic rail. The slider is realized with appropriately arranged permanent magnets in a U-shaped ferromagnetic profile. The rail is made of high magnetic permeability material. Lateral guidance and propulsion can be based on different technologies according to specific requirements and infrastructure design. The magnetic slider interacts with the head of the iron rail creating the suspension force. Ironlev bogie system is composed by two sliders connected by kinematic elements that allow to adapt to various gauges. Propulsion and regenerative braking can be obtained by electric motors connected to lateral centring wheels. Slider centring and magnetic gap control is obtained by using electric actuators.

In a Hybrid MDS configuration, Ironlev system is based on the coupling of a standard wheel-based bogie with a series of bogie systems. On the infrastructure side, the system is applied in a standard track with traditional switching systems. Ironlev bogie system is designed to be anchored and disconnected to the rail based on the operating phase of the vehicle: for switch crossing, the system is magnetically removed from the rail and the vehicle operates on wheels; instead, during speed cruise phase, the Ironlev system is engaged, and it magnetically bears the load of the wagon. For high efficiency and high-speed applications, Ironlev slider is coupled with a custom rail designed to minimize *eddy* currents, composed of a laminated head connected to a T-shape steel drawn profile. According to the application, guidance and traction are based on lateral wheels or electromagnetic systems. The Ironlev system with custom rails can be adopted in combination with traditional wheeled systems to obtain a hybrid system architecture, with EMS guidance or with lateral centring wheels. The Ironlev technology reached TRL6 for the application to standard railway shape/tracks.

The solutions based on air levitation for railway vehicles are increasing their potential and becomes worthy to study, since the air multiplier technology has enabled enough air levitation forces for trains [7], but it can also take advantage of traditional wheel-rail contact as support means.

1.3 Conventional systems upgraded with Maglev-Derived System

A Conventional MDS Upgraded system uses traditional wheel-rail contact as support, while relying on other forms of propulsion technology to get advantages, such as increase in the allowable track slope, thanks to a better adhesion between the wheel and the rail, absence of rotating components and more compact wagon design.

An example of a MDS upgraded vehicle is the *MagRail Booster*, a linear motor-powered retrofitted wagon (Figure 2). It is a rail system used to transport goods using existing rail infrastructure e.g., in freight yards, sidings, but also, if applicable, in the open railway network.

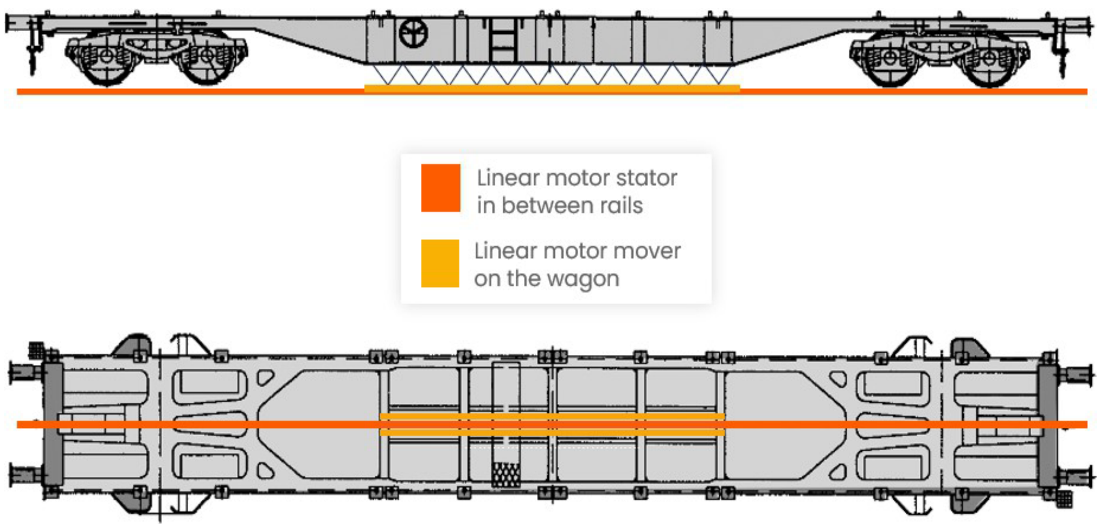

Figure 2: *Linear motor-powered retrofitted freight platform - MagRail Booster*

It uses modified freight wagons equipped with a linear motor rotor (with permanent magnets), as well as the necessary vehicle electronics. The conventional rail infrastructure is supplemented with a linear motor stator and linear motor power and control systems, as well as communication systems. The linear motor-powered retrofitted wagon system allows goods to be moved conveniently and quickly within industrial plants (closed railway network) or between facilities through European common network without the need of heavy shunting locomotive.

MagRail can be also applied for higher speed. *Nevomo* developed vehicles propelled by a linear electric motor and equipped with an EDS. MagRail infrastructure includes the linear motor, which is a permanent magnet synchronous motor with a long stator. The tests carried out in 2023 proved the operation of the system at a speed of 130 km/h.

2 RESULTS AND DISCUSSION

2.1 Cross-check with Technical Specification of Interoperability

Technical Specifications for Interoperability (TSI) is intended to ensure the efficient operation of rail networks between EU member states. To increase efficiency, safety, and dependability, these standards address a variety of railway system components, such as infrastructure, rolling stock, signaling, and telecommunication. TSIs play a critical role in easing cross-border rail traffic, enabling interoperability across various national rail networks, and improving the overall performance of the European rail system.

2.1.1 General requirements to adapt MDS subsystems and components to TSI

To determine whether subsystems and components of the MDS are compatible with the TSI, a systematic cross-check analysis was conducted with reference to the system breakdown structure represented in Figure 3. The analysis converted the existing compatibility into a functional representation of the interfaces required to ensure the potential compatibility.

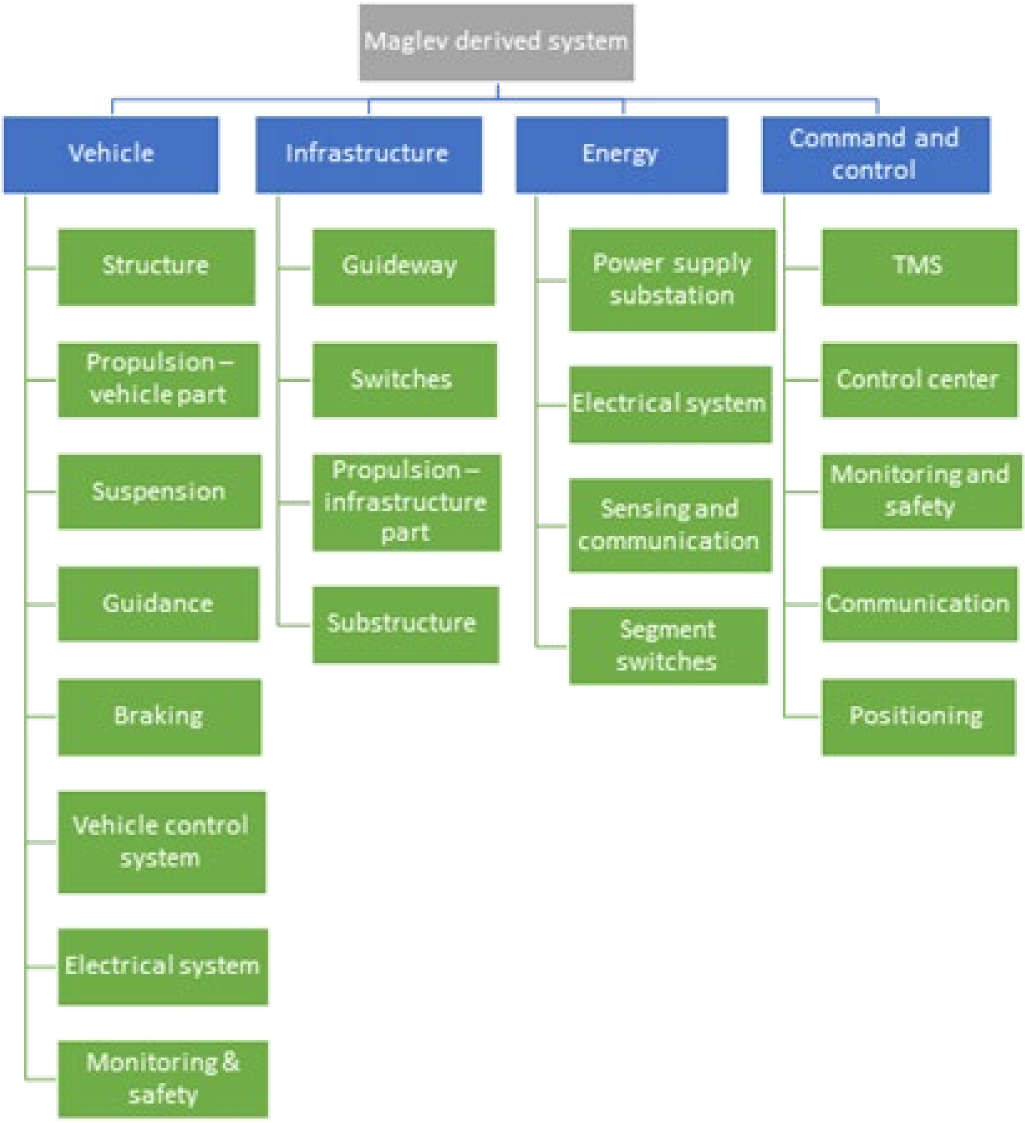

Figure 3: *System breakdown structure of a generic MDS*

Rolling stock for speeds up to 350 km/h must adhere to fixed criteria, according to the TSI. Higher speeds are not considered and would eventually need innovative solutions. MDS structural elements should comply with the requirements defined in TSI Appendix J-1, which covers:

- Mechanical interfaces,
- Gangways,
- Strength and passive safety of vehicle structures,
- Lifting and jacking points,
- Attachment of devices,
- Access doors for staff and freight,
- Mechanical characteristics of glass,
- Load conditions and weighed mass.

2.1.2 Track Interaction and Gauging

The MDS should ensure that their loading gauge complies with TSI requirements. At least one of the track gauges specified by TSI must be compatible with the vehicle's structure. This involves considering:

- Gauging,
- Axle load and wheel load,
- Rolling stock parameters affecting ground-based systems,
- Dynamic behavior of rolling stock,
- Running gear and minimum curve radius,
- Lifeguards.

2.1.3 Propulsion

The MDS's propulsion systems need to cooperate with other electronic track equipment used for control, command, and signaling, as well as train detection systems built on track circuits. Moreover, adherence to the electromagnetic compatibility requirements listed in Appendix J-2 is another requirement set down by the TSI.

2.1.4 Suspension

The suspension system should account for the suspension element load, axle spacing, train length, and maximum allowed speed. These factors align with the infrastructure performance parameters specified in clause 4.2.1 of TSI concerning the rail infrastructure [8].

2.1.5 Braking system

The MDS braking system should include three control modes under various conditions:

- Emergency braking, providing with a predefined braking force within a maximum response time to stop the train at a defined performance level,
- Service braking, applying an adjustable braking force for speed control, including stopping and temporary immobilization.
- Parking braking, keeping permanent immobilization without counting on any onboard energy.

2.1.6 Electrical system

The electrical system of the MDS should be compatible with the power supply systems specified by the TSI, which include AC 25 kV 50 Hz, AC 15 kV 16.7 Hz, DC 3 kV, and DC 1.5 kV. The electromagnetic interference limits for traction currents are outlined in Appendix J-2 of [3].

2.1.7 Vehicle Control System

The vehicle control system should provide information to train staff or the control system regarding degraded conditions, such as reduced braking performances. This allows at the application of specific operating rules, ensuring continued safety and reliability.

2.1.8 Monitoring and Safety

To ensure uniform safety and performance standards, the MDS should be interoperable with monitoring systems and safety regulations that apply to conventional rolling stock. This thorough cross-check guarantees that every MDS subsystem satisfies the criteria established by the TSI, promoting interoperability, safety, and dependability throughout the European train network.

2.2 Interfaces for the technologies' implementation

The MDS vehicle is a train designed to operate on the infrastructure with respect to the railway regulations and the TSI. The rails provide with the physical pathway for the train, while switches would enable the routing of trains to different tracks or segments within the MDS infrastructure. The propulsion subsystem plays a vital role in controlling the vehicle's movement, encompassing functions like acceleration and deceleration, ensuring a smooth and controlled ride. The substructure provides the necessary support and stability to the entire system. A significant focus is placed on the integration and efficiency of energy systems, which are main components that contribute to optimal performance, efficient energy utilization, and sustainability within the MDS. These systems are essential for powering and managing the train's operations. The command-and-control system is a vital component overseeing vehicle movement, safety protocols, alignment, communication, and vehicle positioning. It ensures precise vehicle localisation, monitors components' wear, and coordinates with infrastructure systems for seamless operation. Additionally, it may provide passenger information, contributing to the safe and efficient functioning of MDS.

The interfaces for the technology implementation are outlined according to the system breakdown structure (Figure 3) and can be divided into vehicle-internal MDS interfaces and external vehicle- infrastructure interfaces.

As an example, in a Hybrid MDS vehicle, the main interfaces between the subsystems are as follows:

- Structure:
  - Traditional wheel-based systems,
  - MDS suspension,
  - MDS propulsion/braking,
- Propulsion/braking:
  - Structure,
  - Electrical system,
  - Vehicle control system,
- Suspension:
  - Structure,
  - Traditional wheel-based systems,
  - Guidance,
  - Propulsion,
  - Electrical system,
  - Vehicle control system,
- Guidance:
  - Structure,
  - Traditional wheel-based systems,
  - Suspension,
- Propulsion:
  - Electrical system,
  - Vehicle control system,
  - Monitoring & safety.

3 CONCLUSIONS

The paper, as a follow-up of the MaDe4Rail project, offered an overview of MDS, essential for evaluating solutions potentially importable into the EU interoperable railways.

Although some systems in operation, such as Chinese and Japanese Maglev and metro systems propelled by linear motors, are not designed to be interoperable with the EU railway network, it emerges that various MDS under development meet the requirements to be potentially integrated with conventional railways. .

Moreover, MDS under development, such as MagRail or MagRail Booster proposed by *Nevomo*, as well as MDS components being developed by *Ironbox* or *TACV Lab* are designed to be potentially interoperable solutions.

Though the analysed systems use a variety of solutions for the traction systems, the most promising technology is the linear motors propulsion. Therefore, it would be recommendable to focus next studies on achieving the compatibility of linear motors with the conventional railway network.

Regarding the suspension systems, the most mature are standard wheels and magnetic levitation, meanwhile air cushion suspension systems are also under active development, though with lower TRL.

In addition, the MDS not intended to be interoperable with railway systems, show anyway a potential compatibility of certain technologies and subsystems that could be considered anyway helpful to pursue the railway-MDS integration, especially for urban applications.

Therefore, at the subsystems level, the MDS shows a potential alignment with the railway system, though specific subsystems (e.g. linear motors) need relevant further development and testing to afford integration and compatibility with the interoperable EU railway network.

A fundamental recommendation is to invest future research and innovation resources to the identification of MDS aligned or easy-to-align with EU railway regulations and standards, to the detection of the divergences an to check the technical and economic feasibility of the required interfaces between MDS components and the most promising configurations, particularly for the MDS-based upgrade of the conventional systems and for the deployment of Hybrid MDS.

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5 DISCLOSURE OF INTERESTS

The authors have no competing interests to declare that are relevant to the content of this article.

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