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INSTITUTION OF ENGINEERS
ELECTRICAL DIVISION**

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Thursday
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***SMART SUSTAINABILITY:
TRANSFORMING ENERGY, CITIES AND INDUSTRY***

Ballroom
Sheraton Hotel
Nathan Road
Kowloon
Hong Kong

SYMPOSIUM PROGRAMME

- 08.30 Registration and Coffee
- 09.00 Welcome Address
- Ir Ben C.K. Lam
Chairman, Electrical Division, The HKIE
- 09.05 Opening Address
- Ir Hon. Aaron K.M. Bok
Member (Functional Constituency - Engineering)
Legislative Council, The Government of the HKSAR
- 09.20 Keynote Speech
- Mr. Terry P.S. Wong
Chief Executive Officer
Hong Kong Science & Technology Parks Corporation

1. LV & MV Systems

- 09.50 BESS in LV Network: Unleash the Full Potential of Grid Management and Flexibility
- Mr. Michael T.H. Kwong, Senior Engineer
- Mr. Tim P.C. Ho, Senior Engineer
- Mr. Jason K.W. Cheung, Senior Engineer
- Ms. Cindy W.H. Tung, Engineer
- Mr. Andy T.S. Cheung, Engineer
Smartgrid & Innovation Department
CLP Power Hong Kong Limited
- 10.10 Enhancing Low-Voltage Network Visibility: An IoT-Enabled Low-Voltage Management System at HK Electric
- Ir H.M. Leung, Head of Engineering Systems
- Ir P.C. Tang, Chief System Operations Planning Engineer
The Hongkong Electric Co. Ltd.

- 10.30 SF₆-Free and Digital Medium-Voltage Gas-Insulated Switchgear for Sustainable Power Distribution
- Ms. Vivian J.M. Chen, Head of Product Lifecycle Management
 - Mr. L.T. Wang, Product Lifecycle Manager of IoT
 - Ms. F. Wang, Senior Product Lifecycle Manager
Smart Infrastructure Electrification & Automation, Siemens Ltd., China
 - Mr. Vingo Y.Z. Que, Product Manager
Smart Infrastructure Division, Siemens Ltd., Hong Kong
- 10.50 Discussion
- 11.05 Coffee Break

2. **Power Grids & Networks**

- 11.35 AC 400V Interconnected Distribution Network with “Zero Power Outage” Coordinated by Regional Autonomy and “Source-Grid-Load-Storage-Charging-Discharging”
- Professor X.G. Wang, Vice Professor of Power Electronics
School of Mechanical & Electrical Engineering, Guangzhou University
 - Mr. Z.H. Ru, Deputy General Manager
GDEPRI Power Control Systems & Equipment Co. Ltd.
- 11.55 Grid Impacts of AI Data Centres
- Professor Q. Wang, Associate Professor
 - Dr. G. Hu, Post-Doctoral Fellow
Department of Electrical and Electronic Engineering,
The Hong Kong Polytechnic University
- 12.15 Discussion
- 12.30 Lunch

3. Smart Technology Applications

- 14.00 Future-Proof Artificial Intelligence (AI) Data Centres for Ultra-High-Density Racks
- Ms. X.L. Lim, Senior Power System Technical Expert
Energy Management - Electra
Schneider Electric Singapore
- 14.20 Achieving Sustainable Train Maintenance Through Advanced Automation and Digitalization. The Solution - iWMC
- Ir Eliza C.S. Yang
Chief Rolling Stock Asset Development Manager
Hong Kong Transport Services
MTR Corporation Limited
- 14.40 Bridging the Semantics-to-Action Gap: An Architecture for Deploying Agentic AI for Smart Building Framework and Education
- Ir Raymond K.M. Sze, E&M Engineer
- Mr. Morize K.T. Lau, E&M Engineer
- Mr. Kelvin Y.M. Au, E&M Engineer
Electrical & Mechanical Services Department
The Government of the HKSAR
- 15.00 Discussion
- 15.20 Coffee Break

4. Environmental Protection

- 15.50 Smart Sustainability in Action: Transforming Municipal Solid Waste to Resilient Electrical Power at I·PARK 1
- Ir Louis K.H. Chan, Senior Environmental Business Manager
China Harbour Engineering Co. Ltd.
- Mr. Joseph Geow, Assistant General Manager, Engineering
Keppel Seghers Singapore

- 16.10 Solutions to Premature Retirement of Lithium Batteries in High-Density Urban Environments
- Dr. Frank L.Y. Lam, Associate Dean of Students and Assistant Professor of Engineering Education
The Hong Kong University of Science and Technology
 - Ir Ian Y.L. Lee, Founder & Chief Executive Officer
 - Mr. Warrick W.H. Mak, Chief Knowledge Officer
I-Charge Solutions International Ltd.
- 16.30 Discussion
- 16.45 Summing Up
- Ir Tim C.T. Leung
Symposium Chairman
Electrical Division, The HKIE
- Closing Address
- Ir Professor Frank F. Chan, JP
President, The HKIE

Acknowledgement

The Electrical Division of The Hong Kong Institution of Engineers would like to express its sincere appreciation and gratitude to the following persons and organizations for their contributions to the Symposium.

Authors/Speakers

Ir Hon. Aaron K.M. Bok	Professor X.G. Wang
Mr. Terry P.S. Wong	Mr. Z.H. Ru
Ir Professor Frank F. Chan, JP	Professor Q. Wang
Mr. Michael T.H. Kwong	Dr. G. Hu
Mr. Tim P.C. Ho	Ms. X.L. Lim
Mr. Jason K.W. Cheung	Ir Eliza C.S. Yang
Ms. Cindy W.H. Tung	Ir Raymond K.M. Sze
Mr. Andy T.S. Cheung	Mr. Morize K.T. Lau
Ir H.M. Leung	Mr. Kelvin Y.M. Au
Ir P.C. Tang	Ir Louis K.H. Chan
Ms. Vivian J.M. Chen	Mr. Joseph Geow
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Paper No. 1

**BESS IN LV NETWORK: UNLEASH THE FULL POTENTIAL OF
GRID MANAGEMENT AND FLEXIBILITY**

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Mr. Tim P.C. Ho, Senior Engineer
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ABSTRACT

The growing adoption of distributed energy resources (DERs), particularly rooftop photovoltaic (PV) systems and electric vehicles (EVs), is reshaping the operating conditions of low-voltage (LV) distribution networks. Battery Energy Storage System (BESS) provides a controllable and scalable resource for voltage management, localised network optimisation and peak demand management. This paper presents CLP Power's practical experience in developing distributed BESS applications, progressing from a 100kW/240kWh ground-mounted system to East Asia's first 40kW/85kWh pole-mounted BESS. Simulation and network studies illustrated the potential contribution of coordinated BESS operations to improve voltage and load-profile management. A structured engineering assessment framework is presented to guide deployment decisions, while customer-owned BESS is considered cautiously as a complementary pathway for future distributed flexibility, smart grid development and enhanced network resilience.

1. INTRODUCTION

In support of Hong Kong's target of achieving carbon neutrality before 2050, Hong Kong's Climate Action Plan 2050 identifies net-zero electricity generation and green transport as key decarbonisation strategies [1]. The continued growth of distributed energy resources (DERs), particularly rooftop photovoltaic (PV) systems and electric vehicles (EVs), is changing the network conditions of low-voltage (LV) distribution networks. Customer-connected PV systems introduced bi-directional power flows [2], while increasing EV adoption is influencing local demand patterns.

High penetration of rooftop PV generation may contribute to voltage rise and reverse power flow during periods of high solar output and low local demand. Increasing EV adoption may also alter local demand profiles and loading patterns on distribution transformers and feeders. These evolving network conditions can be particularly pronounced on rural and semi-urban LV circuits, creating a need for more flexible and controllable network solutions.

Similar challenges are being addressed by utilities and network operators in different regions through the

deployment of distributed and community battery systems. Examples include community battery programmes in Australia [3] and Community Energy Storage System (CESS) initiatives in Malaysia [4], where energy storage is applied to support renewable energy integration, local network operation and grid flexibility. While the operating environments and regulatory frameworks differ, these developments reflect the growing recognition of BESS as one of the effective tools for managing increasing DER penetration.

CLP Power has been developing a portfolio of low-voltage smart grid solutions to address specific network needs. These include a 100kW/240kWh ground-mounted system coordinated with a line voltage regulator (LVR) and smart grid controller, a compact pole-mounted BESS, the first of its kind in East Asia, alongside emerging integration approaches for customer-owned energy storage. Together, these configurations provide different combinations of energy management, voltage support, monitoring and coordinated control.

This paper presents CLP Power's experience in developing BESS applications for LV network management, covering both ground-mounted and compact pole-mounted configurations. It examines the associated engineering, safety, integration and operational considerations, and demonstrates how BESS configurations can be evaluated through a structured assessment framework to support future deployment decisions. Potential integration approaches for customer-owned BESS are also introduced as an area for further study.

2. BESS AS AN ENABLER FOR LV NETWORK FLEXIBILITY

Figure 1 illustrates the Low Voltage Smart Grid (LVSG) concept, where real-time monitoring, communication and control enable the coordinated operation of DERs, including rooftop PV systems and EV loads. The enhanced visibility and controllability of local energy resources support more effective management of power flows and network conditions. Within this framework, BESS provides flexible energy storage and dispatch capability to support reliable and efficient LV network operation.

BESS has emerged as an important enabler for supporting the increasing adoption of DERs in LV networks. Through dispatchable charging and discharging control, it can provide targeted peak support, enhance utilisation of existing network assets and improve local network controllability. For circuits with high rooftop PV penetration, BESS can support voltage management, improve renewable energy utilisation and increase hosting capacity within existing network infrastructure. BESS can also support increasing electrification and EV adoption by providing local peak support and load shifting capability, thereby optimising utilisation of distribution transformers and LV feeders while maintaining network reliability.

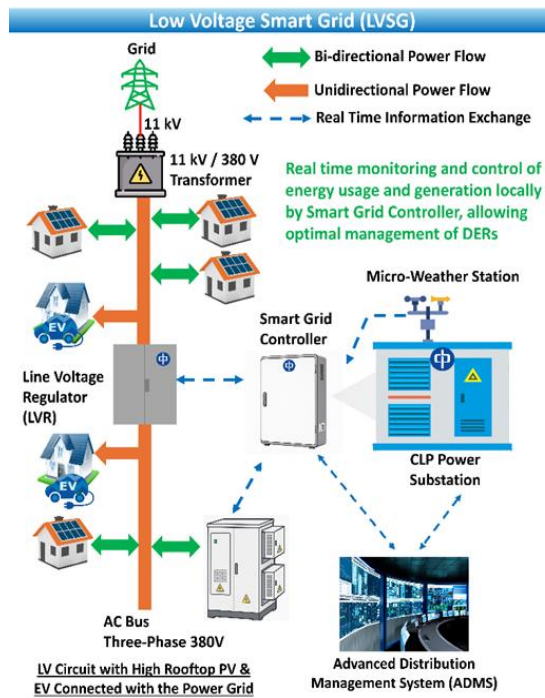


Fig. 1 - System Architecture of LVSG

3. GROUND-MOUNTED BESS APPLICATION

3.1 Application of Ground-Mounted BESS in LV Networks

Ground-mounted BESS, as shown in Figure 2, forms an important part of CLP Power's LV smart grid architecture, providing network support capability where suitable sites and equipment space are available. In the system architecture, a 100kW/240kWh ground-mounted BESS is coordinated with LVR and AI-enabled smart grid controller to support voltage management, demand management and more efficient utilisation of local network assets.

As shown in Figure 3, network assessments and simulation studies indicated that coordinated operation of the ground-mounted BESS and LVR by smart grid controller can support voltage management on circuits

with high PV penetration. The studies also provided practical inputs for system integration, monitoring and control strategy design, while establishing a reference framework for optimising the charging and discharging windows throughout the project lifecycle.



Fig. 2 - Photo of Ground-Mounted BESS Deployed in LV Network

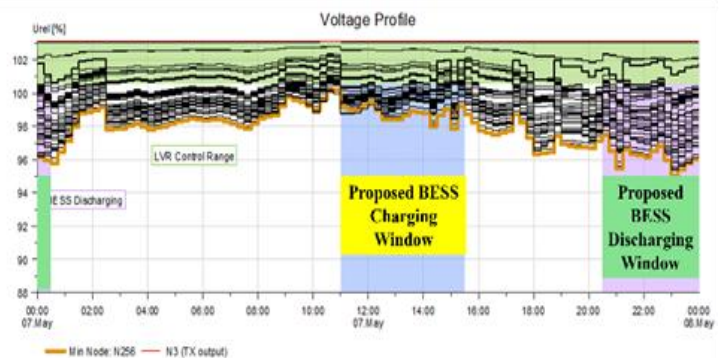


Fig. 3 - Simulated Voltage Profile with Coordinated BESS and LVR Control (for illustration only)

3.2 Grid Integration, Monitoring and Dispatch

The deployment of the ground-mounted BESS requires careful consideration of circuit conditions through network simulations, including transformer loading, feeder configuration, voltage profile and anticipated DER growth. Once connected to the LV network, the system is integrated with utility communication infrastructure and the Advanced Distribution Management System (ADMS) to provide real-time monitoring and control capabilities.

Relevant operating parameters for monitoring and control include state of charge, active and reactive power, alarms and equipment status. Subject to the implemented system architecture and control arrangements, the collected data can enhance operational visibility and the development of control strategy for voltage and demand management.

3.3 Interoperability and Operational Considerations

Effective coordination requires seamless interoperability among the BESS, smart grid controller, existing communication infrastructure and ADMS. Communication architecture should support secure and reliable data exchange, real-time monitoring and control functions across the integrated system.

With appropriate system and network planning strategies, including circuit-level assessments, robust communication integration and operational control design, ground-mounted BESS provides a practical and scalable solution for enhancing network resilience while complementing conventional network reinforcement approaches.

3.4 Evolution Towards Distributed BESS Applications

The deployment of ground-mounted BESS has demonstrated the value of integrating energy storage, voltage regulation and coordinated control within LV networks. Through network assessments and pilot deployments, the approach has established a practical foundation for applying energy storage as an active network support resource.

While ground-mounted BESS can effectively support LV network operation, LV network requirements may vary considerably between feeders due to differences in network configuration, DER penetration levels, customer load characteristics and geographical constraints. Consequently, the locations where energy storage can deliver the greatest network value are often localised and feeder-specific.

As DER adoption continues to increase across a wider range of LV circuits, there is growing interest in more distributed deployment approaches that can be located closer to the point of network need while retaining the benefits of energy storage and advanced power-electronics-based network support. These considerations, together with the need for deployment in land-constrained environments, subsequently led to the development of the pole-mounted BESS (P-BESS).

4. P-BESS DEPLOYMENT AND PRACTICAL PROJECT EXPERIENCES

4.1 Design Concept of P-BESS

To extend the application of distributed energy storage to locations where equipment footprint availability is a key consideration, CLP Power developed a P-BESS as a compact solution for LV circuits with high rooftop PV penetration or emerging local network support requirements. The pole-mounted configuration enables deployment closer to the point of network need while minimising land and installation requirements, making it particularly suitable for space-constrained environments such as Hong Kong.

Through coordinated charging, discharging and voltage support capability, P-BESS enhances local network controllability, facilitates greater integration of DERs, supports demand management by reducing local peak loading and shifting demand to off-peak periods, and improves the flexibility and utilisation of LV network assets.

The P-BESS comprises an 85kWh battery cabinet and a Grid Connection Enclosure (GCE), mounted on a dedicated pair of utility poles. The 40kW power conversion system is integrated within the P-BESS configuration. The GCE houses the protection, isolation, control and communication equipment required for grid connection and operation.

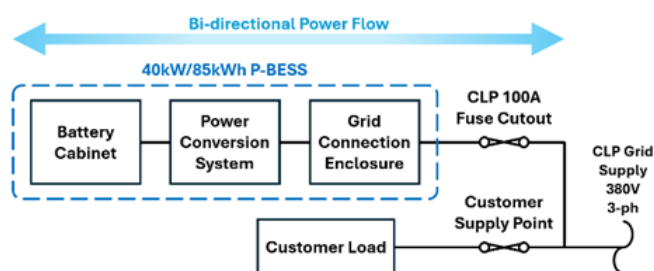


Fig. 4 - Grid Connection Diagram of P-BESS

The P-BESS incorporates a power conversion system (PCS) with four-quadrant operating capability. The PCS includes static synchronous compensator (STATCOM) functionality to enhance voltage control, alongside the provision of energy storage and dispatch functions.

Connected in parallel with the LV network, the P-BESS can provide local voltage support at its point of connection. Its active and reactive power capability provides flexibility to respond to feeder conditions, subject to the implemented control strategy and operating limits.

The integrated arrangement also provides a basis for evaluating phase-balancing support and improved utilisation of local network capacity. These functions are relevant where feeder characteristics, DER concentration and customer demand vary between locations.

By combining energy storage, voltage support and reactive power management within a compact footprint, P-BESS demonstrates an integrated approach to localised LV network support. The configuration provides a practical engineering reference for safe and scalable deployment in footprint-constrained locations, while recognising that each application remains subject to network, site and operational assessments.

4.2 Deployment, Safety & Operational Considerations

The P-BESS installation design requires careful consideration of safety, accessibility and maintainability

throughout the asset lifecycle. Safe access is essential to support inspection, maintenance and operational activities.



Fig. 5 - Photo of P-BESS Trial Installation

The deployment of P-BESS required considerations of network connection, structural suitability, maintenance clearance and site accessibility. A site-specific assessment is conducted to verify compliance with safety and risk mitigation requirements, taking into account relevant international standards, such as NFPA 855 [5] and recommendations from local specialists and consultants. More than ten installation configurations were evaluated through engineering assessments, including wind-load simulations, to identify the most suitable arrangement while satisfying operational, structural and safety requirements.

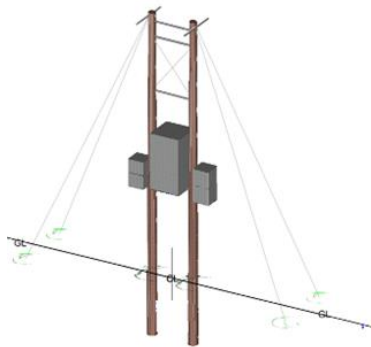


Fig. 6 - Illustrative Wind-Load Simulation Assessment of P-BESS Configuration

4.3 Operational Strategy and Expected Network Benefits

The P-BESS is configured to operate under a time-based control logic designed to support demand management applications. The controller schedules the P-BESS to

charge during off-peak periods and discharge during peak periods of demand. The active power output or input of the P-BESS is managed in accordance with the scheduled 24-hour operating profile, with the active power varying at 30-minute intervals. By applying this control logic, the projected daily load profile of the circuit to which the P-BESS is connected is modified as illustrated in Figure 7.

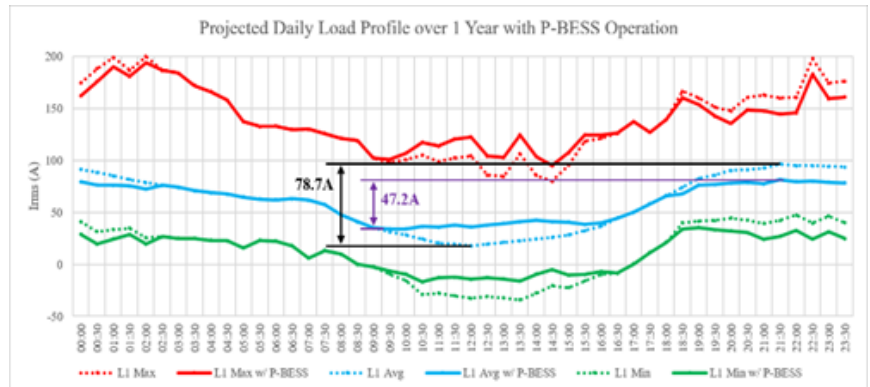


Fig. 7 - Projected Daily Load Profile (L1 Phase) with P-BESS Operation (for illustration only)

The blue solid line represents the yearly average projected daily load profile of Phase L1 of the circuit after P-BESS operation in place. The dotted line represents the original yearly average load profile of L1 without P-BESS. The projected load profile indicates that the P-BESS operation effectively flattens the load profile curve, in which the variation (i.e., difference between the maximum and minimum value) of the average daily load profile is reduced from 78.7 A to 47.2 A, representing a 40.0% reduction. A flatter load profile can reduce local peak loading, improve utilisation of distribution transformers and LV feeders, and increase operational flexibility within the existing network. By shifting demand from peak to off-peak periods, the P-BESS supports more efficient use of network assets while accommodating growing electrification and DER integration.

To further evaluate the effectiveness of the P-BESS scheduled operation in suppressing load variation, daily load variation of the circuit with P-BESS operation is derived individually for each calendar day, as illustrated in Figure 8.

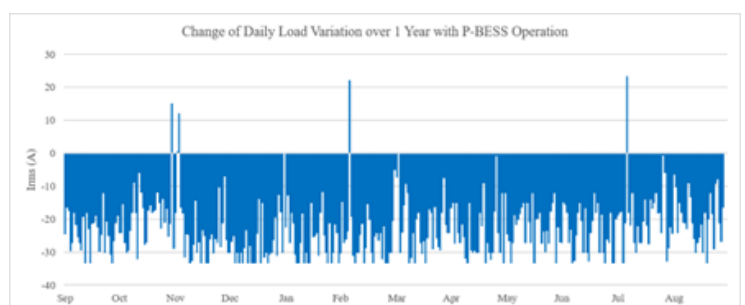


Fig. 8 - Change of Daily Load Variation with P-BESS Operation (for illustration only)

Across the one-year assessment period, the simulated P-BESS operating schedule successfully mitigates daily load variation on 357 out of 362 assessed days. Load variation increased on only 5 days, while data was unavailable for 3 days. This corresponds to a success rate of approximately 98% in suppressing daily load variation on the circuit. The yearly average daily load variation is reduced from 119.3A to 96.2A following P-BESS implementation, representing a reduction of approximately 19.3%. These results demonstrate the effectiveness of P-BESS in reducing daily load fluctuation and supporting network stability.

5. CUSTOMER BESS INTEGRATION AS FLEXIBILITY OPTION

Customer-owned BESS may provide a potential source of distributed flexibility for future LV network applications. Its potential contribution depends on suitable customer participation, connection arrangements, asset availability and operating constraints. Accordingly, customer-owned BESS is treated in this paper as an area for structured evaluation rather than an established network resource.

Evaluation of customer-owned BESS should consider the monitoring and communication capability required to establish asset status, availability, state of charge and available flexibility. Any exchange of operating requests would require secure interfaces, defined responsibilities and arrangements that respect customer operating requirements.

Where appropriate technical and operational arrangements can be established, coordinated customer-owned BESS may provide opportunities to support specific local network requirements. Further study is required to evaluate technical performance, interoperability, customer participation, operating boundaries and commercial considerations before such arrangements or specific applications can be determined.

6. ASSESSMENT FRAMEWORK FOR BESS DEPLOYMENT

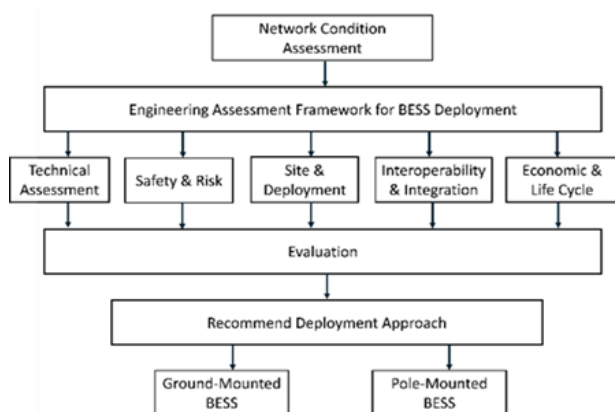


Fig. 9 - Assessment Framework for Evaluating BESS Deployment Approaches

The deployment approaches presented in the preceding sections demonstrate that different BESS configurations may be suitable for different network conditions, operating objectives and site constraints. A structured assessment framework can assist engineers and network planners in evaluating available approaches while ensuring consistent consideration of technical, operational, safety and economic factors.

6.1 Network Condition Assessment

The assessment should begin with an understanding of the network conditions and intended operational objectives. Typical considerations include voltage performance, loading constraints, DER integration requirements, demand management needs and resilience objectives.

6.2 Technical Feasibility Assessment

Technical assessment should consider power and energy ratings, duty cycle, control requirements and compatibility with existing LV infrastructure to ensure the proposed solution can support the intended network application.

6.3 Safety and Risk Management

Assessment should consider compliance with applicable safety requirements, fire and electrical safety, emergency access, and site-specific risk mitigation measures. Different deployment approaches may present different safety considerations depending on installation arrangements, site conditions and public accessibility.

6.4 Site and Deployment Assessment

Site assessment should evaluate footprint availability, structural suitability, accessibility, maintenance requirements and environmental conditions. Additional considerations may vary depending on the selected deployment approach.

6.5 Interoperability and Integration

Assessment should consider communication requirements, monitoring capability, control architecture, interoperability, cybersecurity and integration with utility systems such as ADMS.

6.6 Economic and Lifecycle Assessment

Economic and lifecycle assessment should consider cost-benefit analysis, maintenance requirements, operational complexity, expected service life and overall lifecycle value.

Table 1 summarises the key evaluation criteria associated with each assessment area. The framework is intended to support a consistent comparison of ground-

mounted and pole-mounted BESS deployment approaches. It provides a structured basis for evaluating network conditions, technical requirements, safety, site conditions, interoperability, system integration and lifecycle value. Its purpose is to identify the deployment approach that best fits the local application rather than to prescribe a single preferred solution.

Assessment Area	Key Evaluation Criteria
Network Condition	Voltage performance, feeder or transformer loading, peak support, hosting-capacity constraints and resilience needs
Technical Feasibility	Power and energy rating, duty cycle, charging and discharging windows, control strategy, protection and network compatibility
Safety and Risk Management	Applicable safety standards, emergency access, structural suitability and site-specific risk mitigation
Site and Deployment	Footprint, siting constraints, delivery route, lifting and maintenance arrangements, environmental exposure and replacement requirements
Interoperability and Integration	Communications, monitoring, control architecture, data requirements, cybersecurity and interface with relevant utility platforms (e.g. ADMS)
Economic and Lifecycle	Capital-cost optimisation, expected utilisation, maintenance, operational complexity, service life and overall network value

Table 1 - Assessment Framework for Ground-mounted and Pole-mounted BESS Deployment

7. FUTURE DEVELOPMENT & CONCLUSION

The ground-mounted BESS and East Asia's first P-BESS demonstrated two complementary approaches to applying energy storage in LV networks. The ground-mounted arrangement provides a solution for coordinated operation with voltage regulation and control equipment, while P-BESS offers a compact configuration for localised applications where siting constraints are significant.

P-BESS integrates energy storage with active and reactive power capability in a compact pole-mounted configuration. Together with the engineering assessment framework, the project provides a practical reference for the safe, scalable and innovative development of distributed energy storage.

Future work will focus on performance evaluation of deployed BESS assets under different network conditions, including assessment of operational effectiveness, demand management, voltage support capability, asset utilisation and long-term operational performance. Continued evaluation will support optimisation of deployment strategies and provide further insights into the application of distributed energy storage in LV networks.

In addition, further study will be conducted on integration approaches for customer-owned BESS, including monitoring, communication and coordinated operation arrangements. As BESS adoption continues to grow across commercial and industrial sectors, customer-owned resources may provide flexibility to support specific LV network applications.

The deployment experiences and assessment framework presented in this paper provide practical references for engineers and utilities evaluating future energy storage applications. Through appropriate deployment, integration and operation, BESS can support LV network management, facilitating renewable energy and distributed energy resources integration, and contributing to a more flexible, resilient and sustainable power network.

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Paper No. 2

**ENHANCING LOW-VOLTAGE NETWORK VISIBILITY:
AN IoT-ENABLED LOW-VOLTAGE MANAGEMENT SYSTEM
AT HK ELECTRIC**

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ABSTRACT

Low-voltage (LV) distribution networks are traditionally not equipped with advanced real-time monitoring facilities due to their extensive coverage, complex topology, and communication constraints, resulting in predominantly passive management strategies. To address these challenges, HK Electric commenced to develop a Low-Voltage Assets Operations and Maintenance Management System (LAOMMS) programme in 2023, aiming to enhance visibility, fault response, and operational efficiency of its LV network. Central to this initiative is the development of a Low-Voltage Control Centre (LVCC), supported by a Supervisory Control and Data Acquisition-based Low-Voltage Management System (LVMS), and a network of IoT sensors, including a cost-effective in-house developed Low-Voltage Fault Indicator (LVFI), connected with own corporate IoT platform (SmartLink @ HK Electric).

The LVMS was designed with flexible, interoperable communication standards and integration capabilities with other enterprise systems such as the Outage Management System (OMS) and Geographical Information System (GIS). A deliberate data update workflow ensures a single source of truth for LV network connectivity, enabling accurate fault identification and near real-time system visibility.

Commissioned in November 2025, the LVMS provides a platform to deliver near real-time monitoring of LV networks, facilitating improved fault location, faster service restoration, and enhanced operational decision-making.

This paper presents the overall system architecture, hardware design, and deployment of LVFI, and mechanisms for maintaining up-to-date network connectivity. It also highlights key operational features, cybersecurity considerations, and opportunities for future integration with smart-grid initiatives. The phased deployment of LVFI sensors and continuous system enhancement are expected to further expand analytical capabilities and strengthen end-to-end monitoring across the electricity supply chain, supporting more proactive and resilient network management.

1. OVERVIEW OF SYSTEM ARCHITECTURE DESIGN OF LVCC

Multiple LV Fault Indicators (LVFIs) installed across low voltage feeders continuously monitor network

conditions and transmit data and fault alarms through the LoRaWAN communication network to the LoRaWAN servers. The data are then integrated into LVMS, which serves as the central platform within the LVCC.

LVMS also interfaces with key enterprise systems, including the New HK Electric Geographic Information System (NHGIS) to obtain geographical and asset information. By consolidating real-time measurements, LVMS provides operators and users with enhanced visibility of the LV network. This enables faster location of faulty section, improved situational awareness and more effective operational coordination and decision-making during network operations and service restoration.

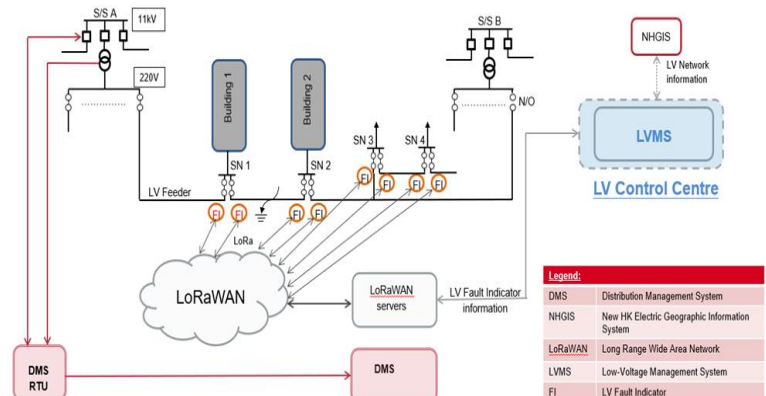


Fig. 1 - Overall System Architecture

2. SmartLink @ HK ELECTRIC DATA GOVERNANCE, OPERATIONS & MANAGEMENT FRAMEWORK

To support the digitalisation of power system operations and the wider adoption of Internet of Things (IoT) technologies, HK Electric has developed and deployed a proprietary LoRaWAN infrastructure, known as SmartLink @ HK Electric. The platform comprises a private LoRaWAN network with dedicated gateways, redundant backend servers, secure integration with LVMS, connectivity to the Corporate Data Network (CDN), and interfaces to an Enterprise Data Platform (EDP).

SmartLink @ HK Electric serves as the common communication platform for a growing range of operational IoT applications, enabling secure and reliable collection of field data from geographically distributed devices across the electricity network. By providing a standardised and scalable communications

infrastructure, SmartLink @ HK Electric facilitates the integration of operational technologies with enterprise systems and supports the increasing digitalisation of network monitoring and asset management functions.

In parallel with infrastructure deployment, HK Electric established a governance framework covering sensor onboarding, operation, modification and decommissioning to ensure sustainable growth of the ecosystem. A key consideration is the adoption of a holistic sensor lifecycle management approach, under which clear responsibilities are assigned to different stakeholder groups. Users remain the owners of sensors throughout their lifecycle, including deployment, monitoring, maintenance and retirement. Under this framework, the Transmission and Distribution Division (T&D) is responsible for approval of sensor types, connectivity of the sensors and providing technical consultancy to the users. T&D maintains the approved sensor catalogue, provides technical support for sensor selection and deployment, and manages sensor onboarding to the LoRaWAN network and ensures data connectivity. For LVFI, the Information Technology Division (IT) provides data integration services and standard interfaces between LoRaWAN and LVMS. This well-defined workflow ensures effective coordination among all parties and enables the rapid deployment of new sensors with minimal turnaround time.

To streamline onboarding procedure, a standardised process was established based on three governing documents: the LoRaWAN Sensor Registration Form (SRF), LoRaWAN Sensor Evaluation Form (SEF) and IoT Cybersecurity Assessment Form (CAF). For sensors already included in the approved list, onboarding mainly involves coverage verification, cybersecurity review, network registration and commissioning. For new sensor types, an additional technical assessment is performed to verify system compatibility, LoRaWAN technical compliance, security compliance and data integration requirements before the necessary configuration. Similar procedures are defined for sensor modification, relocation and decommissioning, ensuring asset records, cybersecurity controls and data repositories remain up to date throughout the sensor lifecycle.

To maximise the value of the investment to platform, HK Electric maintains a curated and continuously evolving catalogue of approved sensors covering a wide range of applications. Sensors are categorised by functionality and operating environment, enabling users to easily identify suitable devices for their business needs. The catalogue includes both commercial products and self-developed devices such as the LVFI, which has been deployed for monitoring of low voltage network. User feedback, application surveys and operational experience are continuously collected to identify emerging requirements, source suitable sensor technologies and refine the approved sensor list. In

parallel, promotion activities, knowledge sharing and IoT application showcases are conducted to encourage wider adoption across business units, thereby maximising utilisation of the SmartLink @ HK Electric and accelerating innovation throughout the organisation.

3. HARDWARE DESIGN AND INSTALLATION OF LVFI

3.1 Considerations and Rationale Leading to the Current Design

The LVFI version 2 (V2) is engineered to solve a very concrete operational problem in HK Electric's LV network: locating the exact faulty section quickly and safely in a mixed open ring/radial topology where multiple customers branch from a single supply point and where traditional manual tracing easily takes an hour or more. To make the solution scalable and operationally light, this version extends the original LVFI with richer sensing, battery free autonomy, and secure, low touch communications designed to feed LVMS with near real time telemetry and event data for analysis and restoration of power network. In other words, the current design is a balance between measurement precision at the LV service cutout (hereafter referred to as LV cutout), installation simplicity in tight cable chambers, reduced lifecycle maintainability through battery-free operation, and cybersecurity measures aligned with HK Electric's operations environment and governance requirements. These design choices are also motivated by system level benefits, specifically granular LVMS-assisted situational awareness once event and load data are consistently available at LV cutouts.

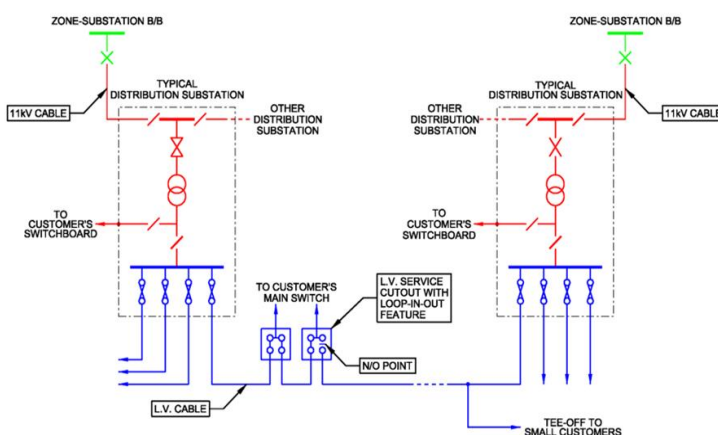


Fig. 2 - Typical Arrangement of HK Electric's Low Voltage Distribution Network

One of the major design drivers for developing LVFI V2 is to ensure ease of installation within existing LV cutouts. To achieve this, two key considerations were prioritised: avoiding any live work on electrical equipment and minimizing modifications to existing infrastructure. Consequently, a fully non-invasive measurement approach was adopted. Under this design philosophy, only the neutral conductor is directly

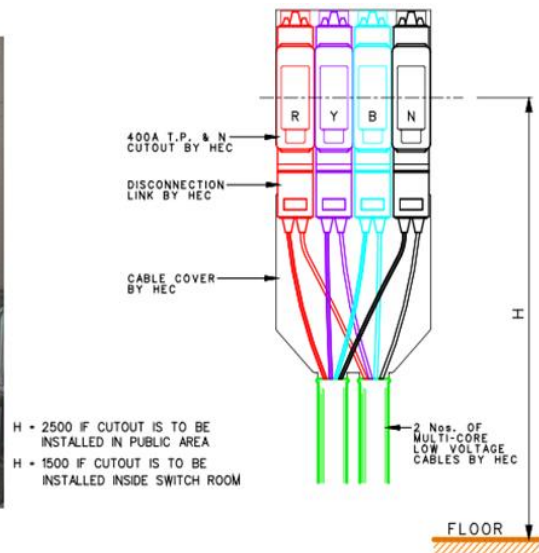


Fig. 3 - EMMCO LV Cutout

connected to the device to provide a stable potential reference, while all other sensing functions, such as current and voltage detection, are performed using non-contact techniques. This approach significantly reduces installation complexity and safety risks while ensuring compatibility with LV cutout having legacy configurations.

At the sensing layer, two complementary sensing capabilities are being explored to support different fault detection objectives: current sensing and voltage sensing. The LVFI V2 employs Rogowski coils to monitor all three phases and the neutral conductor on both the incoming and outgoing LV cables of a cutout, providing a total of eight current sensing channels. Monitoring both sides of the cutout enables rapid determination of the locations of fault current, allowing the failed section between adjacent devices to be identified directly rather than merely indicating an affected feeder.

The analogue front-end integrates and amplifies the millivolt-level signals generated by the Rogowski coils. Two separate measurement channels are established for monitoring both short-duration events, down to 10 ms and periodic measurements for statistical purposes. Detection thresholds are configurable, enabling field personnel to optimise sensitivity according to site-specific network conditions.

Complementing current sensing, non-contact voltage (NCV) detectors provide per-phase voltage presence and brownout indications without requiring additional cable penetrations or hardwired voltage transformer connections to energised equipment. This non-invasive approach significantly reduces installation time and safety risks, while enhancing the capability of fault detection by identifying brownout and fuse-out conditions that may not be distinguishable using current measurements alone, particularly under very light load conditions.

An e-paper display is incorporated to provide a persistent visual indication of fault status, including fault detection across all three phases at the incoming or outgoing side of the LV cut-out. Unlike conventional displays, the e-paper technology retains information without power, allowing maintenance personnel to access critical fault information even after supply interruption and before backend records are reviewed.

Device	LVFI	LVFI V2
Detection Principle	Summation Current Detection	Individual Phase Detection
Phase to Phase Fault	×	✓
Phase to Neutral Fault	×	✓
Phase to Earth Fault	✓	✓
3 Phase Fault	×	✓
3 Phase to Neutral Fault	×	✓
3 Phase to Earth Fault	✓	✓
High Impedance Fault	×	×
Overload	×	×
Intermittent Fault	×	✓

Table 1 - Comparison of Various Fault Detection Capabilities of LVFI and LVFI V2

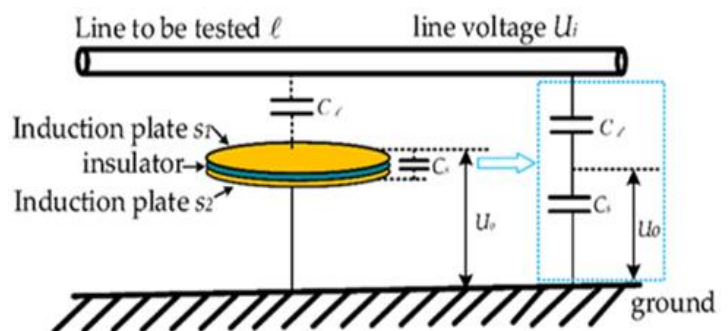


Fig. 4 - Illustration on Capacitive Coupling Sensing

LVFI V2 is battery free, it harvests energy from two metering current transformers (CT) clamped around LV cores, with the power path designed to boot and run from as little as 25 A of load on any one phase. The harvested energy charges up a supercapacitor sized to provide at least 5 minutes of ride through to preserve alarms and enable final uplinks after a trip. A USB-C port is provided which is only used for commissioning or in the laboratory, and is physically blocked when in-service to minimise local attack surface and unplanned resets. The harvester supports independent and parallel modes across two CTs to accommodate feeder load unbalanced.

For communications, LoRaWAN (AS923) Class C was selected for its availability. The stack enforces over the air activation (OTAA) for secure activation, Adaptive Data Rate (ADR) to converge on the most efficient data rate per site, confirmed uplink/downlink with acknowledge message handling, and a bounded retransmission policy that steps down the data rate up to a maximum of eight attempts while honouring a $\leq 1\%$ duty cycle. A minimal downlink command surface, “report now” and “power reset”, is a conscious cyber design choice that reduces the remote actuation surface while keeping operational control intact.

Mechanical and installation constraints strongly shape the hardware. A robust Acrylonitrile Styrene Acrylate (ASA) enclosure with Ultraviolet (UV) resistance and compliance to UL94 V0 houses a cover mounted printed circuit board (PCB), enabling an easy device swap by replacing the lid during maintenance. Conformal coating protects against humidity and dust; connectors are grouped by function (left cable currents, right cable currents, metering CTs, NCVs) to cut clutter and error in crowded chambers. Collectively these measures reduce in chamber time, installation variance, and the kinds of wiring errors that are hard to detect once the chamber is closed.

Reliability and longevity targets reflect the utility environment and experience. LVFI V2 targets a ≥ 20 year service life using industrial grade components, environmental protections, and accelerated life testing. The design is owned by HK Electric, enabling in house evolution, security review, and forensic capability throughout the product’s lifetime, which is the approach HK Electric has used to sustain high availability and maintainability across other operations systems. LVFI also acquired a Hong Kong short-term patent for protecting our intellectual property.

4. ONBOARDING AND COMMISSIONING PROCESS OF LVFI

4.1 Onboarding and Commissioning Process

The onboarding and commissioning of LVFIs are intentionally designed as a two-stage process to ensure that all physical wiring, power harvesting capability and

baseline communication performance are fully validated before any event logic is enabled. This structured approach prevents nuisance alarms, reduces avoidable rework, and provides clear and traceable checkpoints for installation teams, system support teams and system operation team.

The two-stage method also recognises that most site difficulties arise not from hardware defects but from environmental conditions, such as insufficient LV loading for energy harvesting or weak radio coverage in enclosed spaces, and from human factors such as incorrect phase placement or mis-mapping of the cutout Supply Point number (SN) and DevEUI (Device Extended Unique Identifier). Besides, the two-stage approach allows the segregation of “LVFI and location mapping” to a later stage, which is much preferred by site staff in actual operations. By separating validation of physical location from system mapping, the overall process becomes more flexible, robust and less prone to early operational issues.

Before site commissioning, a workshop acceptance test was conducted to ensure the quality of the LVFI V2 units. This testing also confirmed that all functions of the LVFI V2 were operating satisfactorily prior to handover for site installation. The workshop test items included current injection and voltage simulation to verify the core measurement functions. Communication performance was also tested using a designated test system to ensure proper connectivity.

4.2 Stage 1 - Physical Installation, Power Sufficiency and Communication Readiness

In the Stage 1 commissioning, site personnel install the field device and verify the correctness of the installation through direct measurement and functional checks. Key electrical parameters measured on site, including voltage and currents are compared against the values reported by the device to confirm proper operation and calibration. The communication and operational status of the devices are also verified and recorded.

Where practicable, all tests are performed under normal operating conditions without the use of temporary supporting equipment. However, if site conditions prevent the device from powering up, operating correctly, or establishing communication with the system, temporary aids can be used to facilitate commissioning and verification activities. Whenever such assistance is required, site personnel shall record the relevant observations and reasons for follow-up in subsequent stages.

Once the installation and verification activities are completed satisfactorily, the site engineer records the asset identifier and the device identifier in the commissioning records and captures supporting evidence demonstrating the association between the installed asset and the device. The identifying

information shall be clearly visible and readily traceable from the recorded evidence.

The commissioning records and supporting evidence are then shared with the relevant system support personnel as a prerequisite for subsequent system configuration and registration. The asset-device association shall be communicated to all relevant stakeholders within the prescribed reporting period following completion of Stage 1 commissioning. Upon receipt of the information, the system support team updates the central asset register and marks the device as “Stage 1 Completed.”

4.3 Stage 2 - End-to-End System Mapping and Data Validation

Stage 2 Commissioning focuses on verifying that the asset identifier and device identifier have been correctly configured and synchronized across all relevant systems and data pathways. Based on the information submitted in Stage 1, the system support team updates the required configuration records, registers the device in the communication infrastructure, and ensures that the asset-device association is accurately reflected in the relevant operational systems.

After configuration is completed, the operation team performs Stage 2 commissioning by comparing the device telemetry received through different system pathways. This validation ensures that all systems are referencing the same physical device and that the transmitted data are consistent across platforms, and ensures no discrepancies are introduced during configuration, integration, or data loading processes.

Once the verification is completed successfully, the responsible system owners update the commissioning records and notify the relevant stakeholders. The central commissioning register is then updated. Future enhancements may include automation of the cross-system validation process to reduce manual effort and improve commissioning efficiency.

If any discrepancies are identified, the relevant support teams jointly review the commissioning records, supporting evidence, configuration data, and system settings to determine the cause and implement corrective actions. Such investigations may include validation of asset-device associations, configuration parameters, data mappings, and communication settings.

If a device is found to be offline or unavailable during Stage 2, the support team reviews the observations recorded during Stage 1 to determine the likely cause. Where site conditions prevent the device from operating continuously, temporary measures may be arranged to facilitate completion of the verification activities. Where communication performance is identified as the root cause, the communication infrastructure, coverage, or installation environment shall be reviewed and improved as necessary. If environmental or site-specific

factors continue to adversely affect connectivity, the responsible parties shall coordinate with relevant stakeholders to assess and implement appropriate mitigation measures.

Completion of this stage confirms that the device is correctly registered, integrated into the relevant systems, successfully communicating through the required data pathways, and delivering consistent data across all designated platforms.

5. KEY PHASES OF LVMS DEVELOPMENT

HK Electric adopted a phased and pragmatic roadmap to establish a utility-scale LVCC for near real-time monitoring and management of the LV distribution network. The initiative commenced in 2020 with a proof-of-concept (PoC) to validate the end-to-end data communication path from LVFIs, through the LoRaWAN network, to the LVMS. This was followed by a blueprint phase in 2021 to define operational requirements, system architecture and overall system scope, alongside initial LVFI field trials.

In 2022, a field-testing LVMS environment was deployed using a commercial Supervisory, Control and Data Acquisition (SCADA) platform in use. The LVMS is integrated with the emerging corporate LoRaWAN infrastructure. Functional user acceptance tests were completed in 2023, followed by further integration with the NHGIS, cybersecurity assessments and pre-production activities in 2024. The LVMS and LVCC were successfully commissioned and put into production in November 2025.

5.1 Implementation of LVMS by SCADA

A strategic consideration was to extend the existing SCADA-based data acquisition and monitoring philosophy from Distribution Management System (DMS) operations to LV network management rather than adopting a cloud-native architecture. One key rationale was HK Electric’s established in-house capability in developing and supporting SCADA systems. The LVMS was implemented on the new generation of SCADA platform, using an engineering approach similar to the existing proven EMS/DMS platform based on an earlier platform from the same supplier.

By adopting this approach, existing expertise in network modelling, topology management, connectivity tracing and fault analysis could be directly leveraged. In particular, the comprehensive network tracing and analytical functions developed in-house for DMS applications were extended to support LV network platform and commercially available off-the-shelf products while minimising customisation of the systems. This approach improved long-term maintainability and reduced implementation risk. management. The project

also maximised the use of the standard functionality provided by the new-generation

Another consideration was the scale of the LV network. HK Electric's service area comprises approximately 9,000 LV circuits, a size that can be effectively managed within a modern SCADA system without encountering data-volume and scalability challenges faced by significantly larger LV networks.

Compared with cloud-based LV monitoring platforms that are increasingly being adapted by some utilities worldwide, the SCADA-based approach offers different strengths and trade-off. Cloud platforms generally provide greater scalability, flexible computing resources and simplified deployment of advanced analytics applications. Conversely, a SCADA-based LVMS offers deterministic performance, lower-latency data processing, integration with operational technology (OT) systems, and unified operational environment for control room operators.

For HK Electric, extending the existing SCADA environment was considered an efficient and sustainable solution because it leveraged established infrastructure, engineering expertise and operational process. The resulting LVMS provides an appropriate balance of operational performance, maintainability, cybersecurity and cost-effectiveness while meeting the requirements of HK Electric's LV network management strategy.

6. CONNECTIVITY DATA MIGRATION AND LIFECYCLE MANAGEMENT FOR LVMS

6.1 The Low Voltage Management System (LVMS)

The LVMS provides an accurate and up-to-date digital representation of the low voltage electricity network. During the initial migration, existing network connectivity data were exported from the NHGIS in standardised Common Information Model (CIM) format. Before being imported into LVMS, the connectivity data undergo a validation process to identify and resolve missing or incorrect network connections, ensuring a reliable initial network model for LVMS.

Following the initial data migration, HK Electric established a structured process for ongoing preparation, validation and maintenance of the network model. The process involves several integrated systems, including the LVMS Database Preparation Tool, the Information Model Management (IMM) module of the SCADA system, NHGIS, and the Engineering Systems Information Model Repository (ESIMR). Each system performs a specific role in keeping network information accurate, consistent and traceable throughout its lifecycle.

The LVMS Database Preparation Tool (LVMS DBUI) is a tool developed by HK Electric for preparation of

LVMS data, apparatus and connectivity. It can handle complete database job lifecycle for both planned and unplanned changes to the low voltage network, including new substations or customer supplies, cable installation or diversion, equipment replacement, temporary wiring arrangements and other network reconfigurations.

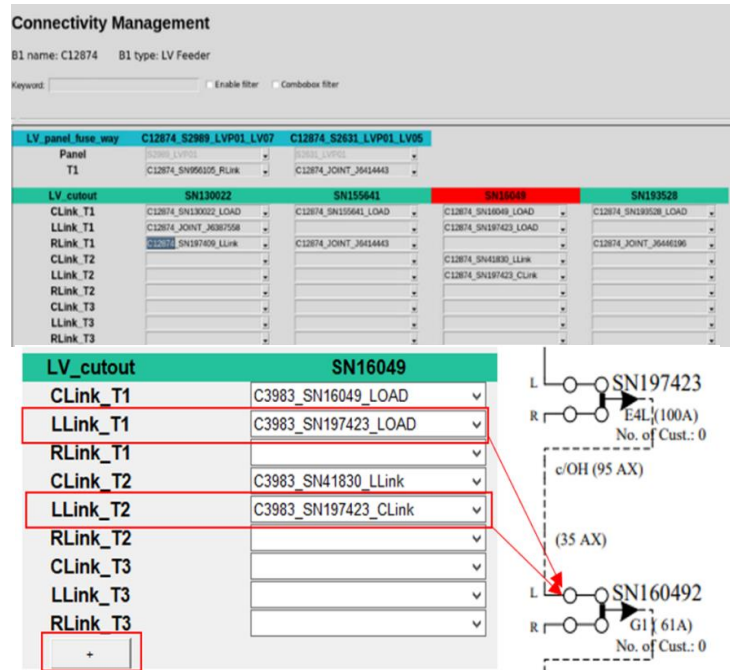


Fig. 5 - LVMS DBUI - Making Connections to Equipment via Selection Menu

Once the information has been prepared, the network changes are converted into CIM format and transferred to IMM of the LVMS SCADA system. Only data relating to the relevant changes are transferred, rather than the entire network database. This incremental approach reduces the volume of data to be processed and lowers the risk of unintentionally affecting other parts of the operational network model.

IMM provides the central engineering environment for managing network data and schematic diagrams in LVMS. Its Job Management function allows engineers to prepare, check, validate and approve network changes separately from the live operational system. During data import, the changes are checked against defined business rules and data-quality requirements. After a job has passed these checks, IMM generates the corresponding low voltage network schematic diagrams. The approved job is then ready for job-based activation in LVMS at the time when the planned and unplanned changes are implemented at site.



Fig. 6 - Typical Workflow of LVMS Data Updates

6.2 LVMS as the Master Source of LV Network Connectivity Information

Following the rollout of LVMS, it became the master source of low voltage network connectivity information. Whereas the geographical and asset information, including cable routes, cable lengths and other equipment attributes continues to be maintained in NHGIS.

To ensure close alignment of LV network information of LVMS and NHGIS, daily incremental change of NHGIS would be sent through its CIM Adapter to ESIMR, which compares the connectivity information in NHGIS with that in LVMS on a circuit-by-circuit basis. The geographical and asset information is transferred to LVMS only when the connectivity information in both systems is consistent. If a discrepancy is identified, the affected circuit is excluded from synchronisation until the issue has been investigated and corrected.

ESIMR generates a daily discrepancy report for follow-up by the responsible engineers. This controlled process manages update latency between NHGIS and LVMS and ensures that LVMS remains the single source of truth for low voltage network connectivity.

7. KEY FEATURES OF LVMS

LVMS provides centralized monitoring, analysis and operational support for the low voltage distribution network. The system delivers comprehensive network visibility through both schematic and geographic displays, enabling operators to visualise network topology, equipment status and operational conditions from different perspectives. The schematic feeder and substation display present detailed electrical connectivity, while the geographic display integrates network information with GIS data to provide spatial awareness of network assets and customer connections. The two display modes are fully linked, allowing seamless navigation between geographic and schematic views for efficient network analysis.

LVMS supports multiphase operation. Phase-operated devices such as LV fuse switches can be monitored and managed in either combined mode or on an individual phase basis, enabling operators to analyse phase loading, switching status and network imbalance. The system also provides real-time power flow visualization. Power flow indicators and cable loading percentages are displayed directly on network diagrams. This enables operators to quickly identify loading conditions, power transfer paths and flow directions throughout the network. This capability enhances operational situational awareness and supports contingency analysis and power restoration activities.

For fault management, LVMS incorporates LVFI alarm monitoring. When an LVFI operates, alarms are

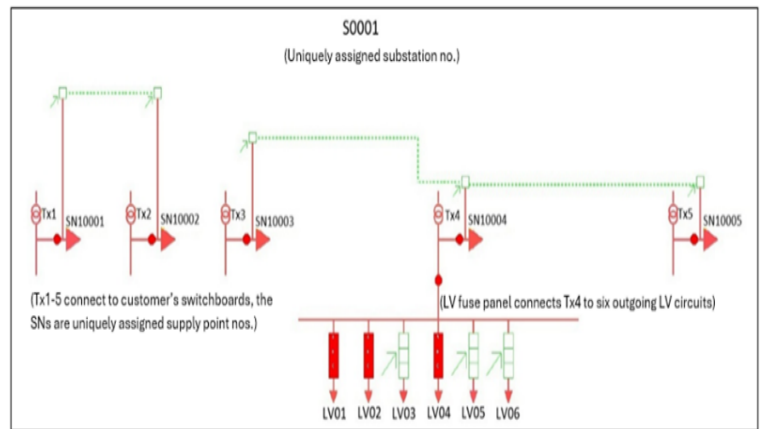


Fig. 7 - Schematic of a Distribution Substation of LVMS

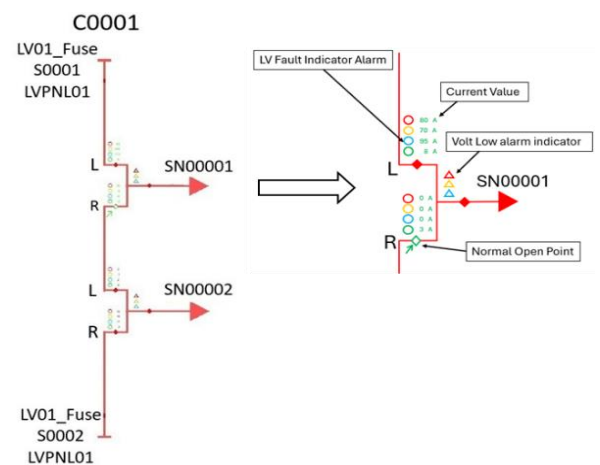


Fig. 8 - Schematic of an LV Cable Circuit with LVFI

presented through the alarm management interface and the affected cutout location is automatically highlighted on the corresponding feeder diagram, enabling rapid fault location and investigation.

A distinctive feature of LVMS is its support for Temporary Network Elements (TNE), which enables operators to model temporary network configurations during maintenance activities and emergency restoration. Temporary jumpers, cable cuts, grounding points and mobile generators can be inserted directly into the network model, with network topology, tracing and analytical functions automatically updated to reflect the temporary configuration.

To further support service restoration, IT/ES developed a Temporary Supply Source Analysis function to assist operators in identifying potential backfeed supply points. The analysis evaluates network connectivity, the proximity of potential supply points and available spare capacity to facilitate the assessment of temporary supply arrangements and the selection of suitable restoration options. This capability improves restoration planning efficiency and helps minimise customer outage duration.

8. CYBERSECURITY CONSIDERATIONS AND MEASURES

8.1 Securing IoT Communication Protocols and SCADA Integration

The cybersecurity architecture of the LVFI V2 solution follows HK Electric's defence-in-depth philosophy for OT systems. The design emphasizes minimization of attack surfaces, segregation of operational networks, strict device identity management, limited remote control capability, and comprehensive operational visibility for monitoring and forensic investigation.

The solution inherits security principles established in HK Electric's Distribution Management System (DMS) and Remote Terminal Unit (RTU) environments, where controlled communication architectures and limited external exposure have contributed to high operational reliability. As the distribution network evolves towards IP-enabled and IoT-connected assets, these principles remain applicable and are extended through secure device authentication, controlled communications, and centralized governance.

8.2 Device Identity and Authentication

Each LVFI is provisioned with a unique device identity and cryptographic credentials. Device authentication is based on OTAA, with individual security credentials assigned to every device. The use of shared credentials, vendor default keys, or key reuse is prohibited.

Security credentials are centrally managed under HK Electric governance rather than by installation contractors, ensuring consistent control throughout the device lifecycle. The communication stack enforces frame-counter integrity and supports re-authentication when session limits are reached, reducing the risk of replay attacks, device impersonation, and unauthorized network access.

This approach enables secure device onboarding, simplified device replacement, and efficient revocation of compromised devices without affecting the wider deployment.

8.3 Physical and Local Interface Security

Physical security controls are incorporated to protect the device from unauthorized access in field environments.

The enclosure is designed for outdoor deployment and incorporates protective features for critical interfaces. Maintenance and service access points are not exposed during normal operation and require authorized access procedures. Local controls used for testing, diagnostics, or maintenance are protected to prevent accidental operation or unauthorized manipulation.

These measures help ensure the integrity of field-installed devices located in publicly accessible or semi-accessible environments.

8.4 Firmware Security and Operational Monitoring

The device firmware is designed using a structured architecture that supports predictable operation, fault handling, and diagnostic traceability.

Operational logs are retained locally and can be retrieved through authorised maintenance procedures when troubleshooting or forensic investigation is required. Diagnostic information supports root-cause analysis following communication failures, abnormal operating conditions, or cybersecurity events.

Ownership of firmware source code, design documents, and technical documentation provides HK Electric with the ability to conduct independent security reviews, perform future hardening activities, and maintain long-term supportability without reliance on proprietary vendor controls.

Cybersecurity assurance is further strengthened through laboratory and field acceptance testing, including verification of communication reliability, acknowledgement handling, fault recovery behaviour, and operation under abnormal conditions.

At the backend, LVFI integrates with HK Electric's in-house LoRaWAN and LVMS, consistent with an operations model that favours segregation of critical telemetry from the public Internet and that preserves strong governance over provisioning, routing, and data handling. Within that model, incremental hardening steps are recommended without changing the bill of materials of the devices: scheduled session key rotation enforced via orchestrated rejoins at the LoRaWAN network server, according to device whitelisting and anomaly alerts on DevEUI/frame counter behaviour. This approach was adopted based on lessons learned from HK Electric's substation automation journey, where in-house communications and carefully controlled upgrade paths have supported high reliability while enabling modernization.

8.5 Governance, Compliance and Lifecycle Assurance

Governance and compliance close the loop. The product is designed to meet radio compliance that follows HKCA1078 and LoRaWAN v1.0.3 specifications, including duty cycle and spectral constraints. The acceptance plan bakes in accelerated life test for lifetime confidence, structured Lab Acceptance and Site Acceptance tests to verify energy harvesting, event capture, radio behaviour, and abnormal condition resilience, and documentation ownership so that all improvements and investigations remain under the purchaser's control. These governance elements are not

just paperwork; they are the mechanisms that keep a growing LV sensor fleet operationally safe, cyber defensible, and analytically trustworthy for LVMS throughout its lifecycle.

9. POTENTIAL OPPORTUNITIES FOR FURTHER INTEGRATION WITH OTHER SMART INITIATIVES

While LVFIs will be deployed progressively across the LV network, achieving substantial coverage takes time. In contrast, the deployment of approximately 600,000 smart meters has effectively equipped almost every customer supply point in HK Electric's LV network with supply monitoring capability.

To further enhance operational visibility, smart meter event data may be integrated with LVMS to provide a near real-time representation of supply conditions at individual LV supply points. By leveraging the established meter-to-location relationship, meter events such as power-up and power-down notifications can be mapped directly to the LV network model and visualised on both the LVMS geographic and schematic displays. This capability enables operators to quickly identify affected supply points, assess the extent of supply interruptions and gain valuable situational awareness during fault investigation, service restoration and other emergency response activities. By extending visibility to customer supply points at the edge of the network, smart meter data complement LVFI deployment and provide an additional layer of operational intelligence for LV network management.

10. CONCLUSION

The development of the LVCC and LVMS represents HK Electric's phased approach to improving operational visibility and management of the low voltage distribution network. By integrating LVFI telemetry, SmartLink @ HK Electric, NHGIS and other supporting systems, LVMS provides a centralised platform for monitoring network conditions, managing connectivity information and supporting fault investigation and supply restoration activities. The establishment of a structured data governance framework, commissioning process and connectivity lifecycle management workflow also helps ensure data consistency and system maintainability.

A key implementation decision was to develop LVMS on a SCADA platform rather than adopting a cloud-native architecture. This approach leveraged HK Electric's existing engineering expertise, operational processes and infrastructure developed through many years of EMS/DMS operation and support. Proven capabilities in network modelling, topology management, connectivity tracing and fault analysis were extended to the low voltage network, while maximising the use of standard SCADA functionality

and minimising system customisation. Given the scale of HK Electric's LV network and the requirement for close integration with operational technology systems, the SCADA-based approach provides an appropriate balance of operational performance, maintainability, cybersecurity and cost-effectiveness. As sensor deployment continues, LVMS will provide an increasingly comprehensive operational view of the low voltage network and support further digitalisation of low voltage system management.

Paper No. 3

**SF₆-FREE AND DIGITAL MEDIUM-VOLTAGE GAS-INSULATED
SWITCHGEAR FOR SUSTAINABLE POWER DISTRIBUTION**

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ABSTRACT

In the context of global decarbonization and sustainable development, medium-voltage gas-insulated switchgear is evolving towards the integration of SF₆-free technologies and digitalization, representing an important technical pathway for sustainable power distribution. With increasingly stringent international environmental regulations restricting the use of SF₆, SF₆-free medium-voltage gas-insulated switchgear based on Neutral Original Gas, Vacuum Interruption, and alternative gases with low global warming potential (GWP) is gradually maturing and moving towards large-scale application. Meanwhile, digital solutions integrating sensors, the Internet of Things (IoT), and data analytics enable condition monitoring, predictive maintenance, and lifecycle management, thereby improving operational reliability and reducing maintenance costs, system losses, and carbon emissions.

This paper reviews the domestic and international development of SF₆-free and digital medium-voltage gas-insulated switchgear, and examines the main technical approaches, application value, and future trends. It further discusses the key challenges associated with wider deployment, including the verification of insulation and interruption performance, the trade-off between economic viability and compactness, insufficient standardization and interoperability, and issues related to cybersecurity and data quality. The study shows that the integration of SF₆-free technologies and digitalization will be a major development direction for medium-voltage gas-insulated switchgear in enabling low-carbon, efficient, and sustainable power distribution systems.

1. INTRODUCTION

The global transition towards low-carbon energy systems and carbon neutrality is fundamentally reshaping modern power networks. Increasing penetration of renewable energy resources, widespread electrification of transportation, and the growing integration of distributed energy resources have accelerated the evolution of power systems from conventional centralized architectures to highly interconnected, intelligent, and sustainable ecosystems. As the critical interface connecting power generation, transmission, and end users, medium-voltage (MV) distribution networks play a pivotal role in ensuring the

reliability, flexibility, operational efficiency, and environmental sustainability of future power systems. MV Gas-Insulated Switchgear (GIS) has become one of the most important components of modern distribution networks due to its compact footprint, high reliability, superior operational safety, low maintenance requirements, and strong adaptability to harsh environmental conditions. Consequently, GIS has been extensively deployed in urban substations, industrial facilities, transportation infrastructures, commercial buildings, and data centres. Traditionally, the dielectric insulation medium used in MV GIS is sulphur hexafluoride (SF₆), a gas with excellent dielectric strength and arc-quenching capabilities. However, SF₆ is also recognized as one of the most potent greenhouse gases. According to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), SF₆ has a 100-year GWP (GWP100) approximately 23,500 times greater than that of carbon dioxide (CO₂), while its atmospheric lifetime exceeds 1,000 years, resulting in long-term environmental consequences once released into the atmosphere [6].

In response to increasing climate-related concerns, regulatory authorities worldwide have strengthened restrictions on the use of fluorinated greenhouse gases (F-gases). The European Union F-gas Regulation (EU) 2024/573 [5] establishes a progressive phase-down strategy for high-GWP fluorinated gases and introduces restrictions on their use in medium- and high-voltage switchgear applications. These regulatory developments are accelerating the transition of the power industry towards low-GWP and ultimately SF₆-free technologies. Consequently, the development of environmentally friendly MV GIS solutions has become a key technological priority for equipment manufacturers and utility operators worldwide.

At the same time, power distribution systems are undergoing a parallel digital transformation. Increasing electricity demand, large-scale renewable energy integration, rapid deployment of electric vehicles, and growing customer expectations for supply reliability are introducing unprecedented operational complexity to distribution networks.

Traditional maintenance approaches based on periodic inspections are gradually proving insufficient to address evolving asset management requirements. Emerging digital technologies, including the IoT, big data

analytics, Artificial Intelligence (AI), cloud computing, and edge computing, are enabling a transition from reactive and time-based maintenance strategies towards predictive and condition-based asset management. By continuously monitoring equipment status and analysing operational data in real time, intelligent GIS solutions can significantly improve asset visibility, fault diagnosis accuracy, maintenance efficiency, and network resilience [14][15].

Against this background, the convergence of SF₆-free insulation technologies and digital intelligence is emerging as a major development trend for next-generation MV distribution equipment. The integration of environmentally sustainable insulation systems with advanced sensing, monitoring, communication, and analytics capabilities not only addresses increasingly stringent environmental requirements, but also enhances operational reliability, asset utilisation, and lifecycle value. As a result, SF₆-free intelligent MV GIS is widely regarded as a key enabler for achieving sustainable and resilient power distribution networks.

This paper investigates the development of SF₆-free intelligent MV GIS technologies, examining their technological foundations, practical implementation approaches, and application prospects.

The paper further evaluates their contribution to sustainable power distribution, discusses key technical challenges and future development directions, and explores their implications for the evolution of next-generation smart distribution networks.

2. DEVELOPMENT REQUIREMENTS FOR SUSTAINABLE POWER DISTRIBUTION

The rapid integration of renewable generation, distributed energy resources (DERs), energy storage systems, and electric vehicles (EVs) is transforming conventional distribution networks into increasingly dynamic and complex infrastructures.

Consequently, future distribution systems must simultaneously address decarbonisation targets, maintain high levels of reliability, and ensure economically sustainable operation.

2.1 Environmental Sustainability Requirements

The global power sector is undergoing an accelerated decarbonisation transition. Driven by the objectives of the Paris Agreement and national carbon-neutrality roadmaps, utilities are under increasing pressure to reduce greenhouse-gas emissions associated with electrical infrastructure, including MV switchgear and distribution assets [6].

The environmental impact of SF₆ has become a major concern for governments, regulators, and utilities

worldwide. The IPCC Sixth Assessment Report (AR6) identifies SF₆ as one of the most potent greenhouse gases, with a GWP approximately 23,500 times higher than that of CO₂ and an atmospheric lifetime exceeding 1,000 years [6]. Responding to these concerns, Regulation (EU) 2024/573 on fluorinated greenhouse gases (F-Gas Regulation) has established a clear regulatory pathway towards the phased reduction and eventual replacement of SF₆ in medium- and high-voltage equipment where technically feasible alternatives are available [5].

Environmental sustainability evaluation has also evolved from focusing solely on operational emissions toward comprehensive Life Cycle Assessment (LCA) methodologies. For conventional SF₆-insulated equipment, environmental impacts extend beyond operational leakage and include gas recovery, recycling, transportation, storage, and end-of-life treatment. These activities introduce additional environmental burdens and compliance costs over the equipment lifecycle. In contrast, SF₆-free GIS technologies significantly reduce lifecycle greenhouse-gas emissions and contribute to lower overall environmental impacts [7].

At the same time, Environmental, Social and Governance (ESG) performance has become an increasingly important consideration for utilities, infrastructure owners, and investors. ESG-related performance indicators are now widely incorporated into corporate sustainability frameworks and investment assessments. Consequently, the adoption of SF₆-free technologies is no longer viewed solely as a regulatory compliance measure, but also as a demonstration of corporate commitment to sustainability and responsible asset management. As environmental regulations continue to tighten and decarbonisation targets become increasingly ambitious, SF₆-free MV GIS is evolving from a niche technological innovation into a strategic solution for future sustainable distribution networks.

2.2 Grid Resilience and Supply Reliability Requirements

Modern distribution networks face growing challenges in maintaining system reliability and resilience. The rapid deployment of distributed renewable generation, battery energy storage systems (BESS), and electric vehicle charging infrastructure is transforming traditionally radial distribution systems into highly interconnected networks characterised by bidirectional power flows and increased operational complexity.

The intermittent and variable nature of renewable energy sources introduces additional uncertainty into system operation and places greater stress on network assets.

As a result, future MV switchgear must provide enhanced fault-current interruption capability, improved insulation reliability, and advanced operational visibility to accommodate increasingly demanding operating conditions [16].

In parallel, the frequency and severity of extreme weather events, including heatwaves, severe rainfall, typhoons, flooding, and other climate-related disturbances, continue to increase globally. These developments require distribution assets to possess greater environmental adaptability, operational robustness, and fault tolerance. Consequently, grid resilience has become a central concept in modern power-system planning and operation, referring to the ability of a power system to withstand disturbances, maintain critical functionality, and recover rapidly following disruptive events [12].

MV GIS is increasingly evolving into a critical component of distribution automation systems. Through integration with online monitoring sensors, intelligent electronic devices (IEDs), and communication modules, next-generation intelligent GIS can continuously acquire asset condition data and exchange information with Supervisory Control and Data Acquisition (SCADA), Distribution Management Systems (DMS), and Advanced Distribution Management Systems (ADMS). Such capabilities support early fault detection, predictive diagnostics, rapid fault isolation, and service restoration, thereby reducing outage duration and improving network resilience [3].

The experience of Hong Kong provides a practical example of the importance of highly reliable distribution infrastructure. Publicly available information from CLP Power Hong Kong and HK Electric indicates that supply reliability has consistently exceeded 99.999% over many years [18][19]. According to publicly reported operational statistics, customer outage durations remain among the lowest globally. These achievements are closely associated with the extensive deployment of MV GIS technology, distribution automation systems, and intelligent monitoring platforms. The Hong Kong experience therefore offers valuable insight into the future development of SF₆-free intelligent GIS for highly reliable urban distribution networks [21].

2.3 Economic Sustainability Requirements

Sustainable distribution development is not only an environmental challenge but also an economic imperative. As utilities continue to expand digitalisation initiatives and operational expenditures become an increasingly significant portion of lifecycle asset costs, leading utilities worldwide are progressively adopting a Total Expenditure (TOTEX) approach to asset management. This framework evaluates capital expenditure (CAPEX), operational expenditure (OPEX), outage-related losses, and end-of-life costs within a unified lifecycle decision-making process [17].

MV GIS assets typically have operational lifespans exceeding 30 years. Over such extended service periods, cumulative operation and maintenance (O&M) costs often equal or exceed the initial procurement cost of the equipment.

Traditional time-based preventive maintenance strategies may result in either unnecessary maintenance interventions or insufficient detection of emerging asset deterioration between scheduled inspections.

The increasing availability of digital technologies is driving the transition toward Condition-Based Maintenance (CBM) and Predictive Maintenance (PdM). By continuously monitoring critical operating parameters and asset-health indicators, utilities can obtain accurate assessments of equipment condition and implement maintenance activities based on actual asset requirements. This maintenance-on-demand approach reduces unnecessary maintenance activities, improves resource utilisation, and enhances overall asset performance [13].

The economic benefits associated with improved reliability are particularly significant for high-value customers such as financial institutions, data centres, metro systems, airports, and semiconductor manufacturing facilities. For these customers, the economic consequences of unplanned outages may substantially exceed those experienced by conventional commercial consumers.

From a lifecycle perspective, the financial benefits achieved through improved reliability, reduced outage risk, and extended asset life frequently offset the additional initial investment associated with SF₆-free and intelligent GIS technologies.

Furthermore, as carbon-pricing mechanisms, emissions trading schemes, and green-finance frameworks continue to mature, environmental impacts are increasingly translated into direct economic costs. Future SF₆-based equipment may therefore face rising costs associated with emissions management, gas handling, regulatory compliance, and carbon liabilities.

In comparison, SF₆-free solutions are expected to deliver superior long-term asset value and lower lifecycle risk. Accordingly, from both TOTEX and lifecycle asset-value perspectives, the integration of SF₆-free technologies and intelligent digital capabilities represents a key pathway towards economically sustainable power distribution systems and supports the long-term transformation of future distribution networks.

In summary, the development of sustainable power distribution is driven not only by environmental objectives but also by multiple factors including grid resilience and economic sustainability. Its core objective is to achieve comprehensive optimization of environmental, social, and economic sustainability while ensuring grid resilience and highly reliable power supply.

Figure 1 showed the key drivers of sustainable distribution development.

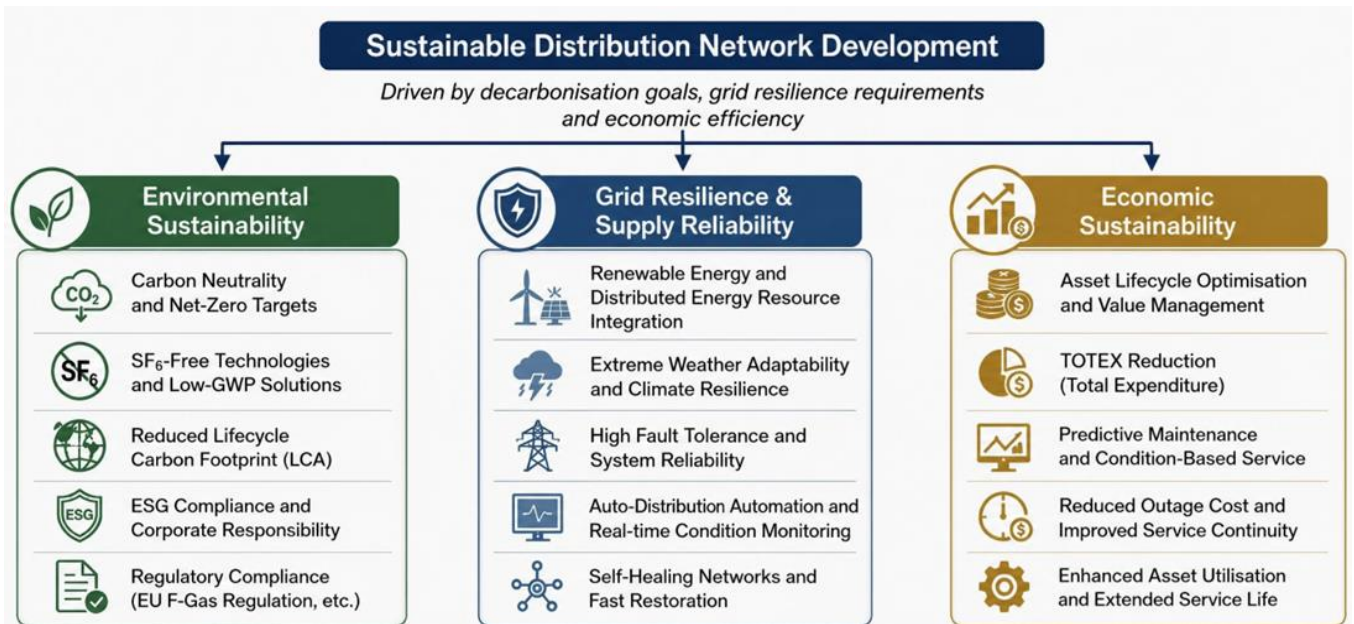


Fig. 1 - Key Drivers of Sustainable Distribution Development

3. TECHNOLOGY PATHWAYS FOR SF₆-FREE MV GIS

SF₆-free technology has become a core direction for the development of MV GIS. Especially after the official implementation of the new EU F-Gas Regulation, zero-GWP or ultra-low-GWP switchgear has become a significant development trend in the future MV distribution market [5].

From a technological development perspective, it is transitioning from the traditional “SF₆ insulation + vacuum interruption” architecture to an “eco-friendly insulating media + vacuum interruption” architecture. See Figure 2. The essence of this shift is the decoupling

of the arc-quenching function from the insulation function. Vacuum interruption technology handles the breaking task, while Natural Original Gas (NOG), eco-friendly gas mixtures, or solid insulation technologies provide the equipment’s insulation [7].

3.1 NOG Insulation Technology

NOG primarily consists of nitrogen and oxygen, the main components of atmospheric air. After purification, drying, and optimization of proportions, it is applied as an insulating medium in MV GIS. It features zero GWP, zero Ozone Depletion Potential (ODP), non-toxicity, and non-flammability, making it one of the most environmentally friendly insulating media available [8].

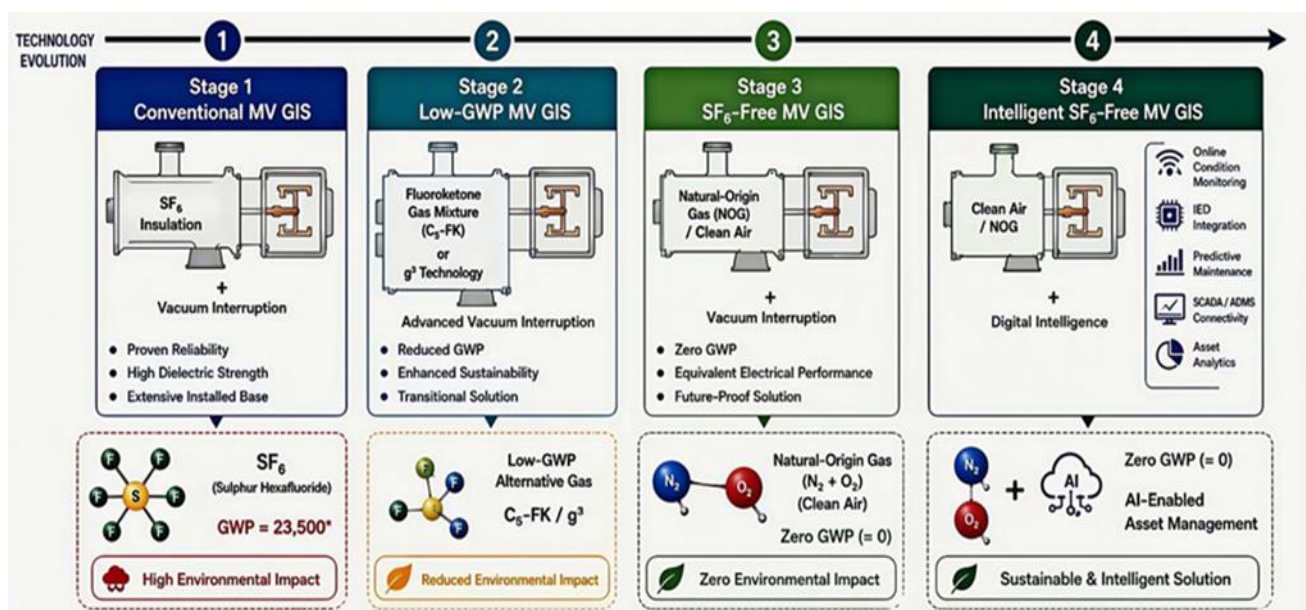


Fig. 2 - Technology Evolution Pathways of SF₆-free GIS

Due to its dielectric strength being approximately 30% to 40% that of SF₆, NOG GIS requires a series of optimized design measures to enhance its insulation performance. These measures include structural and electric field optimization, increasing insulation distances, improving the performance of solid insulating materials, and refining insulation support structures to prevent localized electric field concentrations that could lead to insulation breakdown.

The primary advantage of NOG technology lies in achieving truly zero greenhouse gas insulation, with no environmental impact, no need for gas recovery or treatment, no regulatory risks, wide availability, low cost, and safe, non-toxic, non-flammable usage. Currently, 12kV, 24 kV, and 40.5 kV NOG GIS have achieved technical levels comparable to traditional SF₆ GIS and are commercially mature [8][9][10][11]. This technology pathway is widely regarded as the mainstream direction for future MV SF₆-free equipment.

3.2 Vacuum Interruption Technology

Vacuum interruption technology is one of the most mature and widely applied arc-quenching solutions in the MV switchgear domain. The internal pressure of a vacuum interrupter is typically maintained within the range of 10⁻⁴ ~10⁻⁶ Pa. Interruption is achieved by utilizing the principle of natural arc extinction at current zero crossings in an AC circuit [1].

Modern vacuum circuit breakers have achieved mechanical lifetimes exceeding 10,000 operations and excellent short-circuit breaking capabilities, meeting the demands of contemporary power distribution systems [1].

Current SF₆-free GIS universally adopts a design model combining vacuum interruption with eco-friendly insulating media. This approach decouples the interruption function from the insulation function, optimizing design flexibility, enhancing system reliability, and reducing environmental risks. Consequently, vacuum interruption technology has become a fundamental platform technology for future SF₆-free GIS.

3.3 Other Eco-Friendly Alternative Gas Technologies

While NOG offers optimal environmental performance, for certain high-voltage levels or space-constrained applications, relying solely on air insulation may not meet miniaturization requirements.

To balance environmental friendliness with equipment compactness, the industry has developed various other eco-friendly alternative gases as transitional solutions [7]:

- (a) g³ (Fluoronitrile Gas Mixture): reduces 95% of GWP compared to SF₆ and maintains high dielectric

strength, though at a relatively higher cost. It has found practical application in some European transmission and distribution projects [10].

- (b) Fluoroketone Gas Mixture (C5-FK): This is another novel insulating medium with an extremely low GWP (approaching 1), offering minimal environmental impact. However, it faces challenges such as limited low-temperature adaptability, stringent material compatibility verification requirements, and relatively high costs, which hinder its large-scale adoption.

3.4 Techno-Economic Comparison

From an engineering application perspective, equipment selection considers not only environmental performance but also life cycle economics. Table 1 compares key indicators of different GIS technology pathways.

Parameter	SF ₆ GIS	NOG GIS	g ³ GIS	C5-FK GIS
GWP	23,500	0	<500	<1
Dielectric Performance	Excellent	Good	Excellent	Excellent
Interruption Performance	Excellent	Excellent	Excellent	Excellent
Equipment Size	Most Compact	10-20% Larger	Comparable to SF ₆	Comparable to SF ₆
Operational Complexity	Medium	Low	Medium	Medium
Gas Recovery Requirement	Yes	No	Yes	Yes
IEC Technology Maturity	Very High	High	Medium	Medium
Regulatory Risk	High	Very Low	Low	Very Low
Initial Investment	Reference	+5% to +15%	+10% to +20%	+10% to +25%
Lifecycle Cost	Medium	Lowest	Medium-Low	Medium-Low

Table 1 - Comparison of Different GIS Technology Pathways

While the procurement cost of SF₆-free GIS is slightly higher (+5%~25%), its advantages lie in eliminating SF₆ recovery management costs, reducing leakage detection costs, avoiding future regulatory modification costs, and mitigating carbon emission risk costs. From a full life cycle perspective, its Total Cost of Ownership (TCO) is often optimal. NOG and vacuum interruption technologies are widely considered to be among the ultimate development directions for MV GIS.

3.5 Key Technical Challenges and Future Directions for SF₆-Free GIS

SF₆-free GIS still requires continuous optimization. Research priorities include synergistic insulation design (optimization of solid-gas interfaces, multi-physics field coupling, electric field grading structures, and development of nano-composite insulating materials), equipment miniaturization (nano-insulation, functionally graded insulation, and 3D electric field optimization), digitalization integration (SF₆-free technology + smart sensors + edge computing + digital

twin + AI), and decarbonization development (zero-GWP media, recyclable materials, and low-carbon manufacturing processes).

The development of SF₆-free GIS represents a systemic technological innovation centered on environmental protection, high reliability, and digital integration.

4. DIGITALIZATION AND ASSET MANAGEMENT FOR SUSTAINABLE DISTRIBUTION

As distribution networks evolve towards high penetration of new energy sources, power electronic devices, and high automation, traditional equipment management models relying on periodic inspections and experience-based judgments are increasingly insufficient to meet the reliability, resilience, and economic demands of modern grids. MV GIS, as one of the most critical primary devices in the distribution system, has its operational status directly impacting the continuity of supply and system security.

The new generation of intelligent GIS, through the integrated application of sensor technology, communication technology, cloud computing, big data analytics, AI, and digital twin technologies, achieves end-to-end digital management from equipment condition sensing to autonomous decision-making. Digitalization not only enhances equipment operational reliability but also reduces unnecessary maintenance activities and premature equipment replacement, playing a significant role in achieving a unified environmental, economic, and social benefit for the power distribution system. The application of digital technologies in GIS can be broadly categorized into three levels: Condition Awareness, Predictive Maintenance, and Lifecycle Asset Management, ultimately driving AI and digital twin-enabled autonomous O&M.

4.1 Enhanced Condition Awareness

Traditional MV GIS O&M primarily relies on manual periodic inspections and offline testing. Due to

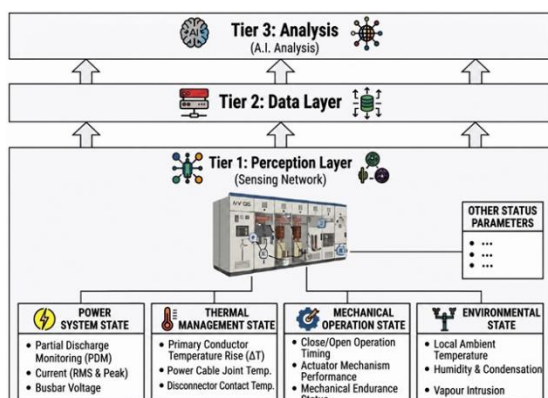


Fig. 3 - Smart MV GIS Condition Awareness and Assessment Architecture

inspection cycles typically spanning months or even years, changes in equipment condition are difficult to detect in a timely manner. With the advancement of IoT technology, new-generation intelligent GIS integrates a large number of online sensors. O&M personnel can continuously monitor equipment operating status, promptly detect abnormal trends, thereby transitioning from offline inspections to real-time online monitoring.

The intelligent GIS condition awareness and assessment architecture is illustrated in Figure 3. This architecture enables real-time transparency of equipment operating status, laying a solid foundation for predictive maintenance and intelligent decision-making.

4.2 Predictive Maintenance

Traditional asset management models for GIS include Run-to-Failure (RTF) and Preventive Maintenance (PM). While RTF involves low initial CAPEX, it frequently leads to unplanned outages and significant economic losses. PM currently the prevailing model in power systems, typically involves scheduled maintenance plans executed at fixed time intervals, such as routine condition checks every two years or major overhauls every six to eight years (Time-Based Maintenance, TBM) [2].

However, operational experience reveals significant heterogeneity in the aging and degradation rates of different switchgear due to varying load levels, installation practices, and operating environments. Rigid periodic inspections can lead to “over-maintenance” and wasteful resource allocation.

Concurrently, some equipment undergoing accelerated degradation may experience critical failures between two scheduled inspections. To address these limitations, PdM has emerged. Its core philosophy is to abandon rigid time cycles and instead, based on multi-dimensional condition sensing data, continuously assess the equipment’s degradation trajectory to determine the optimal maintenance timing (Maintenance-on-Demand). PdM aims to optimize OPEX, reduce outage durations, and extend the physical lifespan of assets, all while

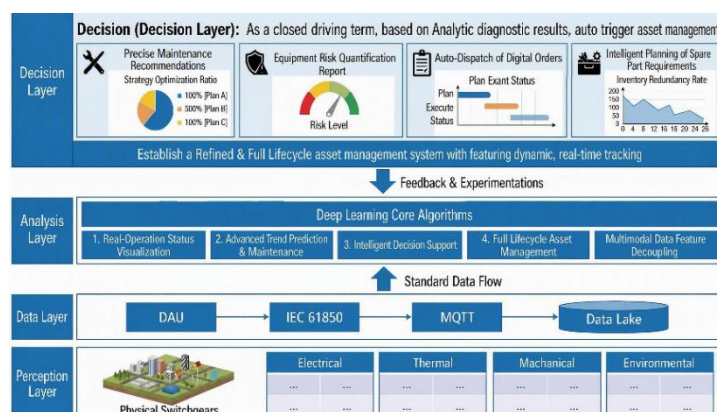


Fig. 4 - Four-Layer IoT Architecture for Smart GIS Condition Awareness and PdM

ensuring high reliability throughout the system's life cycle.

This approach has become a significant evolutionary direction for advanced power grid companies worldwide [13][16].

To quantify the health status of GIS equipment, international power grid companies commonly employ a Health Index (HI) model:

$$HI = \sum W_i S_i$$

where:

W_i - represents the weighting factor;

S_i - represents the condition score.

Below is the one example of GIS HI classification, including the metric type and weighting value in Table 2.

Metrics	Weighting
Partial Discharge (PD Spectra)	30%
Thermal Rise	25%
Mechanical Condition	20%
Electrical Stress	15%
Environmental Condition	10%

Table 2 - Example of GIS Health Index Classification

By continuously calculating and tracking HI, operators can dynamically ascertain equipment condition and degradation trajectories. See Table 3. This data-driven approach supports the timely implementation of recommended actions, thereby preventing equipment failures, minimizing service interruptions, and averting significant financial repercussions.

HI Value	Asset Condition	Recommended Action
≥ 90	Excellent	Routine Monitoring
80-89	Good	Increased Surveillance
60-79	Fair	Maintenance Planning
< 60	Poor	Immediate Intervention

Table 3 - Example of GIS Condition Classification & Recommended Action

By monitoring the trend of dynamic HI changes and integrating AI algorithms, fault trend analysis or Remaining Useful Life (RUL) prediction can be achieved. This enables O&M departments to accurately grasp equipment aging status, thereby reducing maintenance costs and enhancing equipment reliability.

4.3 Lifecycle Asset Management

With the accelerated integration of advanced digital technologies, the management paradigm for modern

power distribution equipment is undergoing a profound transformation, shifting from traditional "equipment-level physical maintenance" to a higher-level "asset-level value operation" strategic approach. The core objective of digital asset management is no longer limited to passive fault response or singular equipment state repair. Instead, it aims to leverage digital platforms to span all stages of an asset's life cycle - from planning and design, procurement and manufacturing supervision, installation and commissioning, to operation, maintenance, and eventual decommissioning - thereby maximizing value throughout the system's entire life cycle (Lifecycle Value Maximisation) [14][17].

Digital twin technology has become a core enabling technology for sophisticated management of modern intelligent power distribution assets. Its central concept involves constructing a digital model in a virtual space that is perfectly mapped, synchronously evolving, and interactively linked with a physical entity based on IoT sensing data. This establishes a Cyber-Physical Closed-Loop Control system comprising "physical asset - digital twin - intelligent decision-making - physical reverse control" [14].

A digital twin integrates geometric models (reflecting equipment characteristics), physical models (electric field, thermal field, mechanical models), data models (receiving real-time operational data), and behavioural models (simulating equipment operational trends based on historical O&M data). Through the combined intelligent decoupling of these multi-dimensional models, the digital twin system can provide 24/7 online holographic mirroring and behavioural insights into physical GIS entities, serving as a high-confidence digital foundation for advanced asset decisions.

Enabled by a highly interconnected cloud-native digital twin platform, utility asset management is transitioning from localized O&M optimization to enterprise-wide lifecycle value optimization, through the integration of real-time asset intelligence, predictive maintenance and risk-informed decision-making support.

This transformation can be characterised in the following four strategic dimensions:

- Optimized Risk Management:** Through multi-scenario behavioural simulations of digital twins, high-risk assets in accelerated aging stages can be identified proactively. This shifts from "passive troubleshooting" to "proactive prevention", significantly curbing potential operational risks (e.g., temperature rise, insulation, mechanical failures).
- Optimized Investment Decision-Making:** Based on long-term evolution predictions of RUL and HI, the optimal timing for equipment retrofitting or replacement can be scientifically determined, avoiding investment risks caused by premature

decommissioning or extended service beyond optimal life.

- (c) **Precise Allocation of O&M Resources:** According to the quantitative assessment results from digital twins, limited expert teams and maintenance tools can be precisely deployed to the most critical circuit breaker units, significantly enhancing the efficiency of on-site maintenance.
- (d) **Optimized Spare Parts Supply Chain Management:** Utilizing trend prediction models, the probability of component consumption within specific future windows can be accurately targeted, enabling adaptive dynamic inventory planning. This significantly optimizes inventory holding costs while ensuring the grid's emergency repair needs are met.

In summary, through the comprehensive empowerment of digital twin platforms, the new generation of intelligent power distribution systems will not only significantly extend the physical service life of core equipment like GIS and substantially enhance the overall utilization rate of grid assets, but also achieve the optimization of TOTEX, encompassing initial CAPEX and long-term OPEX. Ultimately, this dramatically reduces overall corporate operating costs while synergistically improving the overall supply reliability of urban distribution networks.

4.4 AI-assisted Autonomous Maintenance Enabled by Digital Twins

The future paradigm for intelligent GIS is expected to undergo a significant transformation, evolving from

Evaluation Dimension	Conventional / Predictive Maintenance	AI-Assisted Autonomous Maintenance Enabled by Digital Twins	Core Enabling Technologies
Decision-Making Entity	Highly dependent on human expertise and engineering experience. Asset condition data are manually analysed by operators, who subsequently issue maintenance instructions and work orders.	Semi-autonomous decision-making supported by AI analytics, with final validation performed by authorised operators. Real-time recommendations are generated from continuously updated asset digital models.	Large Language Models (LLMs) and Industrial AI Agents.
Data Processing and Analytics	Primarily relies on isolated monitoring signals and threshold-based alarms. Diagnostic accuracy is often limited, and false alarms may occur due to external interference or incomplete information.	Utilises multi-modal data fusion from partial discharge, infrared thermography, vibration, operational records, and environmental monitoring to achieve comprehensive condition assessment and intelligent fault diagnosis.	Advanced deep-learning algorithms including Convolutional Neural Networks (CNN), Graph Neural Networks (GNN), and Transformer architectures.
Process Efficiency and Innovation	Involves multiple manual procedures, including field investigation, maintenance planning, approval workflows, and work execution, resulting in relatively long maintenance cycles.	Provides automated asset health assessment, AI-driven diagnostics, and real-time maintenance recommendations. Human involvement is primarily limited to rapid validation and supervisory approval.	Intelligent work-order generation systems and adaptive spare-parts and maintenance resource planning platforms.
Integration with Power System Digitalisation	Operates largely as an independent physical asset management system with limited interaction and data exchange with wider network operation platforms.	Deeply integrated with modern distribution networks, enabling coordinated operation with network reconfiguration, distributed energy resources, and active grid response strategies.	Interconnected Distribution Automation (DA), Advanced Distribution Management Systems (ADMS), and cloud-based Digital Twin platforms.
Grid Network Resilience and Service Restoration	During extreme weather events or major equipment failures, fault identification and restoration activities rely heavily on field crews, resulting in relatively slow service recovery.	Enables automated fault detection, fault isolation, and rapid service restoration through intelligent analytics and self-healing network functions, significantly improving network resilience.	Closed-loop control algorithms, adaptive network reconfiguration technologies, and self-healing grid capabilities, AI-based Fault Management Systems

Table 4 - Comparison of Technical and Process Core Indicators for Traditional PdM vs. AI-Assisted Autonomous O&M of MV GIS

traditional predictive maintenance to highly automated maintenance. As an advanced stage of digital development for power assets, autonomous O&M aims to endow systems with comprehensive independent decision-making capabilities, effectively functioning as an “AI-assisted Decision Support System” or “Digital Engineer”, thereby achieving closed-loop asset management. Table 4 summarizes and compares the differences in technical indicators and workflows between traditional O&M frameworks and the proposed autonomous O&M model.

4.4.1 AI-driven fault diagnosis

To achieve the high-precision fault identification and accurate root cause localization described in Table 3, future GIS technical architectures must deeply integrate advanced deep learning models, including Convolutional Neural Networks (CNNs), Graph Neural Networks (GNNs), and Transformer-based architectural models. These algorithmic frameworks are capable of automatically processing and analysing complex heterogeneous multi-modal datasets, such as Partial PD phase-resolved partial discharge patterns, infrared thermal images, mechanical vibration signals, and transient operational waveform data. By precisely capturing the inherent spatial topological relationships and time-series dependencies within sensor data, this AI-driven system can achieve automatic classification of incipient latent faults and deep Root Cause Analysis (RCA), thereby completely eliminating subjective judgment errors and response delays associated with traditional manual diagnostics.

4.4.2 AI agent for O&M assistance

Building upon automated intelligent diagnostics, industrial AI Agents will redefine standard O&M workflows by executing a continuous and fully automated life cycle management chain. This technological chain encompasses comprehensive equipment condition analysis, real-time risk assessment, optimal maintenance strategy recommendations, fully automated work order generation, and adaptive spare parts planning. As indicated by the efficiency dimension comparison in Table 4, the traditional O&M process, heavily reliant on manual expert analysis and multi-level approval hierarchies, will be fundamentally replaced by this agile, AI-driven new paradigm. Within this new framework, the system can autonomously perform big data analysis and output optimal operational decisions, requiring only a quick “one-click” human confirmation from on-site managers to complete the loop, thereby significantly enhancing overall O&M efficiency and minimizing equipment outage time.

4.4.3 Intelligent GIS for self-healing grids

In the context of modern urban power infrastructure development, future MV GIS will no longer exist as isolated physical devices. Instead, they will function as

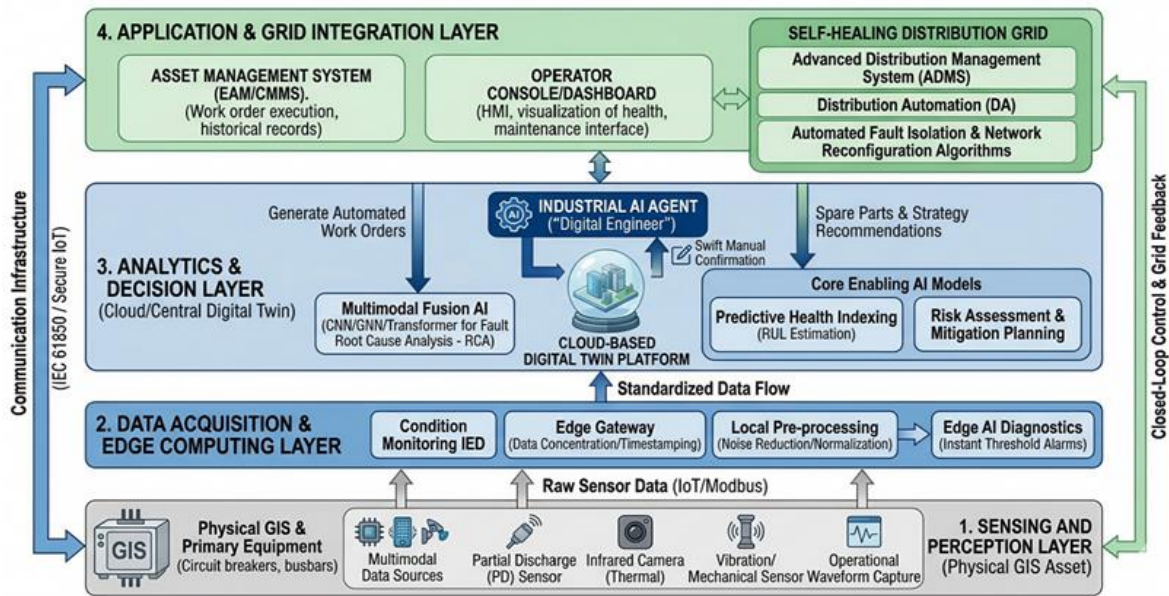


Fig. 5 - Multi-layered Hierarchical Architecture for AI and Digital Twin Driven Autonomous O&M of MV GIS, illustrating Data Flow and Control Logic from Physical Sensing to Grid-Level Self-Healing

core Cyber-Physical Nodes, deeply embedded within self-healing distribution networks. Figure 5 illustrates a multi-layered hierarchical architecture for AI and digital twin-driven autonomous O&M of MV GIS. Intelligent GIS interacts deeply with distribution automation (DA) systems, ADMS, and cloud-based digital twin platforms, achieving seamless bidirectional data exchange and control coupling [13][15].

Leveraging the collaborative intelligence of AI Agents within this network topology, this integrated system can achieve second-level automatic fault identification, automatic isolation of fault zones, and automatic restoration of non-fault zones through adaptive network reconfiguration. Consequently, this closed-loop autonomous control significantly mitigates the impact of sudden fault events and extreme weather disturbances on the wider power grid, directly empowering and enhancing the overall Grid Resilience of urban distribution networks.

In summary, digital technologies are driving the transformation of GIS from traditional primary equipment to intelligent asset platforms. Through the continuous development of condition awareness, PdM, digital twins, and autonomous O&M, the new generation of intelligent GIS will become a crucial foundation for future sustainable power distribution systems, forming, in conjunction with SF₆-free technologies, the core support for green, highly reliable, and efficient power distribution networks.

5. LESSONS FROM HONG KONG'S POWER DISTRIBUTION SYSTEM DEVELOPMENT

Hong Kong, as one of the cities with the highest supply reliability globally, offers valuable insights for future

urban power grid development. The Hong Kong power grid is characterized by high load density, limited land resources, and extremely high demands for supply continuity (consistently maintained above 99.999%) [18][19]. These characteristics ensure that GIS equipment will continue to be a vital component of Hong Kong's power distribution system for a considerable period. Concurrently, with the Hong Kong Special Administrative Region (HKSAR) "Hong Kong Climate Action Plan 2050" [20] and the increasing demand for green finance, ESG evaluation, and sustainable infrastructure construction, Hong Kong power distribution network is progressively moving towards decarbonization and digitalization. MV SF₆-free intelligent GIS holds immense potential and broad application prospects in new underground substations, data centre power supply systems, airport and rail transit distribution systems, new development areas and smart city projects, and zero-carbon building and green park projects. It can effectively reduce the life cycle greenhouse gas emissions of power distribution equipment, while digital monitoring and predictive maintenance technologies can further enhance system reliability and asset utilization efficiency.

Practical experience demonstrates that greening and intelligence are not independent objectives but rather two core pillars driving the construction of Hong Kong's future sustainable power distribution network [21]. The development practices of the Hong Kong power grid underscore the importance of building highly reliable distribution networks. Public data from CLP Power Hong Kong and HK Electric indicates that their supply reliability rate consistently exceeds 99.999%. CLP data shows that the average unplanned outage time for customers between 2022 and 2024 was approximately 6 minutes per year, reducing to about 1 minute after excluding major external events [18]. This exceptionally

high level of reliability is closely linked to Hong Kong's long-term adoption of GIS equipment, advancement in distribution automation, and intelligent monitoring system construction, providing valuable reference for the development of future SF₆-free intelligent GIS.

6. CONCLUSION

This paper has examined the future development requirements of power distribution systems from three key perspectives: environmental sustainability, grid resilience, and lifecycle economic performance. Furthermore, the technological evolution of SF₆-free MV GIS and the increasing role of digital technologies in sustainable distribution systems have been reviewed systematically.

The analysis demonstrates that the combination of air-derived insulation media and vacuum interruption technology has emerged as one of the most technically viable and environmentally sustainable pathways for the replacement of conventional SF₆-insulated switchgear. The rapid advancement of SF₆-free technologies is enabling the power industry to address increasingly stringent environmental regulations while maintaining the high levels of reliability and operational performance required by modern distribution networks.

Digitalisation is playing an equally important role in the transformation of power distribution infrastructure. Through real-time condition monitoring, asset-health assessment, predictive maintenance, and digital-twin applications, intelligent GIS solutions can significantly improve equipment reliability, optimise maintenance strategies, and maximise asset utilisation over the equipment lifecycle.

Looking ahead, continued developments in AI, edge computing, and digital-twin technologies are expected to accelerate the evolution of GIS from conventional primary equipment into intelligent asset platforms capable of advanced condition awareness, prognostic analysis, and decision support. Such capabilities will form an essential foundation for future autonomous and self-optimising distribution networks.

For high-density urban power systems such as Hong Kong, the convergence of SF₆-free technologies and digital intelligence offers substantial opportunities to simultaneously support carbon-neutrality objectives, enhance network resilience, improve supply reliability, and increase asset-management efficiency.

As a result, SF₆-free intelligent GIS is expected to become a key enabling technology for the development of next-generation sustainable distribution networks and smart energy infrastructure.

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Paper No. 4

**AC 400V INTERCONNECTED DISTRIBUTION NETWORK WITH
“ZERO POWER OUTAGE” COORDINATED BY REGIONAL AUTONOMY
AND “SOURCE-GRID-LOAD-STORAGE-CHARGING-DISCHARGING”**

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ABSTRACT

This paper introduces a new low-voltage AC interconnected distribution network technology proposed by GDEPRI Power Control Systems & Equipment (HK) Limited. This technology is centred around low-voltage precision loop control, deploying AC 400V loop closing control boxes, low-voltage self-healing branch boxes, load transfer control boxes, flexible and orderly electric vehicle (EV) charging piles, V2G devices, distributed photovoltaic and grid-forming energy storage devices, and constructing a low-voltage AC interconnection architecture and multi-source data fusion control system for the power supply area of two 10kV transformers. The system integrates photovoltaic and energy storage systems into the grid, adopting a strategy of “closing the loop first and then switching” to achieve “zero power outage” load migration. Through on-site peer-to-peer communication, faults are quickly isolated and supply restored. Combined with the operational capacity of the energy storage network, an important load full scenario supply guarantee mode is formed. Through the flexible and orderly EV charging and discharging control strategy of charging piles, the system achieves source load interaction, regional autonomy, and “source-grid-load-storage-charging-discharging” coordination.

The demonstration application of the system in Guangdong and Xinjiang of China has shown that this technology can effectively improve the level of photovoltaic (PV) consumption, alleviate transformer overload problems, ensure power supply reliability, shorten operation and maintenance time, and significantly enhance the resilience and autonomous regulation capabilities of the distribution network. It will be widely promoted in other regions of China. This study provides valuable insights for low-voltage distribution networks to address the challenges posed by new power loads, and holds significant theoretical and engineering value in promoting the construction of a robust distribution network.

1. INTRODUCTION

In recent years, with the advancement of China’s “dual carbon” goals, the penetration rate of new types of sources and loads, represented by distributed PV and electric vehicle charging facilities, in low-voltage distribution networks has been continuously increasing. By end 2024, the cumulative installed capacity of

distributed photovoltaics in China had exceeded 250 GW, the number of electric vehicles on the road had surpassed 20 million, and the number of charging piles had reached over 8 million. This trend of high-proportion integration of both new sources and loads has posed unprecedented challenges to the operation of traditional single-source radial low-voltage distribution networks. On the source side, the output of distributed photovoltaics exhibits significant randomness, intermittency, and anti-peak shaving characteristics. During periods of ample sunlight at noon, it may lead to local voltage violations and reverse heavy overloads of distribution transformers, while during evening peak load hours, it may cause power supply shortfalls. On the load side, the uncoordinated charging behaviour of electric vehicles often coincides with residential electricity peak demand, leading to frequent issues such as short-term overloads of distribution transformers, line congestion, heavy loading and overheating of lines, and power quality degradation. Furthermore, the integration of numerous power electronic devices has altered the fault characteristics of distribution networks, making traditional protection configurations inadequate for the demands of bidirectional power flow.

Faced with these challenges, traditional approaches to distribution network renovation - such as upgrading transformer capacity or constructing new lines - are confronted with practical difficulties including high investment, long lead times, and complex coordination. How to enhance the regulation capability and operational efficiency of existing distribution networks through digital and intelligent means, without large-scale hardware modifications, has become a critical issue urgently needing resolution in the power industry. Extensive research has been conducted by scholars worldwide on the intelligent upgrade of distribution networks. In terms of loop closing operation, Wu *et al.* explored the feasibility of loop closing operation in 10kV distribution systems, analysed the impact of loop closing current on relay protection and feeder load, and proposed a calculation method for loop closing current [1]. Peng *et al.* further proposed an online loop closing current calculation method for complex distribution networks considering source and load uncertainties, providing theoretical support for precise control of loop closing operations [2]. Li *et al.* proposed a risk assessment method based on fuzzy comprehensive evaluation for loop closing operations in low-voltage distribution networks, evaluating the risk level of loop closing operations from multiple dimensions such as

voltage difference, phase angle difference, and load rate [3]. However, the aforementioned studies mainly focus on the calculation and risk assessment of loop closing current, with relatively little research on how to suppress loop closing inrush current through active control means and achieve “zero power outage” load transfer during the loop closing process.

In terms of source-grid-load-storage coordinated control, Zhu *et al.* studied coordinated control strategies for source-grid-load-storage in distribution networks considering demand response, achieving peak shaving and valley filling through optimal scheduling [4]. Lei *et al.* proposed optimal scheduling strategies for source-grid-load-storage in rural low-voltage distribution networks, verifying the economic efficiency of coordinated control [5]. Wang *et al.* proposed a voltage hierarchical control strategy for distribution networks based on regional autonomy and photovoltaic-storage coordination, achieving voltage regulation through collaboration of devices within the region [6]. Li *et al.* analysed the impact characteristics of source-grid-load-storage interaction on power quality in active distribution networks, providing a theoretical basis for the design of coordinated control strategies [7]. Yang *et al.* considered electric vehicle charging preferences and proposed an adaptive model predictive scheduling method for flexible interconnected low-voltage distribution networks [8]. These studies provide important references for source-grid-load-storage coordination, but most focus on optimization at the scheduling level, with insufficient consideration for local real-time control, and rarely cover the coordinated control between new adjustable resources such as charging piles and V2G with energy storage.

In terms of low-voltage distribution network interconnection and coordinated operation, Zhang *et al.* proposed a coordinated operation optimization method for medium- and low-voltage distribution networks considering flexible interconnected distribution substation areas, improving distribution network operational efficiency through power mutual aid between substation areas [9]. Wang *et al.* proposed integrated planning methods for source-grid-load-storage in regional power grids considering large-scale renewable energy integration [10]. These studies provide planning and optimization methods for the interconnected operation of low-voltage AC distribution networks, but still lack systematic research on key technologies such as fault self-healing and grid-forming energy storage support under the interconnection architecture.

In response to the shortcomings of existing research, GDEPRI Power Control Systems & Equipment (HK) Limited has developed a novel AC 400V interconnected distribution network technology. This paper provides a systematic exposition of this technology, with its main innovations including: proposing a low-voltage precision loop closing control method of “make before

break”, which suppresses loop closing inrush current through rapid power regulation by loop closing inductor or energy storage, achieving zero-outage perception during load transfer; constructing a fault self-healing system based on local peer-to-peer communication, compressing the time for fault clearing and isolation to 200 ms, while the power supply restoration time for non-fault zones is 3 - 8s; designing a comprehensive element coordination control strategy covering photovoltaics, energy storage, charging piles, and V2G, forming an integrated operation mode of source-grid-load-storage-charging-discharging; through the deep integration of grid-forming energy storage and self-healing control, building a full-scenario power supply guarantee capability for critical loads, significantly enhancing distribution network resilience.

2. SYSTEM ARCHITECTURE

This system bases on two 10kV distribution transformers and their respective AC 400V low-voltage power supply areas as fundamental units. These independent power supply areas are interconnected via AC tie lines, forming a “hand-in-hand” ring network structure. Figure 1 illustrates the typical topology of the system. The core equipment of the system is deployed as follows: 400V loop closing control boxes are installed at the tie points of the two transformers’ low-voltage busbars. These boxes incorporate motor-operated moulded case circuit breakers, synchronous closing controllers, and current/voltage transformers, and are responsible for executing precision loop closing operations and circulating current suppression. Low-voltage self-healing branch boxes are distributed at the ends of feeders and key branch points based on load distribution conditions. They possess functions for fault detection, location, isolation, and supply restoration, and support peer-to-peer communication at the local level. Measurement and control devices along with load transfer control boxes are deployed at the low-voltage incoming main switch, enabling automatic load transfer under transformer heavy overload or maintenance conditions. Flexible and orderly EV charging piles are intelligent charging facilities with continuously adjustable power and V2G functionality, supporting real-time interaction with the regional controller for grid regulation. V2G devices facilitate bidirectional energy exchange between electric vehicles and the grid, capable of both charging and discharging, thereby providing flexible regulation capacity to the grid. Distributed photovoltaic inverters are smart inverters with grid-forming capabilities, supporting active voltage and frequency support. Grid-forming energy storage converters possess autonomous voltage establishment capability and black-start functionality, enabling them to support local grid operation in islanded modes.

The control system adopts a “Cloud-Edge-Terminal” three-tier collaborative architecture. The cloud platform is deployed at the master station side and is responsible for global optimization scheduling, historical data

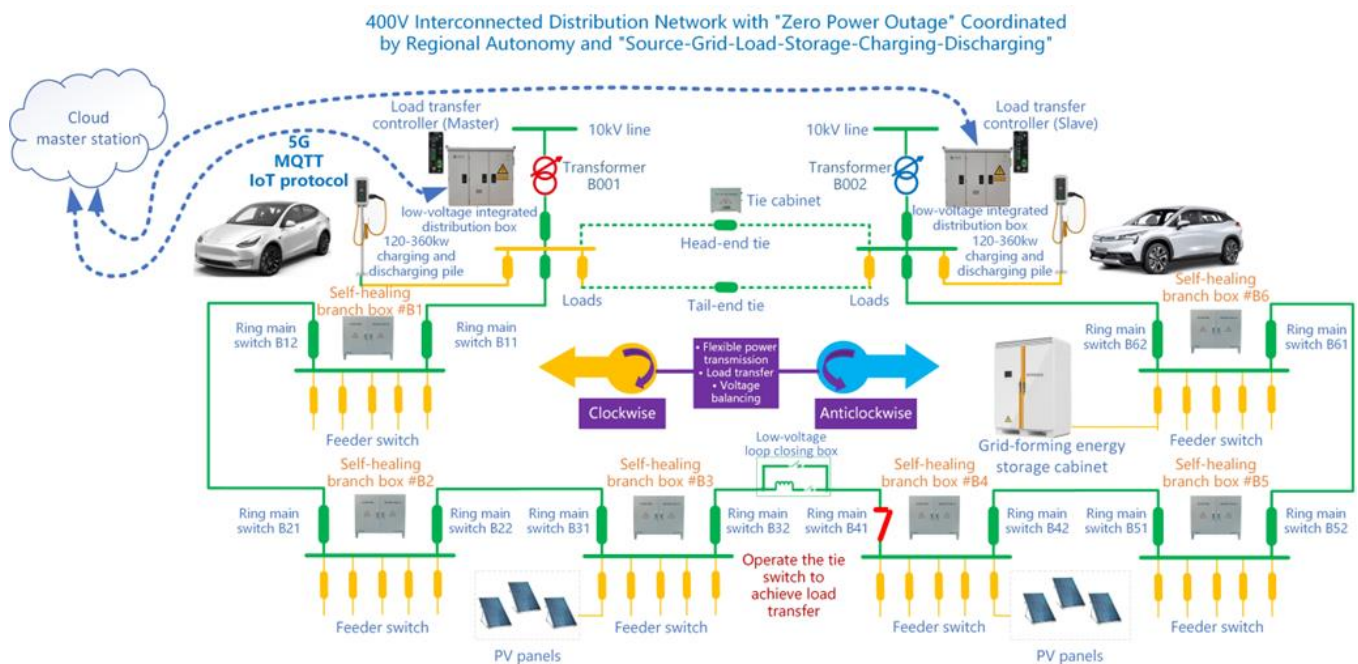


Fig. 1 - Topology of the System

analysis, operational status monitoring, and remote strategy distribution. It generates day-ahead and intra-day optimization plans based on big data analytics and artificial intelligence algorithms. The edge controller, also known as the regional autonomy controller, is deployed at the transformer low-voltage side or within the switching station. It manages real-time data acquisition, local control decision-making, and execution of cloud commands within its jurisdiction. It utilizes high-performance embedded computers to run core control algorithms and connects with various terminal devices via industrial Ethernet or 5G communication networks. Terminal devices include various control boxes, charging piles, inverters, and energy storage converters, responsible for executing specific control commands and uploading operational data.

To meet the communication requirements of different business scenarios, the system incorporates a hybrid communication network. For real-time control communication, the IEC 61850 GOOSE protocol is employed. A local peer-to-peer communication network is constructed based on industrial Ethernet switches, enabling millisecond-level information exchange between devices. Services with extremely high real-time requirements, such as fault self-healing and loop closing control, rely on this network. Monitoring and maintenance communication utilizes the MQTT protocol. Device operational data is uploaded to the cloud platform via 5G/4G wireless networks or fiber optic private networks, while simultaneously receiving parameter configurations and optimization commands distributed from the cloud. Communication between charging piles and the EV network is based on the OCPP protocol, facilitating data exchange between the

charging piles and the operation platform, and supporting functions like remote start/stop, power regulation, and V2G control.

3. KEY TECHNICAL PRINCIPLES

3.1 Low-Voltage Precision Loop Closing Control and "Zero Power Outage" Load Migration

Traditional distribution networks typically adopt a "break before make" approach, leading to brief customer power interruptions. The goal of loop closing operations is to achieve a "make before break" sequence to accomplish seamless load transfer. However, the moment of loop closing generates an inrush current, the magnitude of which depends on the voltage amplitude difference, phase angle difference, and system impedance on both sides of the loop closing point. Two loop closing strategies can be adopted in this system: one is closing via a loop-closing inductor, which uses an inductor to suppress the loop closing current; the other is the precision loop closing control strategy. The precision loop closing control strategy includes the following key steps: First, the regional autonomy controller collects real-time voltage amplitude, phase, and frequency information from the two lines to be loop-closed, calculates the voltage difference and phase angle difference at the loop closing point, estimates the loop closing inrush current, and permits the loop closing operation only when all indicators meet preset thresholds. Second, before the loop closing command is issued, the controller sends regulation commands to the grid-forming energy storage devices on both sides, actively reducing the voltage difference and phase angle difference through their active and reactive power regulation. Then, when the voltage difference is $\leq 2\%$,

the phase angle difference is $\leq 5^\circ$, and this condition persists for more than 200ms, the controller issues a closing command to the loop closing control box. The loop closing control box employs synchronous closing technology to complete the circuit breaker closure near the voltage zero-crossing point, further reducing the inrush. After loop closing, the system continuously monitors the magnitude of the circulating current. If the circulating current exceeds a preset value, it is quickly suppressed by adjusting the output of the energy storage devices on both sides. Finally, after the circulating current stabilizes (typically requiring 3-5 power frequency cycles), the controller issues a trip command to the circuit breaker on the side to be withdrawn, completing the load transfer. Throughout this process, the customer-side voltage remains continuous, achieving a “zero power outage” experience. To verify the effectiveness of the strategy, a simulation model based on MATLAB/Simulink is established, and the simulation results are shown in Figure 2. The peak inrush current of the traditional direct loop closing method reaches 410 A, while the peak inrush current is reduced to 70 A after the adoption of precise loop closing control, which meets the requirements for safe operation.

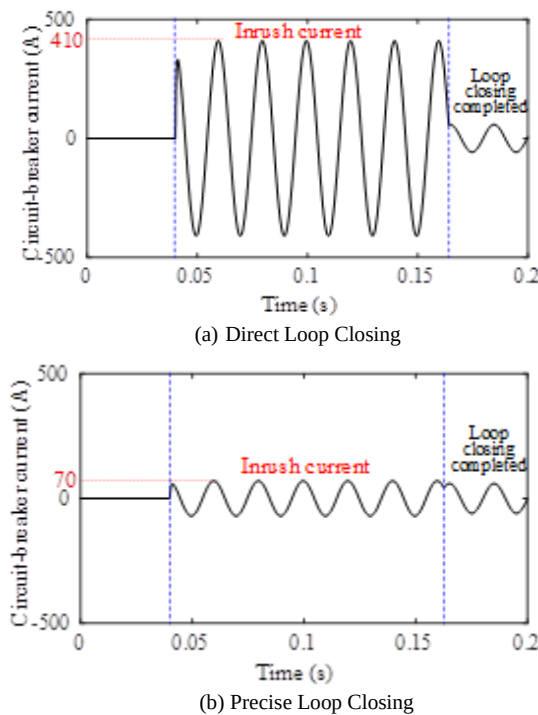


Fig. 2 - Waveforms of Loop Closing Current

3.2 Local Peer-to-Peer Communication and Fault Self-Healing

Traditional centralized fault handling methods are time-consuming and struggle to meet high reliability requirements. This system adopts a local peer-to-peer communication mechanism based on IEC 61850 GOOSE. Each self-healing branch box exchanges status information directly via GOOSE messages without

relying on a master station. Each control box both publishes its own status information (such as current, voltage, switch position, protection action signals) and subscribes to information from adjacent control boxes. GOOSE messages are transmitted directly at the data link layer, with transmission delays controllable within 4ms. Taking a permanent fault occurring on the left feeder in Figure 1 as an example, with the schematic diagram of the relevant part redrawn in Figure 3.

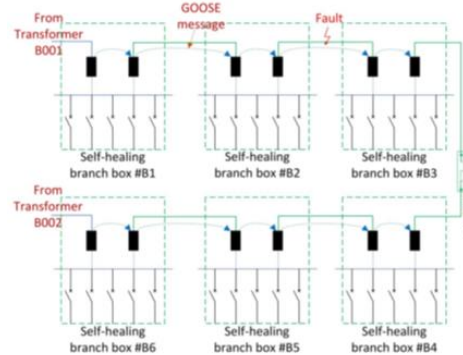


Fig. 3 - Fault Self-Healing

The fault self-healing process works as follows: Self-healing branch box B1, located upstream of the fault point, detects that the abrupt change in current exceeds the set value and that the voltage drops significantly, determining a short-circuit fault. Control box B1 sends fault information to adjacent control boxes B2 and B3 via GOOSE messages. If control box B2 also detects the fault current while control box B3 does not, it can be determined that the fault is located between control boxes B2 and B3. Based on this location result, control boxes B2 and B3 issue trip commands to their respective controlled circuit breakers, isolating the faulty section. This entire process is completed within 200-250 ms after the fault occurs. After fault isolation, control box A detects the downstream power loss, establishes a connection with the other transformer B002 via the loop closing point, and automatically closes the tie switch, allowing B002 to restore power to the non-faulty section. Power restoration is completed within 3 – 5 s after fault isolation. A cable short-circuit fault caused by external damage occurred at the Xinjiang demonstration site. System records show the fault occurred at $t = 0$ ms. The self-healing branch box detected and located the fault at $t = 210$ ms, completed fault isolation at $t = 230$ ms, and restored power to the non-faulty section at $t = 4$ s. The actual power interruption lasted approximately 4.5 seconds. In contrast to the hour-long outages that can result when circuits are restored using traditional methods and the related economic losses, such as frozen food thawing, the affected downstream customers experienced no noticeable interruption.

3.3 Grid-Forming Energy Storage and Critical Load Supply Guarantee

Grid-forming energy storage possesses characteristics such as autonomous voltage establishment, inertia

support, and voltage source behaviour. It can autonomously establish stable voltage and frequency without relying on the external grid voltage and has black-start capability. By simulating the rotor motion equation of a synchronous generator, it provides virtual inertia to the system, suppresses the rate of change of frequency, and actively responds to load changes to maintain voltage stability. This system deploys grid-forming energy storage near critical loads, constructing a “full-scenario supply guarantee mode”: In grid-connected operation mode, the energy storage participates in grid peak shaving, frequency regulation, and PV consumption, charging and discharging according to commands from the regional autonomy controller. In islanded mode, when a loss of power from the upstream grid or severe power quality deterioration is detected, the energy storage automatically switches to islanded mode, forming an independent microgrid with local loads. Multiple energy storage units (ESUs) share power through droop control, jointly supporting island operation. In black-start mode, if the system is completely de-energized, the energy storage can initiate a black-start procedure, gradually establishing voltage, restoring power to critical loads, and assisting other distributed generation sources in synchronizing and connecting to the grid. When multiple grid-forming energy storage units operate simultaneously, an adaptive droop control strategy is adopted. The droop coefficients are dynamically adjusted based on the remaining capacity and location of each storage unit, achieving reasonable power sharing and circulating current suppression. Figure 4 shows the active power sharing among ESUs. The capacities of ESU1 to ESU4 are 20kW, 10kW, 10kW, and 5kW, respectively. Before the adaptive droop control strategy is applied, the active power fails to be proportionally shared among the ESUs. This situation is improved with the application of the adaptive droop control strategy, the ESUs output active powers in proportion according to their capacities, and

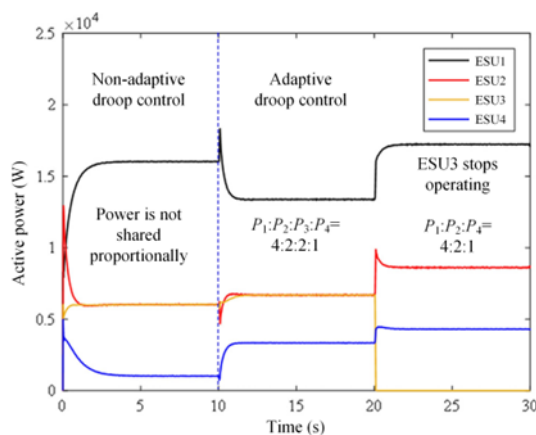


Fig. 4 - Active Power Sharing among ESUs

even after ESU3 stops to operate at 20s.

3.4 Flexible and Orderly Charging and V2G Control

Electric vehicle charging load has significant temporal and power regulation flexibility. With reasonable guidance, charging load can be shifted from peak

periods to off-peak periods, or V2G technology can be used to discharge power to the grid during peak periods, achieving peak shaving and valley filling. This system designs a multi-timescale flexible and orderly charging control strategy that integrates real-time transformer load with forecasted charging and discharging power to formulate an optimal strategy. Day-ahead optimization is based on next-day PV output forecasts and load forecasts. The cloud platform generates a day-ahead charging plan for each charging pile, including the allowable charging power range and target State of Charge (SoC) for each time period. Intra-day rolling optimization involves the regional autonomy controller updating the charging plan every 15 minutes, making corrections based on actual PV output and load variations and combining updated short-term forecasts of charging demand and transformer capacity headroom. Real-time control employs Model Predictive Control (MPC) for second-level regulation of each charging pile, with the objective function comprehensively considering PV consumption rate, user charging demand, and grid security constraints. For electric vehicles connected to V2G devices, the system treats them as bidirectional distributed energy storage resources. The control strategy includes: during the evening peak period (that is, 19:00-22:00), if the transformer load rate is predicted to exceeds 90% based on the integrated assessment, the controller issues a discharge command to the V2G devices, allowing electric vehicles to supply power to the grid, with a single vehicle capable of discharging at 6-10kW. If bus voltage is detected to be low, the controller prioritizes calling upon V2G devices to provide reactive power for voltage support. V2G devices can also participate in primary frequency regulation, quickly adjusting charging/discharging power based on frequency deviation. To incentivize user participation in orderly charging and V2G, the system designs a points-based incentive mechanism. Users who authorize their vehicles to participate in grid regulation earn points that can be used to offset charging fees or exchange for other benefits. Demonstration data shows that over 60% of users are willing to participate in orderly charging, and 15% are willing to participate in V2G discharging.

3.5 Source-Grid-Load-Storage-Charging-Discharging Integrated Coordination

The core of the system's coordinated control is a multi-objective optimization problem. The objective function comprehensively considers maximizing the local consumption of renewable energy generation and minimizing the peak-valley difference of electricity load. The constraints include power balance constraints, node voltage constraints, branch current constraints, equipment capacity constraints, energy storage SoC constraints, and charging pile power constraints, among others. To meet real-time control requirements, the system adopts a hierarchical distributed solution algorithm: The upper-layer optimization is performed by the cloud platform, which uses a Particle Swarm

Optimization algorithm based on day-ahead forecasts to solve the global optimization problem and generate target reference values for each regional autonomy controller. The middle-layer optimization is handled by the regional autonomy controllers. Based on the upper-layer target reference values and real-time data, they employ the Alternating Direction Method of Multipliers (ADMM) to coordinate power allocation among various devices. The bottom-layer control involves the local controllers of each device executing the power commands while simultaneously participating in primary frequency and voltage regulation. This hierarchical distributed architecture balances global optimality with real-time responsiveness. Under typical scenarios, the algorithm can converge within 2-3 iterations, with a single iteration taking approximately 50ms.

4. DEMONSTRATION APPLICATIONS AND EFFECT ANALYSIS

The Xinjiang demonstration site is located in a village or town in Changji, covering a power supply area of approximately 120 square kilometers, serving about 3,000 households, with a power supply radius extending up to 18km. The demonstration site has approximately 1.2 MWp of distributed photovoltaic (PV) capacity integrated and is equipped with 30 charging piles (including 5 with V2G capability). Before the demonstration, issues such as low voltage at the end of the lines, frequent fault outages, and difficulties in PV consumption were prevalent. The system transformation was completed in September 2024. The main implementation content includes: installing 8 low-voltage self-healing branch boxes and 3 load transfer control boxes at key points along the lines; constructing 3 grid-forming energy storage systems (with a total capacity of 0.6MW/1.2MWh); upgrading the charging piles to flexible and orderly charging piles; adding 5 new V2G devices; and deploying 1 regional autonomy controller and a remote operation and maintenance platform.

The operational results show that the minimum voltage at the end of the lines was increased from 190V to 200V, and the voltage qualification rate rose from 96.5% to 99.8%. Since the system was put into operation, three faults have occurred, all of which achieved rapid self-healing. In the most recent incident, a line break caused by strong winds, the system isolated the fault within 150ms. Through islanded operation of the energy storage, it ensured continuous power supply to 67 households downstream of the fault point, resulting in zero outage time for users during the fault repair period. The PV consumption rate increased from 82% to 96%, and the curtailment rate dropped below 4%. The fault location time was reduced from an average of 2 hours to 300ms. The application effects of the two demonstration sites are summarized in Table 1. It can be seen that significant benefits have been realized.

Index	Value	
	Before application	After application
PV consumption rate	82%	96%
Power supply reliability	97.50%	99.98%
Voltage qualification rate	96.5%	99.8%
Self-healing time	Hour-level	3-5 s

Table 1 - Application Effects of Demonstration Sites

5. CONCLUSION

This paper systematically elaborates on a low-voltage AC 400V interconnected distribution network technology based on regional autonomy and the coordination of source-grid-load-storage-charging-discharging. Through low-voltage precision loop closing control, it achieves “zero power outage” migration during load transfer, providing a solution for users with high power supply reliability demands. Based on a fault self-healing mechanism utilizing local peer-to-peer communication, it significantly reduces fault processing time and markedly enhances the distribution network’s fault response capability. The introduction of grid-forming energy storage constructs a full-scenario power supply guarantee mode for critical loads, greatly strengthening the resilience of the distribution network. The flexible and orderly charging and V2G control strategies realize bidirectional interaction between electric vehicles and the grid, improving the level of new energy consumption and the grid’s regulation capability. Demonstrations in Guangdong and Xinjiang have confirmed that this technology can effectively increase the photovoltaic consumption rate, alleviate transformer overload, ensure power supply reliability, and improve voltage quality, yielding significant economic and social benefits. This technology is ready for large-scale promotion and will provide strong support for the construction of new-type power systems and the achievement of China’s “dual carbon” goals.

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Paper No. 5

GRID IMPACTS OF AI DATA CENTRES

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ABSTRACT

Artificial intelligence (AI) data centres are emerging as concentrated large loads for which electricity demand can vary periodically and coherently with training, communication, cooling, and control actions. This makes them different from static load blocks: the grid sees not only high demand, but also correlated ramps, oscillatory components, voltage-sensitive changes, protection events, and recovery rebounds. Existing studies have examined workload power traces, converter and UPS stability, aggregated grid models, observed oscillations, and flexible computing, but these topics have largely been treated as separate problems. It remains unclear which workload features are preserved or reshaped by each supply architecture, under what network conditions a terminal disturbance becomes consequential, how evidence from measurements, hardware tests, and simulations should be combined, and how internal controls should be coordinated with siting and scheduling. This calls for an architecture-conditioned and evidence-graded framework that connects disturbance formation, propagation, grid exposure, and coordinated governance.

We reviewed recent work along this causal chain, compared centralized UPS, distributed battery backup unit (BBU), direct power electronic, 400 and 800 VDC, solid-state transformer (SST) or MVDC, and hybrid architectures, and distinguished evidence according to what each study can establish. We identified four unresolved interfaces: computing to terminal, device to grid, internal control to external scheduling, and planning to operation. The synthesis supports a bounded conclusion: AI data centres are neither intrinsically destabilizing nor automatically reliable grid resources; their effects depend on architecture, operating mode, grid conditions, and verified response envelopes.

1. INTRODUCTION

Artificial-Intelligence computing is turning data centres into grid assets for which electrical behaviour depends on both software and hardware. Training and inference clusters combine large demand with synchronized communication, cooling dynamics, UPS operating modes, storage, converters, and protection.

Measurements show that computing and communication phases can create structured power variations from individual accelerators to multi-node clusters [1]-[5]. The grid question is therefore no longer only how much

capacity a site consumes, but which power variations remain correlated after aggregation and how the facility changes its behaviour during normal operation, external disturbances, and recovery.

This dynamic behaviour is broader than a linearized small-disturbance response. Converter controls and impedances shape continuous fluctuations around an operating point [6]-[9], whereas current limits, UPS transfer, bypass, battery takeover, protection, load shedding, and staged restoration introduce nonlinear and discrete transitions [10]-[13]. At the system level, a terminal disturbance may appear as a ramp, a periodic forcing, a voltage-sensitive load reduction, an oscillation, a sudden loss of demand, or a recovery rebound; its consequence then depends on location, grid strength, and the operating state of the surrounding network [14]-[17]. No single transfer function or aggregate load model can therefore represent the full dynamic range.

Reviews have already established the breadth of data centre interaction with smart grids, including energy management, storage, demand response, markets, and resilience [18]-[22]. Surveys focused on AI facilities add concerns about interconnection, power quality, stability, and regional planning [23][24]. Work on energy use and reliability further shows why annual consumption, peak demand, redundancy, and dynamic response should be treated as different quantities [25]-[27]. These literatures are valuable, but they usually organize the problem by discipline. As a result, workload measurements, converter and electromagnetic transient models, protection-aware phasor models, field events, and scheduling policies are often discussed without a common causal structure or a clear statement of where each model is valid.

This review makes two main contributions:

- a) It establishes architecture as the condition that shapes the external disturbance. The same computing activity can reach the grid terminal as a filtered fluctuation, a coherent oscillation, a protection event, a load loss, or a staged recovery, depending on the supply path, operating mode, storage location, limits, and protection logic.
- b) It frames stability as a coordinated governance problem. Internal controls, storage, protection, siting, workload scheduling, and grid services must be assigned to the time scale at which they can change the disturbance, its propagation, or the system exposure.

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The following sections develop these contributions from architecture to evidence and then to planning, scheduling, and control. Each section ends with a decision rule intended to guide model selection or mitigation design.

2. DATA CENTRE ARCHITECTURES AS DISTURBANCE TRANSFER SYSTEMS

The supply architecture is the first condition on grid impact. A conventional facility may use a centralized double-conversion UPS, whereas newer designs place battery backup units at the rack, distribute power on a 400 or 800 VDC bus, or use a SST and a medium-voltage DC link. Some sites expose power electronic server supplies directly to the AC system, and hybrid sites combine UPSs, batteries, generators, and renewable generation. A recent electromagnetic-transient modelling effort classifies these alternatives into six representative forms and shows that their converter, storage, and protection states must be represented differently [28].

Table 1 summarizes the transfer mechanism relevant to this review. The final column is deliberately a research boundary: an efficient or promising topology is not automatically a validated grid interface.

Architecture	Main Electrical Path	Disturbance Shaping and Protection	Guidance for Analysis
Centralized UPS [8][27][28]	IT load, DC link and inverter, rectifier, transformer, then grid terminal	UPS control bandwidth, battery takeover, bypass, current limits, and staged reconnection	Use a model that depends on operating mode when studying weak grids, faults, or recovery; a static load is insufficient.
Distributed UPS or BBU [26][28]	Rack or server power supply with battery backup close to the IT load	Many local buffers, rack power caps, and coordinated or uncoordinated battery actions	Preserve correlation among racks and the aggregate battery state; diversity cannot be assumed without measurements.
Direct AC power electronic load [6][7]	Server PFC and point-of-load converters directly face the AC network	PFC control, ride-through limits, and protection can turn voltage events into fast load loss	Use impedance or electromagnetic transient models for fast interaction and protection studies.
400 or 800 VDC distribution [28][29]	Front end rectifier, DC bus, DC to DC conversion, then rack load	DC bus storage, multiport converters, and DC fault isolation can filter fast IT changes	Treat 800 VDC as an emerging architecture; distinguish industrial roadmaps from measured academic validation.
SST or MVDC [28][30]	Medium voltage AC, SST or multilevel conversion, DC bus, then rack converters	Multiport power control, possible grid forming behavior, storage, and DC protection	Study converter interactions and fault states jointly; simplified buck or boost models require validation.
Hybrid with storage and onsite generation [18][31]	Grid, UPS, batteries, generators or renewables, cooling, and IT load share the grid terminal	Dispatch of stored energy and local generation changes both net power and recovery	Report the energy state and reserve assignment before claiming grid service capability.

Table 1 - Representative Architectures and their Disturbance Transfer Mechanisms

2.1 Architectures as Nonlinear and Hybrid Disturbance Transformers

Table 1 should be read as a map of a nonlinear and hybrid dynamical system, not as a collection of fixed transfer functions. During normal operation, converter bandwidth, impedance, stored energy, cooling response, and workload diversity shape continuous fluctuations [6][7][9][32][33]. When a limit or disturbance is reached,

current saturation, controller mode changes, UPS bypass or battery transfer, protection, load shedding, and restoration can change the propagation path itself [10]-[13]. New DC and SST architectures add further interactions among multilevel conversion, DC protection, storage, and grid support controls, for which model and field validation remain limited [28]-[30].

The grid terminal is used only as an observation boundary for the aggregate external disturbance. It does not imply that internal dynamics are linear, continuous, or reducible to one terminal model. Small-signal impedance models are appropriate for local resonance around an operating point; electromagnetic transient models are needed for fast controls and protection; phasor models describe electromechanical and voltage dynamics; and hybrid state models are needed when switching, tripping, and recovery determine the response [8][10]-[12][34]. The central review argument is therefore qualitative but testable: architecture and operating state condition how a disturbance is transformed, while connection location and network state condition the external consequence.

The comparison yields a direct design rule: Centralized UPS sites concentrate control and protection at the facility boundary, so their terminal response depends

strongly on operating mode. Distributed BBU sites may absorb fast fluctuations, but a common orchestration signal can make many local buffers act as one large converter. DC architectures move filtering and storage closer to the rack, but expose new DC fault and protection states. SST and MVDC designs add control degrees of freedom while increasing the number of interacting loops. Consequently, architecture selection should include a dynamic interface specification

containing the expected power spectrum, reactive response, current limits, fault ride through, and restoration envelope.

2.2 Equivalent Models Conditioned by Architecture

Equivalent model construction cannot reduce nameplate power directly to a generic load block; retained states depend on architecture and study purpose. Device level power factor correction (PFC) impedance models preserve control loops, DC link energy, and operating point, while virtual impedance models extend the representation to the 48 V server interface [6][7][32], [35]. For racks and distribution systems, aggregate admittance models must retain controller bandwidth, parameter dispersion, and upstream coupling. Otherwise, aggregation can conceal resonance or misstate the stability margin [8][9][33].

At facility scale, the objective shifts from individual converters to the external response of the supply chain. Dynamic distribution models and converter-based emulators provide a hardware path for testing the equivalent [10]. Electromagnetic transient models retain fast controls, energy states, saturation, and architecture specific protection transitions [28][30]. Phasor and transient stability models may collapse the internal network, but should retain active and reactive power response, voltage and frequency sensitivity, UPS and cooling modes, load loss, and restoration [11][12]. The two model classes answer different questions rather than representing accuracy levels of one universal equivalent.

Calibration is part of construction: parameter identification and model structure can both change the predicted response [13][34]. Workload traces, impedance measurements, disturbance records, and emulator tests constrain different model components and are not interchangeable [4][8][10].

Guidance. Start from the architecture and target grid question, retain the controls, energy states, correlations, limits, and mode transitions that alter the relevant disturbance, and report aggregation assumptions, valid modes, time range, parameter source, and validation evidence.

3. DISTURBANCE FORMATION & ARCHITECTURE-CONDITIONED PROPAGATION

3.1 Computational and Facility Sources

The disturbance source is broader than GPU switching. Training alternates forward propagation, back-propagation, collective communication, and checkpoint operations; inference follows request arrival, batching, and service-level policies. Measurements from large GPU clusters show that compute and communication phases create structured power variation [1][2].

Measurements on an 8 GPU H100 node also demonstrate that observed power depends on model and training settings rather than simply on the accelerator nameplate [3]. High-resolution traces from single and multiple GPU nodes provide the sampling and correlation information needed for calibration [4].

The facility adds slower and event-driven sources. Cooling pumps, fans, liquid cooling, backup generators, storage, and auxiliary controls may respond to the same operating event as the IT load. A voltage dip can initiate UPS transfer or staged shedding; a restoration command can then produce a rebound ramp. Production-informed power stabilization and a hierarchical semi-Markov load model both suggest that task state, node count, synchronization, and recovery state should be modeled together [5][36]. The useful output of this subsection is therefore a multirate disturbance description containing a baseline, spectral components, stochastic variation, cross-node correlation, and event transitions.

Guidance. For a grid terminal study, do not replace a measured or replayable workload process with a single peak, variance, or peak-to-average ratio. Preserve the features that can be correlated with converter bandwidth, grid modes, or recovery limits.

3.2 Propagation through the Supply Chain

PFC stages, server supplies, UPSs, transformers, cables, storage, and protection reshape the source signal. Converter controls create frequency-dependent input admittance; tightly regulated converters can exhibit negative incremental impedance over part of the spectrum. Low-frequency PFC impedance models and system impedance methods established this mechanism, while parallel rectifier experiments and aggregation methods showed the effects of controller bandwidth, parameter dispersion, and network impedance [6]-[9].

Server-side virtual impedance provides a complementary control lever at the 48 V interface [35]. The consequence is that a periodic component visible at a GPU or rack need not appear at the grid terminal with the same amplitude or phase.

Architecture determines which transformations are possible. A centralized UPS can filter fast IT variation but may introduce an additional control mode during bypass or battery operation. Distributed BBUs shorten the electrical path from the source to storage, while simultaneous state changes can reduce diversity. A DC bus or SST may absorb fast power through stored energy and multiport control, but the bus, isolation, and fault protection become part of the grid interface.

Recent system studies note that simplified DC to DC models do not yet capture all LLC, high-frequency transformer, SST, NPC, or MMC behaviours needed for realistic electromagnetic-transient validation [28][30]. An active power buffer is an example of source and

pathway co-design: it targets GPU transients before they reach the upstream supply [37].

Three modelling handoffs are essential. The workload model must declare sampling, bandwidth, and correlation. The facility model must allocate the trace among IT converters, cooling, storage, losses, and protection states. The terminal model must expose active and reactive power, voltage and frequency sensitivity, saturation, trip logic, and recovery. Dynamic models of data centre distribution systems and converter-based emulators provide a route for testing this handoff against hardware [10][32][33].

Guidance. Select the least detailed model that preserves the mechanism under study. Use impedance or electromagnetic-transient models for fast resonance, protection-aware phasor models for faults and recovery, and static or quasi-static models only for planning horizons where those states are demonstrably irrelevant.

3.3 Terminal Equivalents and Validation

At the grid terminal, the upstream system may see a filtered ramp, a controller-shaped periodic signal, an oscillatory mode, a protection-induced loss of demand, or a recovery step. Dynamic aggregate models for power-system stability and transient studies make this interface explicit [11][12]. Pattern-consistent calibration and resonance-oriented power-delivery models further show that parameter identification and model structure can change the predicted response [13][30][34]. Static ZIP or constant-power representations cannot express all combinations of saturation, bypass, battery takeover, low-voltage tripping, or staged restoration.

Validation should proceed from the interface outward. Revenue-grade metering establishes baseline diversity but not transient fidelity. Workload replay and rack measurements test whether aggregation preserves dominant spectra. Impedance scans identify control bands. Disturbance records, controller-in-the-loop tests, and converter-based emulators test terminal response and recovery. A model should therefore report its valid frequency range, operating modes, parameter provenance, and validation evidence, rather than only its block diagram.

4. GRID EXPOSURE AND EVIDENCE OF STABILITY CONSEQUENCES

4.1 When a Terminal Disturbance becomes a Grid Problem

The same terminal waveform can have different consequences because system exposure is conditional. Relevant variables include connection voltage, short-circuit strength, local voltage support, modal participation, system inertia, inverter-based resource penetration, reserve headroom, and the spatial

correlation of other large loads. A narrowband workload component is mostly concerning when it overlaps a weakly damped grid mode or a converter control band. A large step is mostly concerning when protection, voltage sensitivity, or recovery actions are correlated across sites. This explains why installed capacity is a poor proxy for dynamic risk.

4.2 Evidence Classes and Bounded Interpretation

Evidence must be read according to what it can establish. A field event provides direct evidence that a mechanism occurred under a particular facility and network condition. Hardware experiments establish reproducibility over a bounded operating range. A calibrated model supports interpolation only when its parameters and protection states are identifiable. A scenario simulation reveals sensitivities and counterfactuals, but not event prevalence.

The 14.7 Hz investigation by Mishra *et al.* used synchrophasor evidence to trace an oscillation to a particular data centre [14]. It supports the claim that UPS and grid controls can interact in the field under specific conditions, not that 14.7 Hz is a universal data centre signature. Ko and Zhu used periodic and stochastic AI workload forcing in WECC and NPCC systems and found that workload frequency, site size, location, grid strength, and modal proximity jointly shape the response [15]. Real-world dataset analysis has begun to connect AI load traces to frequency response, but remains limited in site coverage and internal state visibility [16]. Operational risk assessments and comparisons of load models similarly show that the selected aggregate representation can alter stability conclusions [13][17].

Guidance. Use field and hardware evidence to bound plausible mechanisms, then use calibrated and scenario models to explore sensitivities. Do not use a simulated oscillation to estimate its frequency of occurrence, and do not use one event to generalize across architectures or grid locations.

5. COORDINATED PLANNING, SCHEDULING, & CONTROL

5.1 Internal Governance: Source and Pathway

Internal governance changes the disturbance before it reaches the grid terminal. At the workload layer, power caps, dynamic voltage and frequency scaling, staggered starts, randomized synchronization, and checkpoint policies reduce amplitude or coherence [5][42]. At the rack layer, BBU, supercapacitor, and power shaping absorb fast GPU transitions; at the facility layer, UPS control, DC bus storage, converter damping, and controlled restoration shape the remaining response [37]. Cooling thermal inertia and staged operation can supply slower flexibility, but their limits and recovery must be represented [39][43].

The correct resource depends on architecture. Centralized UPS facilities should prioritize rectifier impedance, mode transitions, fault ride-through, and staged reconnection. Distributed BBU facilities should coordinate local battery states and avoid simultaneous rack actions. An 800 VDC facility should co-design bus storage, multiport DC to DC control, fault isolation, and energy reserve. SST or MVDC designs additionally require coordination across several converter loops. The practical output is a set of safe envelopes for power, ramp, reactive response, energy, and restoration, rather than a generic promise of flexibility.

5.2 External Governance: System Exposure

External governance changes where and when the disturbance is exposed. Siting and interconnection should consider network strength, modal participation, voltage and reactive power margins, staged energization, and the architecture-specific response envelope. Workload shifting has a long history in peak management and demand response [44]-[46], while geographical load balancing and carbon-aware computing extend the decision across sites [47]-[50]. Recent work connects AI flexibility to interconnection queues and planning decisions [51]. These studies show that software flexibility can change the effective load location, but they do not remove network constraints or dynamic exposure.

Market and carbon signals can also synchronize sites. Price-driven migration may concentrate demand and sharpen local ramps under particular network conditions [52]; coordinated shifting can instead reduce impact when traffic, data, and power constraints are modeled together [53]. Therefore, a scheduler should treat nodal voltage, ramp limits, modal exposure, correlation, and restoration time as constraints, not as post-processing diagnostics.

5.3 Cross-Layer Coordination Across Time Scales

Planning, scheduling, and control should divide responsibility rather than collapse all actions into one optimizer. Microsecond to millisecond response belongs to PFC, DC to DC converters, and supercapacitors. Millisecond to second response belongs to UPS, BBU, SST, and station batteries. Seconds to minutes use power caps, cooling, and battery dispatch. Minutes to hours use

job delay, site placement, and cross-site migration. Months to years determine siting, interconnection capacity, architecture, and storage investment. Earlier work on microgrid energy management and workload shifting provides optimization building blocks [54]-[57]; the unresolved step is to make their constraints architecture dependent.

A credible flexibility offer must report capacity, response time, duration, energy state, communication delay, SLA impact, and the recovery trajectory. It must also declare which resource is reserved for reliability and which is available for grid service. This prevents the same BBU or deferrable workload from being sold simultaneously into multiple services and gives the grid operator a bounded response envelope without requiring job-level disclosure.

Guidance. Allocate fast spectral components to local electrical buffers, slower energy imbalance to storage and workload scheduling, and long-term system exposure to siting and interconnection rules. Every layer should pass its residual disturbance and recovery envelope to the next layer.

6. EVIDENCE GAPS AND RESEARCH AGENDA

The literature is not empty at any one layer; the missing results are mostly interfaces between layers. Four priorities follow.

Computing to terminal - Synchronized, anonymized data are needed from task states and GPU nodes through racks, UPSs, storage, and grid-terminal phasors. The key experiment is a cross-architecture comparison in which the same workload is replayed through centralized UPS, distributed BBU, and DC distribution paths.

Device to grid - A common interface and parameter vocabulary is needed for centralized UPS, distributed BBU, 400 or 800 VDC, SST, and hybrid systems. Model reduction should preserve mode transitions, protection, reactive response, and recovery. PNNL models and recent dynamic load studies provide starting points, but site calibration remains essential [11][12][28].

Internal control to external scheduling - Joint workload, UPS, BBU, cooling, and battery optimization exists, but

Question	Evidence that is Available	What can be Concluded	Decision Rule
Can the source contain a coherent disturbance?	GPU, rack, and workload measurements; replay studies [1][4]	Workload phases and synchronization can produce structured spectra	Preserve phase correlation and recovery in the source model.
Can the facility reshape it?	Impedance studies, emulators, hardware tests [8][10]	Converter and UPS modes can filter or amplify selected components	Match model bandwidth and mode states to the question.
Can it interact with the grid?	Field event, dynamic models, and wide-area simulations [11][14][15]	Interaction is conditional on location, strength, modes, and modal overlap	Require node-specific dynamic screening before interconnection.
Can it provide a grid service?	Flexibility models and a 256 GPU demonstration [38]-[41]	Software and facility controls can deliver bounded response	Certify duration, rebound, SLA impact, and delivery probability.

Table 2 - Architecture-Aware Evidence and Decision Rules

most formulations represent the facility as one flexible load. Future studies should compare architecture-specific bandwidth, loss, reserve, and rebound and should certify deliverability rather than theoretical capacity [21][22][57][58].

Planning to operation. Siting and interconnection methods need a dynamic access metric that combines node strength, voltage stability, modal exposure, fault ride-through, and restoration. A site should be approved against a validated response envelope, not only a static megawatt request. This is also where model exchange, confidentiality, and performance testing should be standardized.

These priorities are testable. A minimum benchmark would publish a workload trace, architecture description, operating modes, protection states, grid-terminal measurements, and a reduced grid model with uncertainty bounds. Such a benchmark would make it possible to compare mitigation strategies without assuming that all AI data centres share one dynamic signature.

7. CONCLUSION

In power-system studies, AI data centres can be understood as cyber-physical loads for which grid behaviour depends on their supply architecture. Computing activity forms the source of disturbances, while the supply architecture can shape how these disturbances propagate toward the grid, and the connection location may influence the resulting system exposure. Coordinated planning, scheduling, and control may further help mitigate adverse impacts and support beneficial grid interaction across different time scales.

Existing studies provide evidence of possible converter interactions, voltage and frequency impacts, and forced oscillations, while also suggesting that these effects depend strongly on the architecture, operating conditions, network characteristics, and available evidence. An important near-term direction is therefore to develop and validate architecture-aware models and response envelopes, supported by synchronized measurements and linked to practical interconnection, scheduling, and control considerations.

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Paper No. 6

**FUTURE-PROOF ARTIFICIAL INTELLIGENCE (AI) DATA CENTRES
FOR ULTRA-HIGH-DENSITY RACKS**

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FUTURE-PROOF ARTIFICIAL INTELLIGENCE (AI) DATA CENTRES FOR ULTRA-HIGH-DENSITY RACKS

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ABSTRACT

The rapid growth of Artificial Intelligence (AI) and accelerated computing is driving a significant increase in data centre rack power densities, with next generation deployments exceeding 200kW per rack. As power density continues to rise, electrical infrastructure has become the primary constraint to scalability, reliability and operational efficiency. Traditional power distribution architectures are increasingly challenged by the demands of ultra-high-density environments, requiring a fundamental shift in how data centres are designed and deployed.

This paper draws significantly from the findings presented in WP213 800 VDC Whitepaper, “5 Principles for 800 VDC in AI Data Centres: Rack-Level Architectures as the Immediate Enabler” (hereinafter referred to as “the Whitepaper”). The Whitepaper explores the key electrical design principles required to support future-ready AI data centres, focusing on modular electrical architectures, UPS and energy storage strategies, intelligent power delivery, and resilient rack-level power design. It also examines the benefits of cluster-based electrical topologies, simulation-driven engineering, and digital validation methodologies to improve scalability and reduce operational risk.

1. INTRODUCTION

Next-generation AI deployments are already exceeding 200 kW per rack, and industry projections suggest that rack power densities may surpass 400 kW by 2027, with megawatt (MW)-scale racks expected to emerge as computational demands continue to grow.

AI data centres (AIDCs), often referred to as AI factories, are characterized by ultra-high-density (UHD) compute clusters, GPU-accelerated infrastructure, advanced cooling systems, high-bandwidth networking fabrics, and significantly higher power consumption than conventional enterprise and cloud data centres.

This evolution presents major challenges across the data centre ecosystem, affecting hyperscale operators, colocation providers, telecommunications companies, engineering consultants, and original equipment manufacturers (OEMs). As a result, electrical infrastructure has become one of the primary constraints to scaling AI computing capacity while maintaining reliability, efficiency, and operational flexibility.

At present, rack-level power distribution is predominantly based on 48 VDC or 54 VDC architectures [1]. However, as power densities continue to increase, the practical limitations of low-voltage vertical power distribution are becoming increasingly apparent, accelerating the industry’s transition toward 800 VDC architectures, also referred to as HVDC. It is however misleading to use HVDC, as 800 VDC is still considered LVDC range as per IEC DC voltage classification. Nevertheless, with reference to the DC voltage in the rack, it is considered higher voltage.

A key consideration is determining the most effective location for the AC-to-800 VDC conversion within the power chain, whether at the rack level, within the white space, or centrally within the grey space.

While AI data centres require advancements across multiple engineering domains, including cooling, networking, facility design, and operational management, this paper focuses exclusively on the evolution of the electrical power distribution architecture required to support UHD rack deployments. Cooling technologies, mechanical infrastructure, server design, networking architectures, and other non-electrical considerations are outside the scope of this paper and are addressed only where they directly influence power distribution requirements.

This paper draws significantly from the findings presented in the Whitepaper, and uses its architectural and operational principles as a foundation for evaluating future electrical infrastructure strategies for AI data centres.

As the industry advances toward UHD rack deployments, technologies such as Direct Current Uninterruptible Power Supply (DC UPS) systems, Transformer Rectifier Units (TRUs), and Solid-State Transformers (SSTs) are expected to play a critical role in shaping the next generation of AI data centre power architectures.

The simplified 800 VDC architectures [2] presented below are likely to emerge in the near future. The lines in Green are the power paths that exist in Alternating Current (AC) and the lines in Blue are the power paths that are converted to 800 VDC.

- (a) Sidecar (also known as Power Rack) is a dedicated power rectification and energy storage module that can be installed adjacent to UHD IT racks. It

converts typical 400/415 VAC input to 800 VDC output. Exist within the white space with the IT rack.

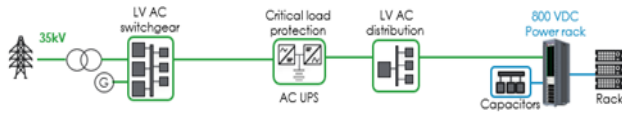


Fig. 1 - Power Rack/Sidecar Architecture

- (b) The DC UPS architecture moves the LV rectification process into the grey space or in the white space. It takes in 400/415 VAC input and converts to 800 VDC output.



Fig. 2 - DC UPS Architecture

- (c) TRU consist of a MV/LV transformer and a DC UPS in one module. It accepts MVAC input and converts to 800 VDC output. Exist in grey space.



Fig. 3 - Transformer Rectifier Unit Architecture

- (d) Solid-state transformers is a collection of high-powered semiconductor components, high-frequency transformers, and control circuitry which is used to provide a high level of flexible control to power distribution networks. It can accept MVAC input and output in LVDC. Exist in grey space.

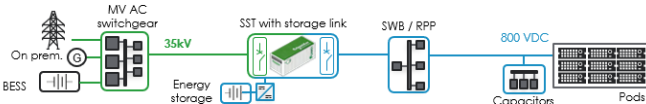


Fig. 4 - SST Architecture

The adoption of an 800 VDC architecture offers several key advantages [1]:

- (a) Simplified power interface to IT equipment:

A standardized 800 VDC interface streamlines the physical interface to rack, simplifying installation, minimizes space usage and improves operational agility.

- (b) Simplified power distribution architecture:

Higher-voltage DC distribution reduces the need for multiple power conversion stages, resulting in a more efficient architecture that reduces equipment layers while increasing reliability and deployment speed.

- (c) Direct compatibility with next-generation GPU racks:

The 800 VDC architecture is being developed to align with the power requirements of future AI platforms, providing a standardized framework capable of supporting ultra-high-density GPU deployments.

- (d) Improved energy efficiency:

By reducing the number of AC/DC and DC/AC conversion stages throughout the power chain, overall system losses can be minimized. This contributes to improved facility efficiency and a lower Power Usage Effectiveness (PUE).

- (e) Enhanced integration of renewable energy sources:

DC-based distribution architectures offer improved compatibility with renewable energy generation and energy storage systems. This enables operators to more effectively incorporate solar, battery energy storage, and other distributed energy resources that are DC native to reduce carbon emissions and decrease dependence on utility-supplied power.

- (f) Future-proofing AIDC architecture:

Moving into 800 VDC helps support higher rack power densities including future data centre distribution architectures.

2. PRINCIPLES TO FUTURE PROOFING DATA CENTRES FOR UHD RACKS

2.1 Modular Electrical Architectures for Scalable AI Deployments

Future-proof AI data centres require modular electrical systems capable of expanding alongside compute growth.

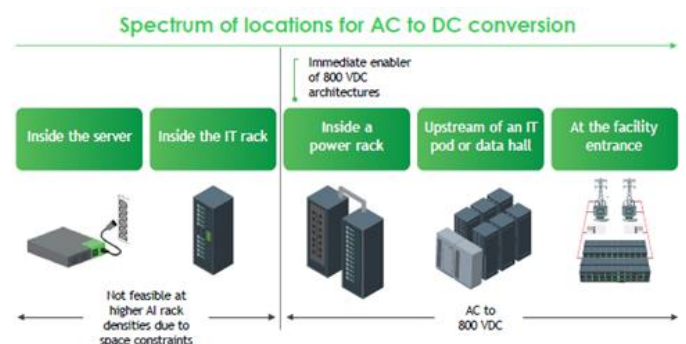


Fig. 5 - Spectrum of Locations for AC to DC Conversion

WP213 5 Principles for 800 VDC in AI Data Centres [3]: Rack-Level Architectures as the Immediate Enabler identifies Power Racks, commonly referred to as “sidecars”, as the most practical near-term solution for supporting ultra-high-density AI deployments. These power racks relocate power conversion, protection systems, and optional energy storage outside the IT rack,

freeing valuable rack space for compute resources while simplifying deployment and maintenance.

Key benefits include [3]:

- (a) It minimizes disruption to the existing AC-based data centre ecosystem. Power racks introduce the smallest architectural change relative to today's AC-based data centres. They avoid re-designing upstream switchgear, protection schemes, grounding strategies, and operational workflows that are well understood. For example, a standard centralized AC UPS can still be used rather than changing the electrical design for a DC UPS.
- (b) There is a more established supply chain. The availability of key components required for rack-level 800 VDC systems (such as power electronics, connectors, protection devices, and controls), benefits from the existing EV market, which has widely developed touch-safe connectors that ensure safety by using mechanical interlocks on all connectors, as to ensure no disconnect occurring under load condition [1]. This market offers component availability and manufacturing scale at the power and voltage levels required for rack-scale systems, reducing procurement uncertainty.
- (c) It reduces the failure zone to a single IT rack. Introducing a new type of distribution system may lead to failures early in its lifecycle. Specific examples might include installation wiring errors, protection mis-coordination, errors in procedures, and human error. Converting at the rack level significantly reduces the risk of downtime at the pod, data hall (IT room), or facility level.
- (d) It shortens qualification and commissioning time. Standardized power racks can be tested, validated, and commissioned as discrete units. This replicable approach allows for accelerated learning, enabling faster installation, which lowers the risk of project delays.

The sidecar modularity approach allows operators to increase capacity incrementally while avoiding disruptive redesigns of upstream electrical systems.

2.2 UPS and Energy Storage Strategies

As AI data centres continue to scale toward multi-megawatt and eventually gigawatt-class facilities, energy storage is becoming an increasingly important component of the electrical infrastructure. Battery Energy Storage Systems (BESS), currently considered optional for most data centre deployments, are emerging as a strategic asset for supporting the operational and grid-integration requirements of large-scale AIDCs.

Recent industry discussions have highlighted the highly dynamic nature of AI workloads and the resulting

variations in power consumption. At sufficient scale, these fluctuations can become visible at the utility grid level, creating challenges for power system stability and infrastructure planning. To address these challenges, several mitigation approaches have emerged, including software-based workload management, GPU-level power smoothing, and energy storage solutions. [4]

UPS systems already play a critical role in AI data centres by providing ride-through capability and buffering short-duration power fluctuations associated with dynamic AI workloads. However, as facility capacities continue to increase, BESS deployments are expected to complement traditional UPS systems by providing additional capacity, resilience, and grid-support functionality at the facility level.

Traditionally, UPS systems have been deployed on a block or module basis to support individual data halls or power trains. In contrast, BESS can be deployed closer to the utility interconnection point, providing an additional layer of resilience and enabling broader facility-level energy management capabilities. Together, UPS and BESS technologies form a layered energy storage strategy capable of supporting both operational reliability and future grid requirements.

Within an AIDC, energy storage systems serve four primary functions [3]:

(a) Backup power

To maintain operation during long-duration upstream power failures. This is done to either keep the critical loads running (hours/days) or to provide enough time to properly shutdown servers and store data (seconds/minutes).

(b) Dynamic load smoothing

To prevent multi-MW load swings from adversely affecting power sources. AI workloads, like training, perform synchronized operations (i.e., orchestration) that can produce rapid power spikes (up to ~150% of nominal load) as well as deeper sustained drops (down to ~40%). Different operations call upon different IT components (e.g., GPUs, memory chips, network cards) at different times, thereby creating a dynamic power consumption profile. This profile varies in magnitude (peak height), duration (how long a peak is held), and frequency (peaks per second). The smoothing function stabilizes the power profile seen by generators, UPS systems, and the grid. It reduces mechanical and electrical stress and avoids frequency and voltage instability caused by sudden load changes. Smoothing requires a two-tiered approach in which each energy storage technology addresses peaks and valleys of varying durations within the power profile. For example, one type of energy storage absorbs the short duration spikes above 100% and fills in rapid dips, while another addresses the longer swings.

(c) Grid fault ride-through (FRT)

To keep the data centre electrically connected to the grid during short-duration disturbances or transients (e.g., fault), FRT prevents an instantaneous drop in grid voltage from cascading to a loss of data centre load which can destabilize the grid for the entire region. Without FRT, a short grid disturbance (<150 ms) can cause a large data centre (e.g., 1 GW) to transfer immediately to onsite sources. If the facility does not return to utility supply shortly after the disturbance restores, the grid will see a loss of 1 GW of load. This rapid decrease in significant load can drive temporary overvoltage and over-frequency conditions. For example, over-frequency relays can trip grid generators offline. These interactions can cascade into grid blackouts. FRT energy storage temporarily “buffers” the power imbalance during the disturbance, maintaining electrical coupling to the grid and enabling a controlled transition back to utility supply once the fault clears. This function becomes increasingly important as AI deployments scale into the hundreds of MWs.

(d) Ramp-up and ramp-down

To control the sudden start and stop of large multi-MW AI workloads, preventing step changes in grid demand. Like FRT, the energy storage gradually supplies or absorbs energy during these transitions, reducing stress on the grid and upstream electrical infrastructure. These controlled ramps occur over seconds and require sizable storage capacity (MWh range). This is specific to AI training workloads and often not required for other workloads (e.g., web hosting, AI inference).

As AI data centres grow in scale and electrical complexity, a coordinated UPS and BESS strategy will become a fundamental element of future-proof power system design [3]. Energy storage technologies for an 800 VDC architecture can be centralised at the facility level, distributed at the data hall or pod level, located adjacent to the rack, or within the server. The optimum strategy is driven by the IT workload, the required function for energy storage, available targets and operational preferences.

Beyond traditional backup power functions, energy storage will increasingly serve as a critical enabler for load management, grid integration, and operational resilience in next-generation ultra-high-density AI data centres.

2.3 Intelligent Power Delivery through System-Level Integration

800 VDC architectures cannot be interpreted as a single, fixed architecture. A holistic system-level approach is required. Instead, future-ready AI infrastructure requires a system-level approach in which power distribution, conversion, protection, cooling, monitoring, and controls must be designed and validated as a complete

system [3]. Decisions made in one part of the architecture can have cascading effects on performance, safety and operability elsewhere.

Critical design principles include:

(a) Coordinated protection and selectivity

Protection and selectivity strategies used in conventional AC data centre architectures are also applicable for 800 VDC. 800 VDC architectures typically include bulk energy storage resources like batteries and capacitors. These represent a significant amount of energy that could be released into the data centre infrastructure. 800VDC converters are typically placed in between bulk energy storage and the DC bus, the converters actively limits output current and eventually shuts down under fault conditions. Despite the converters inherent protection functions, electrical codes do not consider converters to be branch protection. Therefore, external DC protection devices are required. Effective protection in 800 VDC systems is typically achieved through coordinated use of multiple device types rather than reliance on a single technology.

Selectivity, arc-flash mitigations and fault containment are influenced by interactions among utility sources, energy storage, grounding schemes, and upstream and downstream protection devices. Protection and safety performance must be evaluated across the entire power path to avoid miscoordination and unintended fault behaviour.

(b) Adaptive monitoring across operating modes

Transitions between grid-connected operation, battery-supported operation, and grid-interactive modes change available fault current and acceptable protection behaviour. Without monitoring the system state and coordinated control of protection behaviour, faults can result in unnecessary upstream trips or extended recovery times during normal operating transitions.

(c) Real time control of energy storage resources

Helps to secure timely grid access and ensure long-term operations [1]. Real time control allows power compensation to stabilise power consumption, control ramp rates and mitigate large step changes. This is especially important for multiple power sources systems.

For next-generation AI data centres, intelligent power delivery is not merely about supplying more power. It is about creating an integrated, adaptive, and digitally validated electrical ecosystem in which power conversion, protection, controls, energy storage, monitoring, and cooling work together as a coordinated system. This system-level integration improves scalability, resilience, operational efficiency, and fault containment, making it a foundational requirement for future-proof AI infrastructure.

2.4 Resilient Rack-Level Power Design

The application of side car or power racks provides several resilience advantages:

- (a) Failure domains are limited to individual racks.
- (b) Fault containment reduces the risk of widespread service disruption.
- (c) Redundancy can be implemented closer to loads.
- (d) Maintenance activities can be simplified through modular power systems.

The Whitepaper notes that resiliency strategies should include coordinated implementation of redundancy, energy storage, protection systems, and maintenance practices to ensure high availability.

2.5 Evolution towards Cluster-Based Electrical Topologies

While selecting a rack-based architecture today is a pragmatic choice, pod, datahall, and facility-level architectures will become more viable as the industry matures. This includes evolved standards proven protection strategies, improved component availability, and growth in operational experience. These centralised architectures avoid occupying valuable IT space used by power racks.

At this point in time, three mainstream centralised architectures are identified [5]:

- (a) Cluster-based deployment (power centre)

800 VDC implementation at end-of-row rectification and row-level DC distribution. Adjustable up to 2 MW capacity.

- (b) Data hall-level high-density deployment (DC power block)

Designed for future ultra-high-density AI Factory deployments. Centralised power block at approximately 4.8 MW and beyond. Intended to support future native 800 VDC compute racks and high-density AI infrastructure without requiring rack-level sidecar deployment. Covers both Transformer Rectifier Unit (TRU) and Solid-state transformer (SST).

- (c) Next gen architecture

For direct conversion of MVAC at 35 kV to 800 VDC. Targeting power blocks of 10MW and beyond. Suitable for multi-megawatt and gigawatt scale AI factory.

While these cluster-based topologies are likely a more optimal solution for transiting into 800 VDC architecture with higher capacities compared to the

power rack. The current maturity of the industry supports Power rack implementation as the immediate enabler of 800 VDC. As 800 VDC power distribution equipment and data centre operations become more readily available, the side power rack can be replaced by high power density rectifier and being placed at the upstream of power distribution.

2.6 Simulation-driven engineering and digital validation

As 800 VDC data centre distribution is a new emerging architecture, future-ready AIDC would require simulation studies validation before deployment.

The Whitepaper recommends end-to-end system studies that evaluate:

- (a) Protection coordination
- (b) Selectivity performance
- (c) Grounding and fault-current behaviour
- (d) Energy-storage interactions
- (e) Cooling and power integration
- (f) Operational-mode transitions.

By conducting such studies, it will help to confirm that the 800 VDC architecture meets power quality, dynamic response, system stability, grounding, protection coordination and grid compliance requirements before deployment.

3. CONCLUSION AND THE NEXT STEPS

The growth of AI is fundamentally transforming data centre electrical infrastructure requirements. Future-ready AIDC must move beyond traditional power architectures and embrace modular, scalable and intelligent electrical systems capable of supporting UHD compute environments. The findings from the Whitepaper demonstrate that rack-level 800 VDC architectures provide an immediate and practical path toward achieving higher rack densities, improved resilience, efficient energy storage integration, and scalable deployment models. Through modular electrical design, cluster-based power topologies, intelligent power delivery, and simulation-driven validation, operators can build AI data centres that remain adaptable, reliable, and efficient in the face of continuing growth in AI computing demand.

Operating and maintaining 800 VDC systems differs fundamentally from working with conventional AC-powered racks. Procedures, training, and safety practices that are appropriate for lower-voltage AC environments do not directly translate to higher-voltage

DC systems. While higher-voltage DC maintenance practices exist for the EV and solar industries, they are still evolving for the data centre industry.

Staff must be qualified with the skills and knowledge required for the operation and maintenance of the equipment. Work practices must be re-evaluated to identify electrical hazards and reduce associated risks.

Defining operations and maintenance strategies early in the design process helps ensure that 800 VDC systems can be serviced safely, efficiently, and predictably over their full lifecycle. Failing to address these considerations can constrain maintenance practices, reduce availability, or result in safety risks that are difficult or expensive to mitigate after commissioning.

For successful transition toward future-ready AIDC architectures, the paper further recommends the next steps for adopting 800 VDC as and when AI workloads warrant the shift:

(a) Clarify business and workload requirements early

Assess workload homogeneity, rack densities, availability objectives, timelines, cost constraints, and whether the project is greenfield or retrofit. These factors will help to focus on the appropriate 800VDC design.

(b) Evaluate vendors for DC readiness and system level expertise

Select partners with demonstrated experience in DC Systems design, installation, commissioning and maintenance.

(c) Evaluate live-swap capability as an operational and availability advantage

Determine whether the ability to service or replace power components without fully de-energizing IT racks.

(d) Validate the architecture through end-to-end system studies.

Assess power conversion, protection and selectivity, grounding, energy storage interaction, cooling integration, and operational modes.

(e) Stay current on rapid evolving power technologies in this space.

Continuously monitor developments such as centralised AC-DC conversion approached at the pod, datahall, or facility level. Also look for potential shifts beyond 800VDC, solid-state transformers, and advanced DC protection technologies. These innovations can change viable power architectures and design tradeoffs.

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Paper No. 7

**ACHIEVING SUSTAINABLE TRAIN MAINTENANCE THROUGH
ADVANCED AUTOMATION AND DIGITALIZATION
THE SOLUTION - iWMC**

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ACHIEVING SUSTAINABLE TRAIN MAINTENANCE THROUGH ADVANCED AUTOMATION AND DIGITALIZATION THE SOLUTION - iWMC

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ABSTRACT

To support the ever-increasing demand for wheelset maintenance, especially driven by new railway projects, MTR Corporation has developed the Integrated Wheelset Maintenance Centre (iWMC), a highly automated and digitalized facility designed to enhance wheelset maintenance capacity, efficiency, and sustainability. This paper presents the design concept and implementation of iWMC, an advanced automation system, that streamlines heavy-duty maintenance processes and significantly reduces manual handling. The backbone of iWMC is an integration of three digital management systems - namely the Production Management System (PMS), Safety Interlock System (SIS), and Automated Storage and Retrieval System (ASRS) - enabling real-time data monitoring, data-driven decision-making, upholding occupational health and safety, and optimizing workflow control.

Through the use of Industry 4.0 technologies and digital twins modelling, iWMC achieves higher throughput, better resource allocation, and greater operational flexibility. By digitally representing key systems such as plant equipment, the PMS, and the SIS, the facility ensures seamless data integration, traceability, and lifecycle management. This approach supports performance evaluation, and scenario testing, while also delivering sustainability benefits like reduced labour reliance, improved safety, and more efficient use of resources. With maintenance capacity expected to double and processing times significantly reduced, iWMC offers a scalable solution for current and future demands, despite challenges in system integration and workforce transformation.

1. INTRODUCTION

Following the service commencement of Tuen Ma Line and East Rail Line Cross-Harbour Extension in 2021 and 2022, demand for wheelset maintenance has grown steadily. By 2025, annual demand was anticipated to reach approximately 900 wheelsets. Under the traditional workflow, meeting this projected demand would require a 50% increase in maintenance throughput and 30% more workshop space.

Meanwhile, MTR is dedicated to exploring and developing applications of robotics and automation in asset maintenance, as shown in Figure 1, so as to provide sustainable and reliable MTR services. The successful

launch of various automation projects for train component maintenance over the years marks significant milestones in MTR's journey toward smart maintenance.

Highlights of Robotic and Automation Journeys

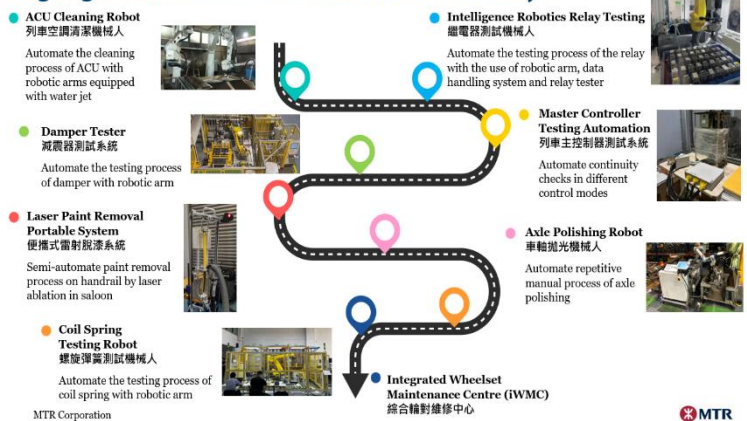


Fig. 1 - Highlights of MTR's Development of Robotics and Automation

Against the backdrop, iWMC was conceived in 2022 to repurpose the 2,600 m² Ho Man Tin Maintenance Siding (Figure 2) into a centralized wheelset replacement facility for Tuen Ma Line and East Rail Line train fleets.

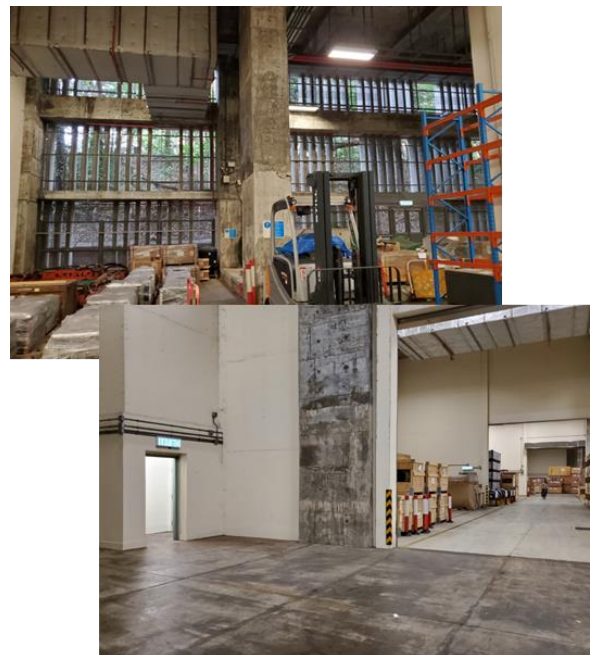


Fig. 2 - Ho Man Tin Maintenance Siding prior to its Development into the iWMC

The project included the following aspects:

- (a) Provision of a new maintenance plant and facilities featuring, automatic overhead gantries and related systems for material handling, advanced inspection, testing and a total of eight six-axis robotic arms, thereby enhancing automation and reducing labour dependency in heavy-duty processes while increasing annual wheelset throughput to 1,500 and facilitating the asset renewal of railway infrastructure.
- (b) Development of digital management systems, namely Production Management System (PMS), Safety Interlock System (SIS) and Automated Storage and Retrieval System (ASRS) to digitalize production control, equipment status and maintenance data, allowing data-driven decisions with proactiveness and flexibility.
- (c) Provisioning of Civil and Electrical & Mechanical (E&M) works to repurpose the area from a warehouse into a maintenance workshop.

This paper focuses on the first two purposes of the project and introduces the innovative features of iWMC while discussing key achievements and the challenges encountered during its development.

2. DESIGN OF AUTOMATED WHEELSET MAINTENANCE FACILITIES

The primary objective of wheelset maintenance is to maintain its structural integrity and the wheel profile, including the shape of the wheel tread and flange to ensure proper wheel-rail contact, even force distribution and minimized contact stress. As mileage increases, wheel reprofiling is required due to wear. Furthermore, wheel blanks may require replacement due to surface defects, fatigue cracking, or wear exceeding prescribed railway standards.

For wheelset replacement, the two wheel blanks of a wheelset are replaced with new ones, while the axle undergoes rigorous inspection and testing to ensure it is defect-free and compliant with stringent specifications. It involves over 14 procedures conducted across specialized plants and facilities. Hence, repeated transportation and positioning of bulky wheelsets, the heaviest weighting over 1,680 kg, is required through overhead cranes. This results in lengthy processing time with multiple operators to ensure safe handling.

At iWMC (Figure 3), the Automatic Material Handling System (AMHS) has been built to utilize advanced industrial automations to manage component handling across individual plants. The AMHS includes Wheelset and Wheel Blank Manipulators, ASRS (Figure 4), and Automated Guided Vehicle (AGV), is significant to the increase of maintenance productivity. Not only does it automate the wheelset transportation, but also facilitates

the automatic and streamlined process control through the PMS. To achieve integrated maintenance, and to maximize land use, the layout of plants and facilities is carefully designed according to the typical wheelset maintenance flows. It offers flexibility to accommodate different cases, including wheelset types that require unique inspection protocols, without obstructing standard production line.



Fig. 3 - Integrated Wheelset Maintenance Centre

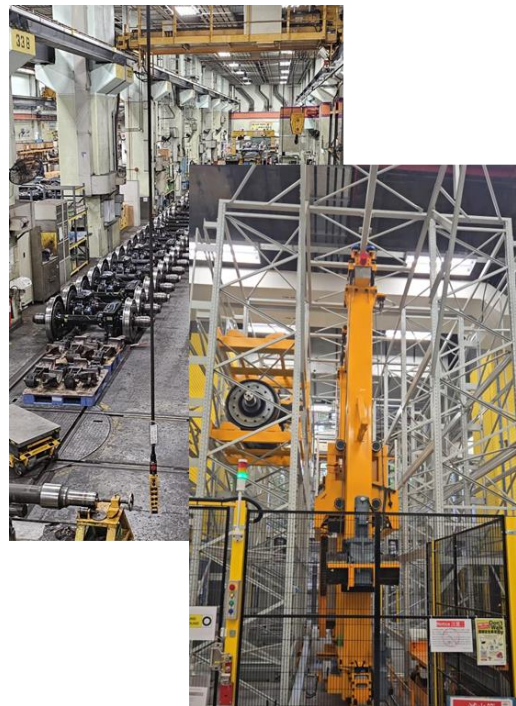


Fig. 4 - Comparison of Traditional and Automated Material Storage and Handlings

2.1 Wheelset and Wheel Blank Manipulators

Another key part of iWMC is the Wheelset and Wheel Blank Manipulators (Figure 5), which are overhead three-axis cartesian gantry robots equipped with end-of-arm tooling specialized for transportation of wheel blanks, axles and wheelsets. In particular, the end-of-arm tooling for wheel blanks provides another three axes of control, which results in a total of six axes to allow for maximum operational flexibility.



Fig. 5 - Wheelset and Wheel Blank Manipulators

As opposed to the conventional use of rail and turntables, the overhead gantry design not only achieves transportation, but allows precise positioning of the materials and greater agility. The modular design of gantry is easily reprogrammable and enable flexible control in sequence of process. Alternative to conveyor design, it efficiently utilizes the vertical space and minimizes the floor footprint, reserving more space for operator collaboration, while facilitating the fallback operations of workpiece transportation by overhead crane.

There are also challenges arising from overhead gantry design: (a) Custom design to handle up to 17 types of wheelsets; (b) Maintaining highest standard of safety without compromising on maintenance throughput; (c) Achieving high positioning accuracy and repeatability. iWMC is designed to be scalable to other train types, the end-of-arm tooling of manipulators are capable to handle up to 17 types of wheelsets, with variations in dimensions and shape, especially the gearboxes of motor wheelsets. The lifting points of the gearbox and mechanical clearance are thoroughly considered. The area is guarded with fencing designed in accordance with ISO 14120 [1] and also ISO 13857 [2], compartmentalized into distinct functional zones where each access door is equipped with a safety interlock that syncs with the plant machinery. Automatic operation of the manipulators is permitted exclusively when the safety-interlocked doors are both closed and locked, thereby ensuring personnel safety within the system area. To achieve the stringent safety performance level (PLe in accordance with ISO 13849-1 [3]) with minimal impact on system throughput, the manipulators are equipped with safety positioning barcode system. These enable door unlocking only when the safe state of

manipulators is confirmed via real-time positioning detection. When staff members must enter the automation area for tasks such as routine maintenance, it is impractical to halt operations across the entire facility. Safe operating limits are dynamically adjusted according to the locking status of the safety-interlocked doors. Consequently, unlocking a door in one zone does not interrupt automatic manipulator operation in other zones. Furthermore, the door unlocking function can only be activated through a Personal Digital Assistant (PDA) governed by the PMS, effectively eliminating both unauthorized access and access events that would compromise system throughput.

2.2 Automated Storage and Retrieval System (ASRS) and Automated Guided Vehicles (AGV)

Apart from the manipulators, other automations are utilized in material transportation, including ASRS and AGV (Figure 6). As wheelsets arrive at iWMC, the wheelsets' asset IDs are checked against the data in the PMS to match the corresponding maintenance processes. The wheelsets are then registered and admitted into the production line. At the start and end of the production process is the ASRS. The ASRS integrated with the PMS would automatically draw the wheelset from the storage rack through stacker crane to the production flow based on the maintenance process and receive the completed wheelset from the production flow. It provides crucial buffer storage before the transportation of the wheelsets out of iWMC, keeping the production flow at maximum capacity. Other benefits include providing high-density storage to increase capacity and flexible rearranging of the priority of the wheelsets.



Fig. 6 - AGV for Wheel Blank Handling

Due to the layout of the Ho Man Tin Maintenance Siding, two distinct automation areas have been established in iWMC: one for the wheelset and axle maintenance, and the other for new wheel blank preparation. These two

areas are separated by a main walkway. To transport wheel blanks between these two areas, the AGVs are employed, enabling a man-machine collaborative working environment. Each AGV supports loads of up to 1,500 kg and achieves accurate positioning by Simultaneous Localization and Mapping (SLAM) navigation, complemented by laser obstacle avoidance system for safety protection.

2.3 Internet of Things (IoT) Integrated Automated Testing and Maintenance Equipment

Other automated equipment developed for iWMC includes the Axle Cleaning Machine and Axle Paint Removal Machine, which completely automates cleaning and surface paint removal process of train axles featuring the use of 6-axis robotic arm, as well as the Wheelset Ultrasonic Testing Machine, which automates the ultrasonic test inspection process of wheelsets. Taking the edge computing approach, the data processing and decision-making of individual machines are performed at the machine programmable logic controller (PLC) level, more reliable results and lower latency in responses are attained. The operational parameters and passing criteria of the processes are also predefined, minimizing human error and maintaining data integrity. The machines in the system are equipped with numerous IoT sensors for tracking equipment status, maintenance results and workpiece locations, which are interfaced with the PMS, allowing the AMHS to generate the most optimal automatic materials transport according to best-matched parameters of axle and wheel blank, scheduled maintenance tasks, process flow and plant occupancies, with adaptability to different operation modes. Engineers could also track the production progress of workpieces and inventory status in real-time, and adjust operational plans, allowing iWMC to operate efficiently.

3. INTEGRATION THROUGH DIGITALIZED MANAGEMENT SYSTEM

The core of iWMC is its digital management systems: PMS, interfacing with SIS and ASRS, to perform the functions of Manufacturing Execution System (MES), Supervisory Control and Data Acquisition (SCADA) and field control. The PMS provides an integrated solution to manage all the maintenance activities within iWMC, incorporating the management, planning, monitoring, and control of production activities into a single platform. The production progress, asset life cycle data, equipment status and performance, inventory and workforce utilization are digitalized and gathered by PMS, enabling smart manufacturing.

3.1 Real-time Insights through PMS

Through adopting Industry 4.0 technologies, the PMS gathers the production data from individual machineries, including real-time status of maintenance tasks, component locations, wheelset inspection data for

control and operation, which are visualized on the system platform accessible within the local area network. Consequently, the PMS eliminates data silos, allowing consistent data sharing among the shopfloor operators, engineers and management, thus enhancing the collaboration.

With improved data visibility, engineers could closely monitor the maintenance quality, material availability, and arrange improved production planning, while reducing manual data entry and administrative work. This leads to streamlined workflows, reduced downtime due to unavailable supply and higher product quality. The system records complete maintenance history, including process steps, inspection results, and operator actions, allowing operator to analyse trends, performance indicators and supports evidence-based decisions for process improvements, ensuring life-long asset performance and also enables traceability in critical parameters to ensure compliance with safety and quality requirements throughout every stage of the process.

The PMS also monitors the availability, faults and alarms of the machines with prioritizations. The operators could instantly identify abnormalities and make quick adjustments to the production plans in response to equipment issues and carry out informed remedial actions. The operators could also be spontaneously dispatched for high urgency alerts, such as alarms on safety or processes critical to the production process, hence ensuring safety at all times and minimizing production downtime.

The data gathered also enables more sophisticated data analytics, such as Overall Equipment Effectiveness (OEE) and manpower utilizations. This allows engineers to identify patterns, trends, and anomalies and provide descriptive and diagnostic analytics for communications with managers. It further empowers agile responses to dynamic business needs, making resource allocation more efficient and cost-effective, reducing waste and enhancing process control.

3.2 Optimizing Throughput and Workflows with Digital Twins Technology

During the design and construction stage, Digital Twins Modelling was applied to optimize iWMC throughput capability and material handling workflows, which was reviewed against the IEC 62832 Digital Factory framework [4][5][6] to ensure its interoperability across platforms. Through simulation of production scenarios on digital twins, the project team designed different workflows, which significantly reduced time and resources spending on design verifications.

The project team was also able to identify the critical processes and manpower bottlenecks, as well as the machine utilization rate, leading to subsequent design enhancement. Examples of the findings included:

- (a) Distribution of personnel within the production line was arranged to optimize manpower efficiency based on staff occupancy (Figure 7).

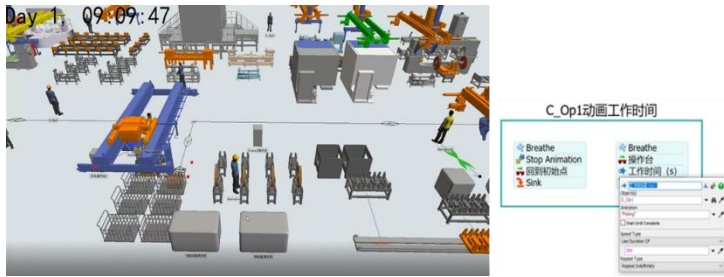


Fig. 7 - Simulation Results of Digital Twins Manpower

- (b) Based on the utilization rate, the current configuration of AGVs can meet the needs of the production process (Figure 8).

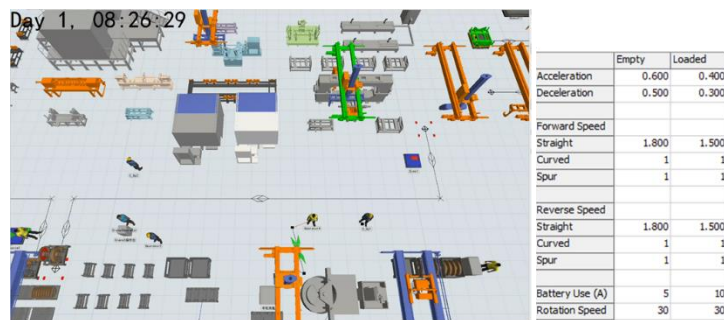


Fig. 8 - Simulation Results of Digital Twins on AGV

With Digital Twins Modelling, tasks priorities and resource allocations were adjusted to maximize overall effectiveness. Throughput capability and material handling workflows are optimized, with comprehensive safety measures in place.

4. CONTRIBUTION TO SMART SUSTAINABILITY

4.1 Optimization of Utilizing Resources

One of the key goals of developing iWMC is to optimize manpower requirements by streamlining the process of wheelset maintenance. As wheelset maintenance involves numerous heavy-duty, repeated manual work, adopting automated facilities enables continuous operation with less reliance on manual labour and consistent production quality. Upon steady operation, only 6 operators would be required for iWMC, saving 31 full-time equivalent headcounts. This enhancement shift allows our skilled workforce to be reassigned from repetitive manual labour to other professional tasks. A saving of around 14 to 17 million HKD per year is estimated. It also supports better resource utilization through precise control of materials, energy, and equipment, resulting in reduced waste and operating costs. The consistencies in iWMC operation would also lead to lower defect rates, which in turn reduce scrap,

rework, and the associated consumption of additional materials and energy.

4.2 Improvement of Occupational Health and Safety

Through adopting a high degree of automation and digitalized production management, iWMC minimizes the labour-intensive works, such as repeated polishing and cleaning of the axles. Through introducing ASRS, it reduces the need for heavy lifting operations. It immensely reduces the risk of occupational injuries, physical strain and fatigue, supporting better ergonomics and long-term worker wellbeing. The advanced automated systems are also equipped with sensors, safety interlocks, and real-time monitoring capabilities that detect abnormal conditions and trigger immediate shutdowns or alerts, helping to prevent incidents. A safer working environment is created, and staff are shifting from high-risk manual tasks to supervisory, control, and maintenance roles.

4.3 Business Sustainability

iWMC is estimated to achieve an annual throughput capability of 1,500 wheelsets, increasing by approximately two times the existing throughput. The completion of wheelset maintenance time is reduced from 3-4 working days to an average of 10 hours per wheelset. This allows sufficient throughput capability to meet current maintenance demands, as well as providing flexibility to support future railway expansion. Processes are more manageable with more predictable and reliable throughput quality, which enables better planning, reduced downtime and more stable maintenance output. Real-time production visibility also empowers agile responses to dynamic business demands. The consistency in quality, production resilience, and thereby business sustainability is enhanced.

5. PROJECT CHALLENGES, LEARNING AND ACHIEVEMENT

In the project, it was found that establishing a roadmap to harness Industry 4.0 technologies for transformation and compliance verification in automation systems has been one of the key challenges, as the system design required ongoing improvements to optimize performance and user experience. Early testing of the equipment and continuous engagement with internal stakeholders helped iWMC team identify potential issues, not only allowing the alignment of project goals but also strengthening partnership and collaboration through shared understanding of quality, maintenance, and documentation. The use of Digital Twins analytics has also further enhanced the processes and maintenance effectiveness.

The empowerment of staff with future-ready skills for automation excellence is a key focus for the project. Opportunities for staff developing new skill sets are being unlocked through seamless transition to iWMC

with significant deployment of new technologies. There has been continuous communication with users for enhancements based on feedback for early user buy-in, also allowing them to be familiarized with the new ideas and working environment.

The integrated Wheelset Maintenance Centre project was awarded the Bronze Medal in the 50th International Exhibition of Inventions Geneva in 2026, a testament to its significance in advancing smart maintenance development and optimizing wheelset maintenance processes within the railway industry.

6. CONCLUSION

iWMC marks a new chapter in railway asset maintenance through the integration of automation, digitalization, and smart manufacturing technologies as well as man-machine interface. By adopting advanced robotic systems, automated material handling, and digital production management, iWMC substantially increases maintenance throughput, reduces end-to-end processing time, and improves operational efficiency. The implementation of data-driven systems and digital twins modelling further enhances decision-making, resource optimization, and workflow coordination, enabling a more responsive and resilient maintenance operation.

Beyond operational improvements, iWMC delivers strong contributions to sustainability by reducing manpower requirements, lowering operational costs, and minimizing material waste through consistent and optimized processes. It also significantly enhances occupational health and safety by reducing exposure to labour-intensive tasks, fostering a safer and more ergonomic working environment.

Overall, iWMC establishes a forward-looking model for railway maintenance, supporting reliable service delivery while providing the scalability and flexibility needed to meet future demands. It serves as a key milestone in MTR's journey towards smart, sustainable, and innovation-driven asset management.

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Paper No. 8

**BRIDGING THE SEMANTICS-TO-ACTION GAP:
AN ARCHITECTURE FOR DEPLOYING AGENTIC AI FOR
SMART BUILDING FRAMEWORK AND EDUCATION**

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ABSTRACT

The Electrical and Mechanical Services Department (EMSD) of the Government of the Hong Kong Special Administrative Region (HKSAR) fulfils a tripartite mandate as a regulator, a service provider managing over one million electrical and mechanical (E&M) assets, and the administration's designated "Innovation Facilitator". To address the escalating operational complexity of facility management and urgent decarbonisation mandates, EMSD is driving a paradigm shift from E&M 2.0 to E&M 3.0.

While E&M 2.0 successfully achieved territory-wide data centralisation - streaming real-time operational data from hundreds of major government facilities to unified digital control centres - E&M 3.0 focuses on extracting actionable intelligence from this data repository using advanced artificial intelligence (AI). However, pervasive system heterogeneity across legacy E&M infrastructure remains a major barrier to scalable AI deployment. To overcome this barrier and advance trade practices, EMSD spearheaded the formulation of comprehensive standardisation frameworks. By issuing the Practice Notes for AI-ready Building Informatics, EMSD established robust guidelines governing data quality and semantic data modelling. This framework codifies complex engineering logic into machine-readable formats, bridging the gap between raw time-series telemetry and domain knowledge. Crucially, this standardised foundation is an essential prerequisite for deploying next-generation autonomous AI agents ("Agentic AI") in engineering operations.

By unifying the data ecosystem, EMSD enables both domain experts and digital systems to interact seamlessly with building informatics, optimizing energy efficiency and streamlining maintenance. This paper presents EMSD's strategic roadmap from data centralisation to intelligent value creation, highlighting how forward-looking policies and standardised informatics guidelines cultivate an AI-ready ecosystem that drives the E&M trade toward resilient, efficient, and sustainable operations.

1. INTRODUCTION

Under the Climate Action Plan 2050, Hong Kong has committed to achieving carbon neutrality before 2050, supported by an interim target to reduce carbon

emissions by 50% from 2005 levels by 2035 [1]. This aggressive timeline imposes extraordinary demands on the city's E&M infrastructure. Buildings account for approximately 90% of Hong Kong's total electricity consumption and the vast majority of its carbon footprint, with space cooling and air-conditioning alone driving roughly 30% of the citywide electrical load [2]. Without a fundamental step-change in how the engineering trade designs, commissions, and operates building services, these 2035 and 2050 decarbonisation mandates will remain unachievable.

EMSD holds a unique structural position in addressing this challenge. EMSD operates simultaneously as:

- (a) The technical regulator governing E&M safety and energy efficiency across Hong Kong;
- (b) A major service provider managing over one million E&M assets across more than 8,000 government premises [3]; and,
- (c) The designated "Innovation Facilitator" for the E&M trade of the Government of the HKSAR.

This tripartite mandate enables EMSD to act not merely as a regulatory policymaker, but as a large-scale lead user. By utilizing its expansive asset portfolio to develop, validate, and de-risk emerging technologies, EMSD translates operational know-how into actionable, industry-wide technical guidance.

Leveraging this institutional standing, EMSD has executed a phased digital transformation guided by successive Five-Year Strategic Plans. The inaugural phase (E&M 1.0) digitised internal workflows. The subsequent phase (E&M 2.0, launched in 2018 as "A New Journey") executed a territory-wide data centralisation initiative, streaming real-time operational data from hundreds of major government buildings into unified Regional Digital Control Centres [4][5]. The current iteration, "E&M 3.0 – Intelligent E&M", shifts focus from data aggregation to intelligent value creation, employing advanced artificial intelligence (AI) for predictive maintenance, energy optimization, and autonomous engineering operations [6].

However, the transition from E&M 2.0 to 3.0 has revealed a fundamental barrier that centralisation alone cannot resolve: the pervasive heterogeneity of legacy

and modern E&M systems. For example, two chiller plants in adjacent government facilities may monitor identical physical variables while employing incompatible point-naming conventions, fragmented equipment hierarchies, and inconsistent engineering units [7]. Consequently, AI models trained on one facility cannot be seamlessly ported to another, forcing engineers to manually re-encode domain knowledge for every deployment. Scaled across EMSD's multi-facility portfolio - and the broader Hong Kong building stock - this manual integration overhead becomes economically prohibitive.

To eliminate this barrier, EMSD exercised its dual capacity as regulator and innovation facilitator. In 2025, the Department published two pioneering Practice Notes for AI-ready Building Informatics, establishing standardised guidelines for data quality and semantic data modelling [8][9]. Designed as cross-industry reference standards rather than internal specifications, these Practice Notes aim to lower the threshold for AI adoption across the trade, empowering small and medium-sized enterprises (SMEs) to execute scalable decarbonisation retrofits.

This paper asserts that these Practice Notes are not merely auxiliary technical supplements to E&M 3.0, but rather its primary enabling foundation. Without standardised building informatics, portfolio-scale deployment of next-generation autonomous AI ("Agentic AI") remains impossible; with them, a new paradigm of intelligent building operation becomes achievable.

The remainder of this paper is structured as follows:

Section 2 traces the strategic digital roadmap from E&M 1.0 to 3.0;

Section 3 analyzes the system heterogeneity barrier;

Section 4 examines the technical architecture of the Practice Notes;

Section 5 demonstrates how this standardised foundation enables Agentic AI deployment; and,

Section 6 highlights broader industry implications and concludes.

2. FROM E&M 2.0 to E&M 3.0: THE STRATEGIC ROADMAP

Fundamentally, E&M 2.0 constituted an infrastructure-driven initiative underpinned by three signature technical platforms. First, the Building Information Modelling - Asset Management (BIM-AM) platform extended construction-stage BIM models into the Operations and Maintenance (O&M) phase by embedding as-installed asset metadata essential for lifecycle planning. Second, the Government-Wide IoT

Network (GWIN) established a secure, long-range telemetry backbone over which distributed E&M assets continuously streamed real-time operational data. Third, the Regional Digital Control Centres (RDCC) synthesized these data streams into unified operational dashboards organized around three functional modes: a daily operations mode for real-time equipment monitoring and alarm management, an energy management mode for portfolio-level performance benchmarking, and a disaster response mode for active telemetry monitoring of critical plant rooms during severe weather events [4][5].

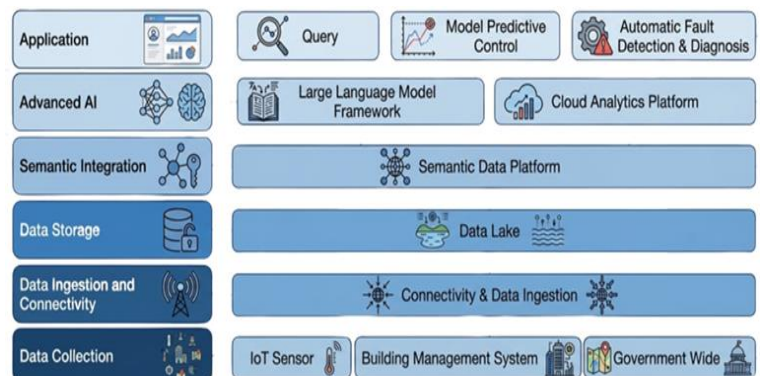


Fig. 1 - Multi-layer Architecture for Smart-City Data Integration

Figure 1 illustrates the multi-step pipeline of data collection, ingestion, semantic integration, advanced AI, and application execution that underpins the evolution of the Regional Digital Control Centres (RDCC) from an operations dashboard into the platform-of-record for portfolio-scale analytics. This framework situates the RDCC within EMSD's overarching multi-layer smart-city architecture. At the foundational level, the Data Collection Layer captures raw operational telemetry from IoT sensors, building management systems, and municipal feeds. The Connectivity and Ingestion Layer routes these signals into an enterprise data lake, above which the Semantic Integration Layer transforms unstructured telemetry points into machine-readable entities and topological relationships. The Advanced AI Layer fuses cloud computing resources with Large-Language-Model (LLM) frameworks to provide autonomous reasoning, while the top-level Application Layer exposes conversational interfaces, model-predictive control (MPC), and automated fault detection and diagnosis (AFDD). The RDCC serves as the primary operational gateway connecting the lower-stack data pipelines to upper-stack decision systems.

Although the initial RDCC architecture integrated baseline machine-learning models - such as localized chiller-plant optimization [10] - its primary milestone during E&M 2.0 was achieving territory-wide data centralisation across hundreds of government facilities. Building upon this consolidated repository, EMSD promulgated its third Five-Year Strategic Plan, "E&M 3.0 - Intelligent E&M", pivoting from data centralisation to intelligent value extraction [6].

Three overarching technical objectives define the E&M 3.0 agenda: (i) portfolio-wide AI energy optimization in support of the Climate Action Plan 2050; (ii) operationalisation of condition-based and predictive maintenance regimes; and (iii) integration of Agentic AI - autonomous systems capable of orchestrating multi-step engineering tasks [11]. Achieving these objectives across diverse facilities requires a seamless, standardised data ecosystem, bridging the integration gap through unified informatics standards.

3. THE HETEROGENEITY BARRIER

Hong Kong’s government building portfolio comprises thousands of premises commissioned across several decades by disparate design consultants and system integrators. Consequently, legacy Building Automation Systems (BAS) overwhelmingly reflect the proprietary point-naming conventions of individual control vendors rather than standardised schema [7][12]. In most cases, metadata is constrained to basic engineering units (e.g., °C, kPa) and generic BACnet object types. Thus, two physically identical chiller plants often expose mutually incompatible data models characterized by divergent naming taxonomies, fragmented equipment topologies, and inconsistent physical sensor aliasing.

While system heterogeneity is a globally recognized challenge in building energy management literature [12][13], Hong Kong’s hyper-dense urban topology, high space-cooling intensity, and accelerated 2035/2050 decarbonisation mandates make the operational cost of data fragmentation uniquely acute. The practical consequence is that domain logic - such as operational rule sets distinguishing normal system performance from thermal degradation, or mapping diagnostic codes to corrective actions - must be manually re-encoded for every building and AI deployment.

As documented in EMSD’s InnoCatalogue, developing AI applications across legacy building stock requires custom data mapping, where non-standardised naming and classification schema severely impede cross-facility model transferability and data integration [7]. Scaled across EMSD’s management mandate of over one million assets in more than 8,000 premises, this manual onboarding overhead renders portfolio-wide AI deployment economically unviable. Crucially, E&M 2.0’s data centralisation aggregated telemetry rather than semantic meaning. While time-series data streams can be centralized into visual dashboards, the underlying spatial and operational topology - such as the physical relationships linking a chilled-water pump to a specific Air Handling Unit (AHU), or an AHU to its served thermal zone - was rarely encoded in a standardised, machine-readable format. Modern LLMs and Agentic AI frameworks rely on this relational context to execute contextual reasoning across diverse built environments.

As summarized in Table 1, this heterogeneity barrier manifests across two primary dimensions.

Dimension	Architectural Barrier	Operational Impact on AI
Lexical Heterogeneity	Inconsistent point-naming conventions, vendor-specific abbreviations, and fragmented unit tags across legacy BAS setups.	Prevents automatic feature mapping; requires bespoke regex or manual translation tables per building.
Structural Heterogeneity	Absence of standardised physical, spatial, and functional relationships (equipment-to-equipment and equipment-to-zone topologies).	Blocks multi-system contextual reasoning, automated fault propagation analysis, and transfer learning.

Table 1 - Dual Dimensions of the E&M Heterogeneity

4. PRACTICE NOTES FOR AI-READY BUILDING INFORMATICS

EMSD’s dual position as regulator and “Innovation Facilitator” allows it to issue technical guidance that is more authoritative than vendor specifications yet more adaptive than rigid statutory codes. The two Practice Notes for AI-ready Building Informatics, published in 2025 and covering data quality and semantic modelling respectively, leverage this positioning to establish an accessible industry baseline that fosters trade co-development [8][9][11].

Three core design principles guide the Practice Notes:

- (a) Formalisation of Domain Knowledge: Translating domain engineering logic into standardised, machine-readable formats to preserve knowledge across software iterations.
- (b) Industry-Wide Scalability: Targeting the broader facility management ecosystem, including private sector owners and engineering contractors.
- (c) Global Interoperability: Harmonizing local guidelines with recognized international open ontologies rather than creating isolated, regional data schema.

4.1 Data Quality Specification

The Data Quality Practice Note addresses the foundational data ingestion tier. In practice, corrupted, intermittent, or incorrectly tagged telemetry - rather than model architecture - remains the primary bottleneck for building analytics [8].

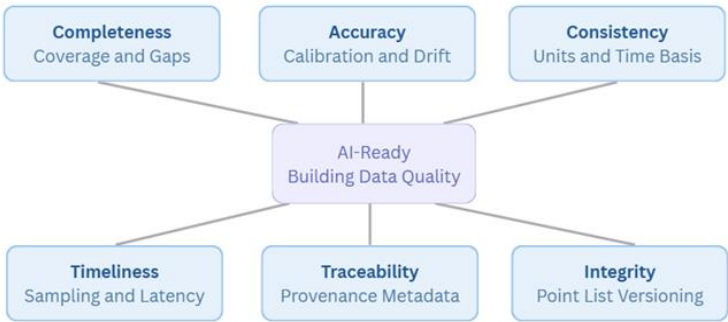


Fig. 2 - Six Dimensions of AI-Ready Building Data Quality

The Practice Note formalizes six canonical dimensions of data quality: Accuracy, Completeness, Consistency, Timeliness, Uniqueness, and Validity (Figure 2). By pairing each dimension with an auditable compliance artefact (such as automated schema validation scripts, physical sensor calibration certificates, and range-bound anomaly triggers), the Practice Note transforms abstract data quality requirements into enforceable contractual clauses for engineering procurement, commissioning checklists, and system acceptance tests.

4.2 Semantic Modelling

The Semantic Modelling Practice Note governs the semantic layer, codifying the functional relationships connecting telemetry points, physical plant equipment, and environmental zones. Where data quality resolves whether a telemetry value is accurate, semantic modelling defines the operational context of the measurement [9][14].

To support this standard, EMSD, alongside academic and research collaborators, deployed a dual-engine semantic platform. The architecture couples a graph database - representing building topology and asset metadata - with a specialized time-series database managing underlying sensor feeds [5]. Under this paradigm (Figure 3), operational entities and physical points are resolved via Semantic API path queries across the graph schema; the platform then uses these resolved relationships to ingest and retrieve correlated time-series telemetry. This hybrid graph-time-series pattern mirrors international best practices, confirming that a semantic knowledge-graph layer positioned above raw data streams is an essential prerequisite for scalable, portable AI deployment in built environments [14][15].

5. ENABLING AGENTIC AI IN ENGINEERING OPERATIONS

Conventional AI implementations in building services are predominantly analytical, generating descriptive or predictive outputs - such as fault probability scores, baseline deviation alerts, or energy forecasting curves - that necessitate manual engineering interpretation and execution. Agentic AI fundamentally shifts this paradigm toward autonomous operational execution. Under this framework, an autonomous engineering agent continuously perceives dynamic building states through semantic data platforms, formulates multi-step action plans, executes physical control adjustments via operational API tools, and iteratively updates its execution strategy based on feedback from the built environment [11].

This transition scales the primary unit of automation from isolated, site-specific analytical models to end-to-end engineering workflows. Table 2 details this architectural shift across five key operational dimensions.

As shown in Figure 4, the operational architecture of an engineering agent synthesizes four interconnected functional modules: a perception module that extracts structured topological entities and time-series telemetry from the semantic data platform; an LLM-based planner that decomposes high-level engineering directives into sequential sub-tasks and selects targeted tools for execution; a tool-execution layer that interfaces via RESTful APIs and control protocols with Building Management Systems (BMS), maintenance management tools, and digital twins; and a memory layer that logs execution traces, reasoning steps, and API

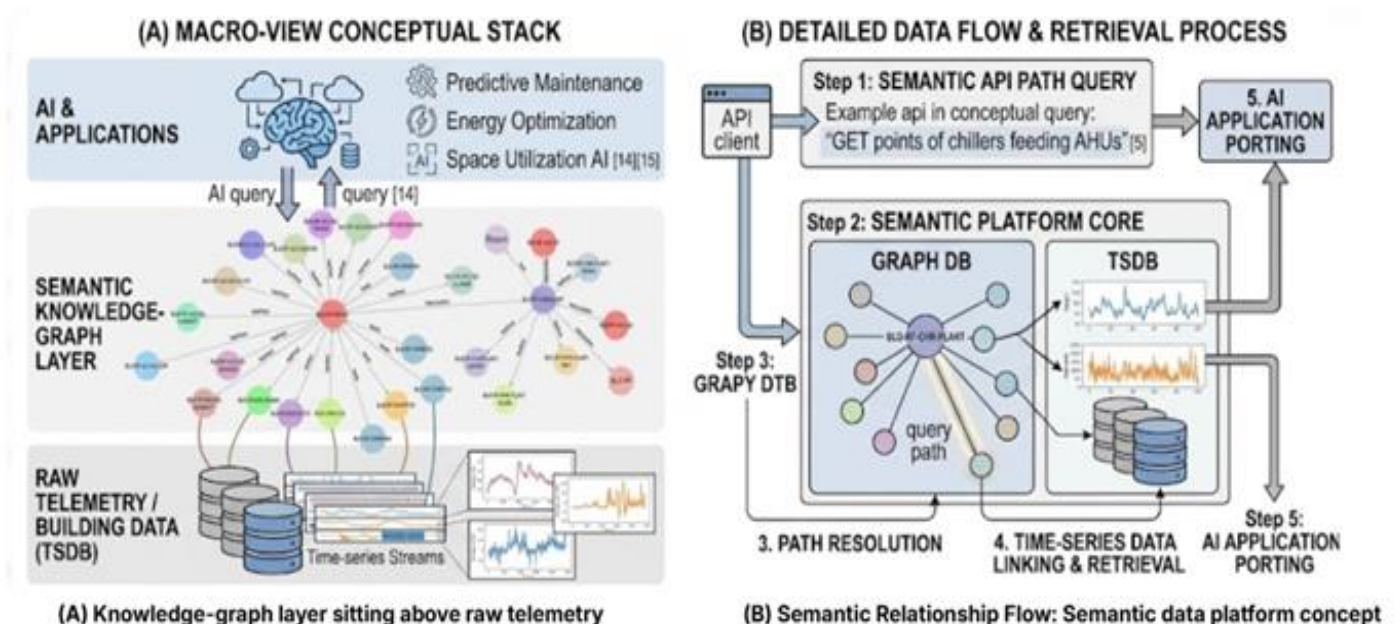


Fig. 3 - Integrated Semantic Architecture for AI Portability in Building Automation: Knowledge Graph and Data Retrieval Process

calls to enable contextual continuity and complete operational auditability.

Aspect	Conventional Analytical AI	Agentic AI
Output	Static metrics, fault predictions, and optimization curves requiring manual action.	Executable multi-step operational plans, direct control actions, and dynamic tool invocations.
Decision authority	Human-in-the-loop; system acts strictly as a decision-support advisory tool.	Human-on-the-loop or human-off-the-loop; autonomous execution bounded by safety guardrails.
Unit of automation	Isolated algorithmic models targeting specific tasks (e.g., chiller COP prediction).	Comprehensive, end-to-end engineering workflows (e.g., automated fault diagnosis and remediation).
Cross-building portability	Low; requires extensive site-specific retraining and manual point-remapping per building.	High; leverages standardised semantic graph queries for zero-shot cross-facility adaptation.
Auditability	Evaluated via model performance metrics	Evaluated via agentic reasoning logs, task execution traces, and auditable decision trees.

Table 2 - Paradigm Shift from Conventional Analytical AI to Agentic AI in Engineering Operations

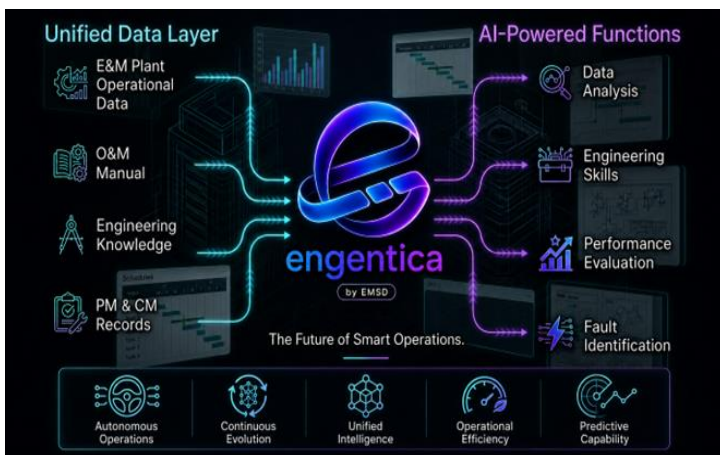


Fig. 4 - Functional Architecture of Engentica Operating Over the AI-Ready Semantic Foundation

Deploying this agentic pipeline at portfolio scale requires absolute schema alignment across all four modules. The semantic graph infrastructure established by EMSD's Practice Notes serves as this universal abstraction layer, providing the common data taxonomy necessary for autonomous agents to reason, plan, and act across diverse building assets.

The semantic layer provides the essential abstraction required for an autonomous agent to navigate a multi-facility portfolio without per-site customization. Grounded in a universal ontology, an agent can issue a single query - such as identifying chiller plants where the 30-day rolling approach temperature drifts beyond 1 °C above design threshold - and resolve that query across facilities with disparate point taxonomies. Operational reasoning is thus concentrated on thermodynamic analysis rather than point-mapping translation.

EMSD demonstrated an early field implementation, the E&M Agent, at the E&M I&T Day 2025 [11]. Built upon the layered smart-city data stack, the E&M Agent

operates directly against the standardised foundation specified by the Practice Notes. This sequential strategy-promulgating informatics standards as a prelude to agentic deployment - was designed to drive industry adoption of semantic AI across Hong Kong's building sector.

Three representative use-cases validate this architecture. First, portfolio-scale energy optimization targets space cooling - the dominant electrical load in Hong Kong [2][10]. Standardised semantic tagging makes chiller-plant optimization logic immediately portable across facilities, enabling an agent to monitor citywide performance, detect efficiency drift, and execute setpoint optimization. Second, predictive and condition-based maintenance correlates vibration, thermal, electrical, and run-hour signatures across asset cohorts. By linking operational telemetry with spatial topology, the agent infers failure criticality - escalating a chilled-water pump fault serving a hospital operating theatre differently from one serving an auxiliary storage space. Third, engineering knowledge assistance automates fault precedent matching, design compliance auditing, and commissioning report generation, with every claim fully traceable to underlying graph nodes.

Defensible autonomy is maintained through two primary governance mechanisms. First, every query, tool invocation, and reasoning trace is recorded as a structured event against the semantic graph to enable decision replay. Second, the agent operates within defined authority boundaries: read-only diagnostics execute autonomously, advisory setpoint changes require single-engineer confirmation, and direct control writes mandate dual-engineer authorization alongside automated safety-boundary checks against equipment design envelopes. Ultimately, this standardised foundation dramatically reduces the marginal cost of onboarding additional facilities, turning AI investment into a scalable multiplier for urban decarbonisation.

6. FIELD IMPLEMENTATION AND ENABLING AGENTIC AI IN EDUCATION

Achieving Hong Kong's Climate Action Plan 2050 mandates requires extending smart energy management beyond major commercial hubs into the long tail of municipal and educational building stock. School premises present a unique operational environment characterized by dynamic occupancy patterns, split-type air conditioning, and mixed ventilation systems. To evaluate cross-site AI model transferability and promote climate-tech literacy, EMSD deployed an AI-driven building informatics framework at Shau Kei Wan Secondary School, bridging operational energy efficiency with youth education.

Deploying advanced AI across decentralized premises historically faced high integration costs due to non-standardised equipment naming and missing semantic topology. Guided by the Practice Notes for AI-ready

Building Informatics, the school's environmental sensors, sub-meters, and HVAC assets were semantically mapped into a unified knowledge graph. By resolving raw telemetry into a machine-readable schema, the AI perception engine continuously ingests real-time time-series data - including ambient temperature, relative humidity, CO₂ concentration, and electrical power draw. Operating on closed-loop feedback, the model executes predictive setpoint adjustments and dynamic ventilation scheduling. This balances indoor thermal comfort and air quality against peak electrical load, reducing operational energy waste without requiring expensive, full-scale BMS overhauls. The deployment proves that standardised informatics drastically lower onboarding overhead, making advanced energy optimization economically viable for small-to-medium institutional facilities.

In line with EMSD's role as the government's "Innovation Facilitator", the technical installation was leveraged as an active educational platform for secondary students. Real-time building telemetry and semantic data models were integrated into an accessible dashboard, turning the school campus into an interactive "living laboratory".

Through structured workshops and interactive demonstrations, students explored core concepts of AI applications in building services engineering, including real-time sensor networks, semantic graph structures, and algorithmic energy management. By directly linking daily campus electricity consumption to algorithmic optimization, the initiative demonstrated how data science directly supports Hong Kong's decarbonisation goals.

7. DISCUSSION AND CONCLUSION

The most immediate economic deliverable of the Practice Notes for AI-ready Building Informatics is the systematic reduction of per-building integration overhead. Prior to standardisation, every building analytics deployment bore a heavy re-encoding cost to manually resolve vendor-proprietary taxonomies. By establishing a shared schema across the trade, integration engineering shifts focus from redundant data translation to site-specific operational tuning: equipment sequencing, supervisory control logic, and occupancy-driven setpoint strategies. Crucially, this lowers adoption barriers for SMEs managing the long tail of Hong Kong's building stock, allowing them to deliver advanced AI services previously restricted to major engineering consultancies.

Hong Kong's Climate Action Plan 2050 establishes aggressive targets, including a 30 - 40% reduction in commercial building electricity consumption relative to 2015 baselines, with roughly half of this reduction targeted by 2035 [1]. As the urban building stock ages, meeting these milestones through capital equipment replacement alone is unfeasible; continuous operational

optimization is mandatory. AI-ready Building Informatics provides the foundational architecture that renders operational decarbonisation continuously measurable, dynamically optimized, and auditable.

In summary, while E&M 2.0 achieved territory-wide data centralisation, E&M 3.0 executes semantic centralisation - transforming unstructured telemetry into a unified, machine-readable knowledge graph over which autonomous engineering agents can operate at portfolio scale. The Practice Notes for AI-ready Building Informatics constitute the primary institutional vehicle enabling this transition. As argued throughout this paper, standardisation is not an auxiliary administrative step, but the fundamental enabling precondition for scalable, AI-driven decarbonisation. By lowering deployment cost curves, unlocking the building stock's long tail to intelligent analytics, and fostering cross-border technical alignment, this framework provides a defensible roadmap toward resilient, highly efficient, and sustainable E&M operations.

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Paper No. 9

**SMART SUSTAINABILITY IN ACTION:
TRANSFORMING MUNICIPAL SOLID WASTE TO
RESILIENT ELECTRICAL POWER AT I·PARK1**

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SMART SUSTAINABILITY IN ACTION: TRANSFORMING MUNICIPAL SOLID WASTE TO RESILIENT ELECTRICAL POWER AT I-PARK1

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ABSTRACT

Integrated Waste Management Facilities (IWMF) Phase 1, publicly known as I-PARK1, is Hong Kong's first modern waste-to-energy facility for treating municipal solid waste. Developed on an artificial island near Shek Kwu Chau, the project combines marine waste reception, advanced moving-grate incineration, heat recovery, electricity generation, mechanical sorting, pollution control and environmental education into one integrated development.

I-PARK1 is designed for treating 3,000 tonnes of municipal solid waste per day and equipped with a mechanical sorting and recycling facility capable of processing up to 200 tonnes of municipal solid waste per day. The facility is designed to produce approximately 480 million kWh of surplus electricity annually for exporting to Hong Kong's power grid, sufficient for use by about 100,000 households. The project is also expected to reduce waste volume by about 90% and curtail approximately 440,000 tonnes of greenhouse-gas emissions per year.

1. BACKGROUND

In 2017, Keppel Seghers Hong Kong Limited (Keppel Seghers HK) and Zhen Hua Engineering Co. Ltd. (Zhen Hua) Joint Venture Partnership was awarded the contract to design, build and operate I-PARK1, by the Environmental Protection Department.

This Design-Build-Operate contract covers the reclamation of approximately 16 hectares, containerized waste reception facility, thermal incineration, mechanical sorting, pollution controls, process utilities, power generation and export, and a 15-year operating period.



Fig. 1 - Potential Site for Reclamation Identified near Shek Kwu Chau



Fig. 2 - Artist's Impression of I-PARK1

With no land access, no sufficient nearby labour catchment, no laydown area before reclamation and logistics governed by sea state and tide, the project faced multiple challenges which compelled non-conventional approaches. The major challenges are addressed in this paper.

2. I-PARK1 PROCESS

2.1 Introduction to I-PARK1's Waste-to-Energy (WtE) Solution

Municipal solid waste (MSW) is compacted into tightly sealed containers and transported by dedicated marine vessels from refuse transfer stations located at strategic locations around Hong Kong. These MSW containers are transported by marine vessels to the waste reception area in I-PARK1. Subsequently, the MSW is tipped into the waste bunker for storage and feeding. The waste bunker is maintained under sub-atmospheric pressure for odour control. Overhead waste cranes mix the waste to maintain homogeneity and thereafter feed the MSW into the incineration line.

The furnace, i.e. first portion of the incineration lines, are designed with Keppel Seghers' proprietary SIGMATRIX waste combustion technology, which combines the SIGMA combustion control and the MATRIX combustion grates into a fully integrated system with superior waste combustion and energy recovery. Byproducts from the incineration are processed, and heat is utilised for steam production.

The flue is processed via a Flue Gas Treatment System that meets stringent international emission standards. Fly ash from the flue gas treatment is solidified into granular modules, and loaded into sealed containers and

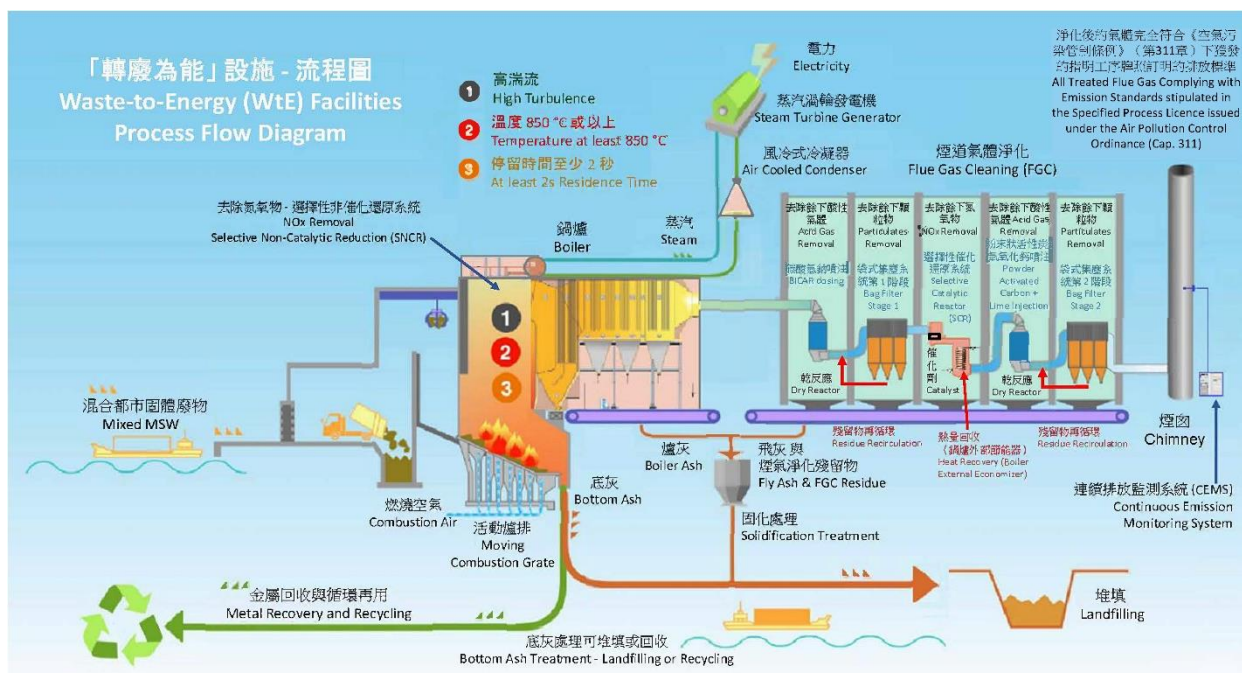


Fig. 3 - I-PARK1 Process-Flow Diagram

tested for compliance before being transported to dedicated landfills for disposal.

Superheated steam from the furnace boilers is directed to steam turbine generators, with sufficient capacity not only to generate power for inhouse consumers, but also surplus power that is exported to the grid and used by households around Hong Kong.

Robust and reliable technology is adopted to extract and shift bottom ash under the grate. The bottom ash comprises of metals and other solid residues from the combustion process. Metals are recovered from the ash for recycling, while remaining bottom ash is transported to landfill for disposal. Bottom ash has the potential to be reused as alternative resource, such as aggregates for the construction of roads. For this project, the bottom ash is handled by overhead ash cranes, packed into ash & residue containers, and currently transported to dedicated landfills.

2.2 Other Key Components of I-PARK1

Other plants work in tandem with the Waste-to-Energy (WtE) Plant elaborated above, these include the Mechanical Treatment Plant, the Water Treatment Plant and the Wastewater Treatment Plant.

The 200 tonnes per day Mechanical Treatment Plant refers to the mechanical sorting and recycling facility, which will make use of automatic waste sorting technology to recover useful resources, such as ferrous metal, non-ferrous metal, plastics and glass from MSW. The Water Treatment Plant is another key asset to I-PARK1, which sustains the artificial island's potable and non-potable water needs. The desalination system processes seawater for use, whilst the demineralization

system ensures the WtE is sustained with necessary boiler feedwater for steam production.

The Wastewater Treatment Plant is also adopted in I-PARK1 to treat the wastewater, both industrial wastewater from the systems in the facilities, as well as domestic sewage from personnel and visitors. In this project, a net zero wastewater discharge is adopted unless otherwise permitted.

The IWMF Substation is another key component in I-PARK1, forming the gateway for electricity transmission from this artificial island to the grid.

Systems and processes are housed within various extensively greened buildings to seamlessly blend the facility with its natural environment.

2.3 Overcoming Challenges

2.3.1 Waste as a fuel

MSW varies in moisture, inert fraction, particle size, volatile content and calorific value. These changes alter furnace temperature, oxygen demand, steam flow and turbine-generator loading. Bunker mixing, grate motion, primary- and secondary-air distribution, furnace thermal inertia and supervisory combustion control are therefore the first stages of electrical-output stabilisation. The proprietary SIGMATRIX addresses this.

2.3.2 Reducing the project schedule

Given the urgent needs for I-PARK1, creative solutions had to be thought through to yield a working facility in the least amount of time. This included an extensive modularisation strategy in which major waste-to-energy

plant modules were assembled off-site and transported by barge to the artificial island.

2.3.3 Interfacing with the grid

As with any grid operator, one of the primary objectives would be the capability to deliver a safe, and highly reliable power supply to end users. One of the parameters the facility had to fulfil was the limitation of fault current contribution into the grid. The I_s -limiter solution was adopted for this Project.

3. PROCESS ISLAND

3.1 Waste Reception and Combustion

Mixed municipal solid waste is a variable fuel. Moisture, inert content, particle size and calorific value influence drying, ignition, combustion-air demand and steam generation. Bunker mixing is the first stabilising measure. The feeding system then transfers waste through the chute onto the moving grate while limiting uncontrolled air entry into the furnace.



Fig. 4 - Typical Feeding-Grate Arrangement

The grate advances the waste through drying, ignition, main combustion and burnout. Primary air enters below the grate to support drying and bed combustion. Secondary air improves mixing above the bed and assists completion of gas-phase combustion.

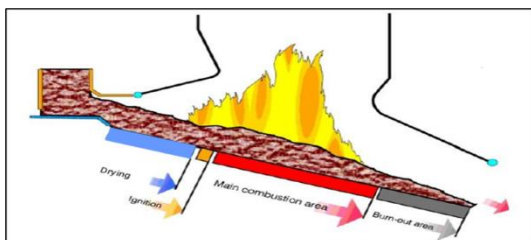


Fig. 5 - Combustion Zones

Grate speed, tumbling action, air flow and primary-air temperature must be well coordinated to maintain stable heat release and acceptable burnout.

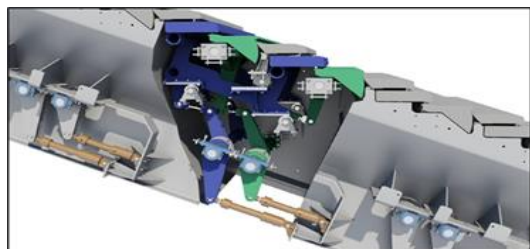


Fig. 6 - Cross Section of Keppel Seghers Moving Grate, Blue for Sliding, Green for Tumbling

3.2 SIGMATRIX Combustion Control

SIGMA is the automatic combustion-control system used to coordinate feeding-grate movement, combustion-grate movement, combustion-air supply and primary-air temperature. Its operating objective is for stable steam flow while maintaining waste throughput and burnout quality. MATRIX adds more localised correction across grate elements and lanes, including adjustments to primary-air distribution, sliding speed and tumbling activity. SIGMATRIX is a combination of these control philosophies.

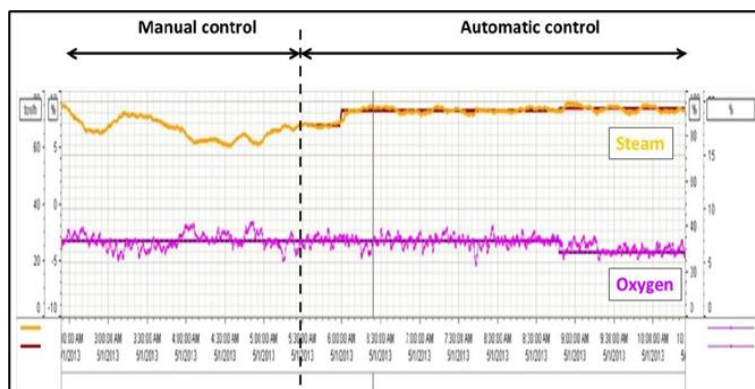


Fig. 7 - Comparison between Manual and Automated Combustion Control

3.3 Heat-Recovery Boiler

The heat-recovery boiler converts furnace heat into steam for consumers inclusive of Power Island. Radiant passes receive the highest-temperature flue gas, while downstream convective surfaces provide evaporation, superheating and economiser duty. Waste-to-energy boiler design must balance thermal efficiency against fouling, erosion and high-temperature corrosion. Tube-material selection, protective cladding, surface arrangement and effective online cleaning are therefore major design considerations.

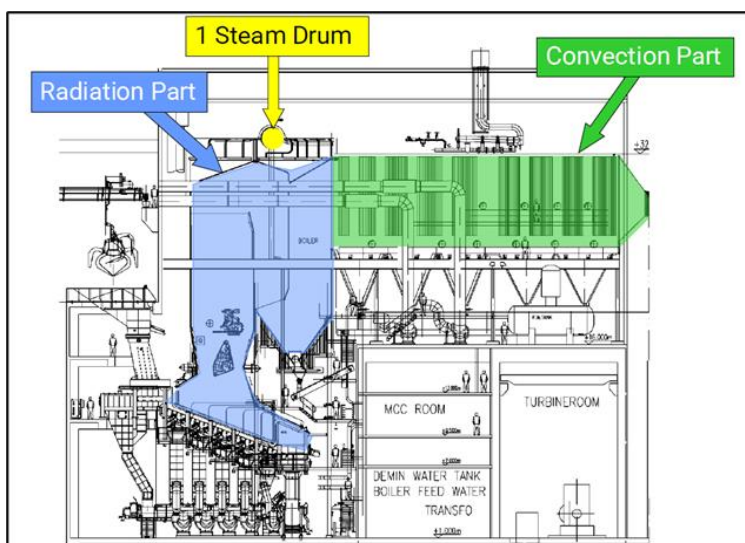


Fig. 8 - General Waste-to-Energy Boiler Arrangement

3.4 Flue-Gas Treatment, Residues and Utilities

I-PARK1 employs high-efficiency air-pollution-control systems to treat acidic gases, nitrogen oxides, particulates and other pollutants before discharge. An action level is set at below the applicable emission limits, allowing corrective action before a limit is reached. Monitoring stations at Shek Kwu Chau, Cheung Chau and South Lantau provide information on local air quality.

Bottom ash is collected after combustion, and ferrous metals are extracted for recovery. There are opportunities in treatment of bottom ash for other uses, which is something to be considered in future.

Treated wastewater is reused in plant processes, washdown and irrigation, supporting the net-zero wastewater discharge requirement.

4. POWER ISLAND

4.1 Steam and Condensate Cycle

The steam and condensate cycle is a continuous loop where the boiler turns water into superheated steam, which enters Power Island where it releases its heat energy, and then turns back into liquid water (i.e. condensate) at the condenser, and returns back to the boiler to be used again.

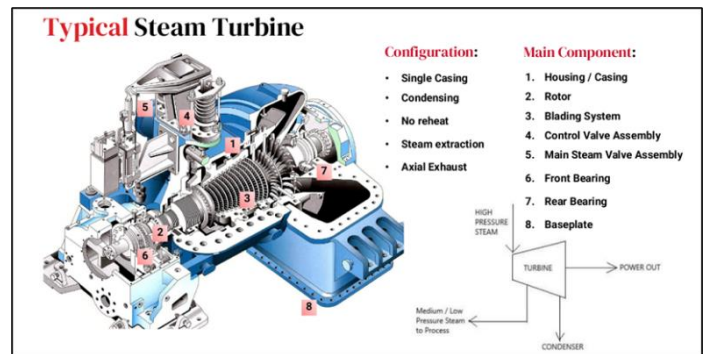


Fig. 10 - Typical Steam Turbine

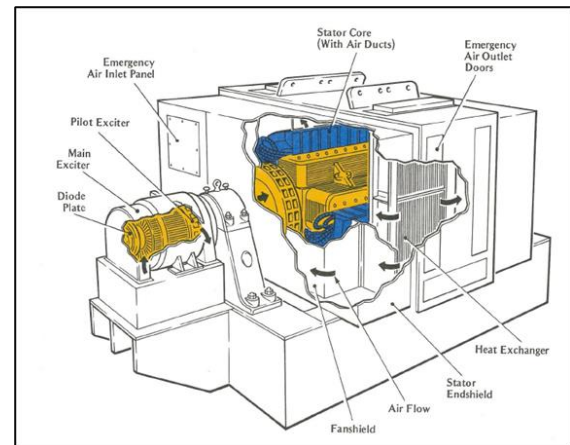


Fig. 11 - Typical Generator

4.3 Turbine Bypass Station

Working in tandem with the steam turbine is the turbine bypass station. Its function includes diverting of excess steam away from the steam turbine during startup, shutdown, or load changes for smooth operation. Precise valve control ensures safe plant operation and maintains system stability in various power plant conditions.

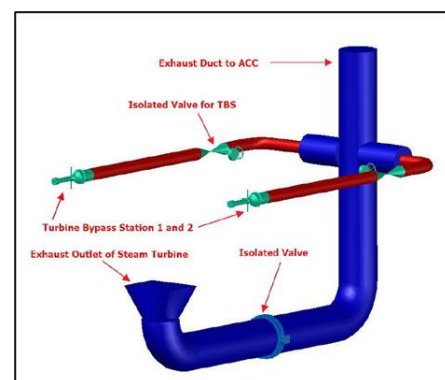


Fig. 12 - Typical Turbine-Bypass Arrangement and Principal Components

4.4 Condensation and Steam-Water Return

Exhaust steam is condensed in the air-cooled condenser. Vacuum equipment removes non-condensable gases, and condensate pumps return the recovered water through condensate heating and deaeration to the boiler-

Steam and Condensate Cycle

Scheme Diagram

- Main Steam Header
- Steam Turbine & Generator (STG)
- Turbine Bypass Station
- MP & LP PRDS
- Air Cooled Condenser (ACC)
- Condensate Tank
- Condensate Pump
- Cartridge Filter
- Condensate Preheater
- Secondary Condensate Tank
- Deaerator

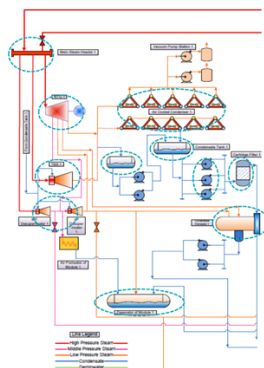


Fig. 9 - Typical Steam and Condensate Cycle

4.2 Steam Turbine Generator and Auxiliaries

Power Island receives superheated steam from the boilers and converts this thermal energy into mechanical energy via the steam turbine, and thereafter converts the energy into electricity via the shaft driven generator. This represents a typical steam turbine and generator system.

The turbine-generator package has auxiliaries which support its operation, which typically include lubrication and control oil, gland sealing, drains, cooling, excitation, neutral grounding, mechanical supervision and electrical protection. Supervisory instrumentation monitors speed, vibration and expansion, while the digital electro-hydraulic system controls steam admission.

feedwater pumps. This closed cycle preserves treated water and supports continuous steam generation.

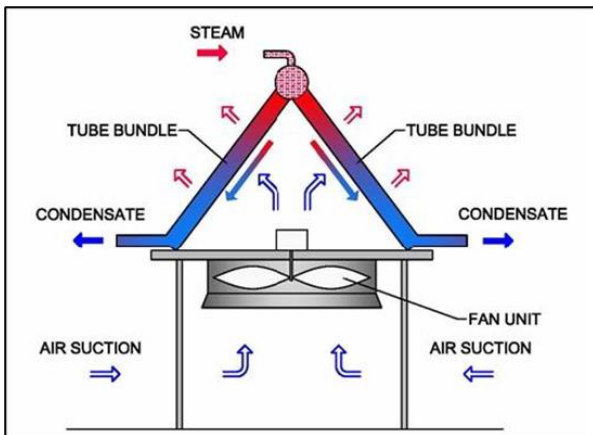


Fig. 13 - Typical Air-Cooled Condenser

4.5 Electrical Integration

4.5.1 Overall single line diagram

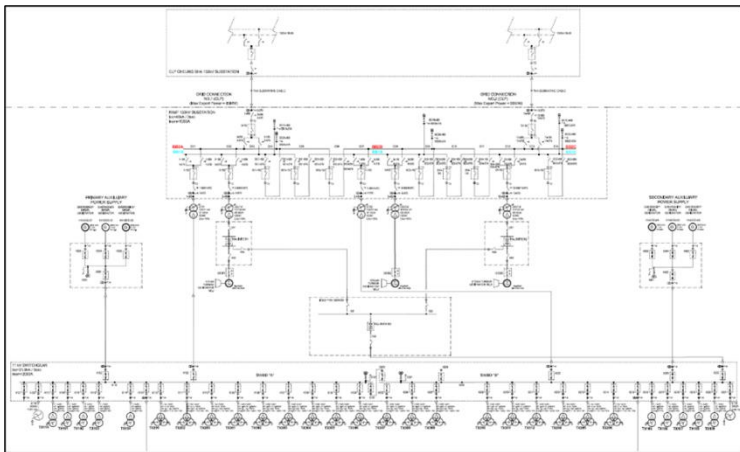


Fig. 14 - Overall Electrical Single-Line Diagram

Power is generated from the three 11kV steam turbine generators in the facility. Each of these steam turbine generators are connected to the 132kV switchgear via its dedicated 11/132kV generator step up transformer.

The 132kV switchgear adopts a double busbar configuration, with two outgoing feeders that interface to the Grid via submarine cables, and another two outgoing feeders for inhouse use via 132/11kV station transformers. Electricity transmitted via the submarine cables are received at the Cheung Sha Substation for distribution to various households and consumers in Hong Kong. 132kV switchgear and associated transformers are gas insulated.

At the 11kV level, the facility adopts one 11kV main switchboard, which distributes power to another dedicated 11kV berth switchboard, and the various low voltage switchboards. The 11kV main switchboard consists of four incomers, two of which are from 132/11kV station transformers, whilst the other two

from the auxiliary power supply systems (primary and secondary).

The auxiliary power supply systems consist of a primary set and a secondary set. Each of these sets consists of three 3,000 kVA 11kV diesel generators. Upon necessity, they will be brought into operation with appropriate synchronization to sustain the needs for safe shutdown and black start of the Facilities.

Downstream from the 11kV switchboards are the low voltage distribution, 660V and 380V, which are via step-down dry type transformers.

4.6 Electrical Operating Modes of the Facility

4.6.1 Normal operating mode

The Facilities are envisaged to be operating in this mode for most of their lifetime. In normal operation, the 132kV switchgear is supplied with power generated by the steam turbine generators. From here, there will be two pathways for the distribution of power, namely via the station transformers for in-house use, and via the submarine cables for exporting the surplus power to Hong Kong's grid.

4.6.2 Light load operating mode

This mode of operations is envisaged for periods where minimal or no transmission of power into Hong Kong's grid is indicated. In this scenario, the grid operator would be informing the Facilities in advance of certain periods of which restricted export is expected into the grid.

This mode of operation is to fulfil certain scenarios that the grid had envisaged periods, such as the Chinese New Year holidays and some exceptional occasions where power demand is low. Minimal power contribution from the Facilities is needed in this period.

4.6.3 Island mode operation

The primary objective of I-PARK1 is to support waste management of Hong Kong. In occasions where the Facilities are disconnected from the grid, inhouse consumers cannot be interrupted and must be sustained with power to continue operations. In this mode of operation, the generators will continue to supply in-house consumers with power, whilst disconnecting from the grid.

4.6.4 Safe shutdown operating mode

In the unlikely event that the facility's capability to sustain operations with its own power generation is suddenly interrupted, critical equipment such as operating incineration lines, etc., must be shut down in a safe manner. Power for these activities is provided via Primary and Secondary Auxiliary Power Supplies,

comprising of a set of three 11kV diesel generating units each. These diesel generators will automatically kick in upon detection of a dead bus at the 11kV switchboard, to sustain safe shutdown operations.

4.6.5 Black start mode

This is the mode required for facility start-up or following a complete shutdown of the facility. Both the Primary and Secondary Auxiliary Power Supplies are also relied upon during this mode of operation.

4.7 Uniqueness to the Project

4.7.1 Grid-connection protection and the I_s -limiter

Connecting multiple synchronous generators to the external grid increases the facility's potential contribution to fault current. For I-PARK1, key on grid prerequisite is to limit fault current contribution from the generator upon a fault at the grid. The challenge is not only to interrupt a fault, but to prevent the selected generator sources from contributing to the high first current peak that can impose significant mechanical and thermal stress on switchgear, transformers and cables.

An I_s -limiter solution was adopted as part of the project's fault-current-management strategy. The device combines a low-loss main conductor with a parallel high-rupturing-capacity fuse. When the measured current and its rate of rise indicate a severe fault, the main conductor opens and transfers the current into the fuse. The fuse then limits and interrupts the selected generator contribution before the prospective first peak fully develops. This differs from a conventional circuit breaker, which generally clears the fault after the current has already begun developing towards its peak.

The project arrangement applies I_s -limiters to selected generator feeders so that their fault-current contributions can be removed rapidly during qualifying external faults. The associated generator circuit breakers subsequently disconnect the affected generating units, while a defined remaining electrical path supports the facility's post-event operating condition. The protection concept thus addresses both fault-current limitation and the electrical configuration that remains after the I_s -limiter operates.

4.7.2 Independent redundant electrical system (IRES)

As the power from the steam turbine generators flow through the 132kV switchgear before it reaches inhouse consumers, there was also a concern on having to sustain operations in the unlikely event 132kV switchgears in its entirety is out of service. This project adopts a bypass route via an intermediate 11kV switchboard, IRES, used only when 132kV switchgear in its entirety is unavailable.

In this scenario, electricity flows from the generator to the generator circuit breaker, and to the I_s -limiter as

normal. The I_s -limiter has a branch that directs to the IRES, which directs electricity into the 11kV main switchboard.

5. TESTING & COMMISSIONING

The transition from mechanical completion to operational service is controlled through a structured programme of site acceptance tests, functional checks and grid-synchronisation activities. The sequence confirms that the turbine-generators, auxiliary systems, protection functions and grid interface operate together safely before sustained loading is permitted.

5.1 Pre-Start Verifications and Auxiliary Systems

Before steam is admitted to the turbine, the commissioning team verifies that the work area is secure, housekeeping is complete and firefighting provisions are available. Cooling-water systems, instrument and service air, fluid levels, drainage and other auxiliaries are checked against the approved operating requirements. Lubricating and control oil are verified for cleanliness and suitability, while electrical circuits are inspected for earthing, insulation integrity and correct termination. Automatic trips and safety interlocks are then functionally tested to confirm that identified abnormal conditions will initiate the required protective response.

5.2 Turbine Cold Start and Critical-Speed Management

A cold start is carried out progressively to control thermal stress and rotor vibration. Support systems, including cooling water, lubricating oil, turning gear, steam and condensate systems, are placed in service before steam admission. Steam lines and the turbine casing are warmed in a controlled manner to limit differential expansion and thermal shock. The turbine is initially starting up at a low speed, after which speed is increased in accordance with the designed start-up curve. Acceleration through identified critical-speed bands is managed without unnecessary dwell so that resonance and elevated vibration are avoided before the machine reaches a stable operating speed.

5.3 Dead-Bus Checks, Simulated Synchronization and Dummy-Load Testing

Before connection to the live network, dead-bus testing is used to verify electrical phasing, voltage-transformer circuits and synchronising logic. The 132 kV generator step-up transformer is energised in the approved configuration so that phase relationships between the generator terminal voltage transformers and the 132 kV voltage transformers can be confirmed.

Simulated synchronisation checks the coordinated response of the synchronising equipment, automatic voltage regulator and turbine governor without closing

onto the live grid. Recorded signals and breaker closing times are reviewed to confirm that the synchronising command is issued with the required lead time. Where provided by the approved test arrangement, resistive dummy-load testing at 11kV allows generator loading and load-rejection behaviour to be assessed before live on-grid operation. The load-rejection test is particularly important for confirming that the governor and steam-control system can contain the resulting overspeed transient.

5.4 Live-Grid Synchronization and Performance Demonstration

Following the required authorisation from the grid operator and completion of the prerequisite checks, the 132 kV submarine-cable circuit is placed in the approved condition and the generating unit is synchronised with the live grid. Grid-interface and dynamic-response tests may then be completed in accordance with the approved commissioning procedure, including the applicable loss-of-mains and power-system-stabiliser checks.

The unit load is raised in controlled stages, with key thermal, electrical and mechanical parameters monitored throughout. The commissioning sequence identified in the source material uses a manufacturer approved loading rate, with hold points at various stages before progressing to the full load test condition. At the full load, turbine and generator temperatures, vibration, steam conditions, electrical output and protection indications are logged. The site acceptance programme concludes with an uninterrupted eight-hour run at the specified full load condition to demonstrate sustained operation of the integrated power island.



Fig. 15 - Connecting to Grid (Left) & Commissioning of Power Island (Right)

5.5 Commissioning Evidence and Acceptance

The principal lesson is that successful synchronisation is not a stand-alone electrical milestone. Acceptance depends on evidence across the complete functional chain: auxiliary availability, oil cleanliness, turbine thermal condition, rotor vibration, governor response, excitation, synchronising circuits, generator and transformer protection, submarine-cable switching and stable steam supply. Test records should therefore preserve the sequence of conditions, alarms, interlocks,

trends and operator actions so that the demonstrated operating envelope can be traced and transferred into future operation and maintenance.

6. CONCLUSION

I·PARK1 represents a significant development in Hong Kong's treatment of municipal solid waste. The project combines large-scale thermal treatment, resource recovery, electricity generation, environmental controls and public education within an artificial island served by marine transport. Its modular delivery, offshore location and ecological measures demonstrate that essential infrastructure can also be designed as a viable environmental project.

I·PARK1 directly contributes to the "Zero Landfill" vision and carbon neutrality commitments in Hong Kong, as set out in the Waste Blueprint for Hong Kong 2035 and Hong Kong's Climate Action Plan 2050. More so than not, it is proof that when people come together, overwhelming challenges can be overcome, and incredible strides can be made.

Paper No. 10

**SOLUTIONS TO PREMATURE RETIREMENT OF
LITHIUM BATTERIES IN HIGH-DENSITY URBAN ENVIRONMENTS**

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ABSTRACT

Hong Kong is facing an escalating concern - crisis of massive premature retirement of high-capacity lithium-ion batteries. Sourced from disposed electric vehicles (EVs), commercial EV fleets, and Uninterruptible Power Supply (UPS) systems in data centres, these batteries are discarded far earlier than technically necessary - often retaining 70 - 80% of their original capacity. This trend is driven by manufacturer warranty gaps, aggressive price wars leading to production overcapacity, lack of cost-effective maintenance pathways, and inadequate regulatory support for second-life applications. The result is severe safety risks, resource waste, infrastructural strain, and missed economic opportunities in Hong Kong's hyper-dense urban setting.

At the same time, lithium-ion batteries are indispensable for supporting the power grid, enabling data-centre resilience, Battery Energy Storage Systems (BESS), replacement of diesel generators, and integration with photovoltaics and renewables. This creates a fundamental dilemma: greater deployment is needed for decarbonisation and resilience, yet it amplifies fire risks, rare-material dependency, and the growing problem of "battery cemeteries."

Fortunately, key industry players in Hong Kong have begun bridging large-scale EV battery disposal and recycling gaps while researching second-life applications before material recovery.

This paper presents a comprehensive, actionable framework that integrates advanced diagnostics, circular-economy strategies, safety technologies, smarter charging infrastructure, alternative chemistries, and targeted regulatory reforms. The goal is to extend battery lifecycles, safely repurpose retired units, promote "smarter use," and transform a growing liability into a strategic asset for urban energy resilience and green economic growth.

1. INTRODUCTION: THE PREMATURE RETIREMENT CRISIS AND THE LITHIUM DILEMMA

The transition to electrification in high-density environments such as Hong Kong has exposed a critical flaw in the battery lifecycle: premature retirement. High-

capacity lithium-ion batteries are entering the waste stream while still highly viable. Simultaneously, society is surrounding itself with these energy-dense devices - in vehicles, buildings, portable electronics, and emerging robotic systems - raising the spectre of living alongside potential "silent bombs" if thermal runaway risks are not rigorously managed.

1.1 The Dual Imperative: Benefits versus Risks

Lithium-ion batteries deliver essential benefits for urban power systems:

- Grid support and peak-shaving through stationary BESS;
- Resilience for data centres and critical infrastructure via UPS;
- Replacement of highly polluting diesel generators (e.g., at construction sites and temporary facilities);
- Synergy with distributed photovoltaics and other renewables to enhance power resilience;

Yet these same batteries present and future challenges: dependence on scarce raw materials (lithium, cobalt, nickel), the inherent fire risk of thermal runaway, and the rapid accumulation of premature-retired packs that create "battery cemeteries".

The rational path forward is not simply "use more" or "use less," but "smarter use" -maximising service life, enabling safe second-life applications, and reducing total battery mass through denser charging infrastructure.

1.2 Drivers of Premature Retirement

Several converging factors force viable batteries out of active service:

- **Manufacturer Warranty Gaps:** Expiration of OEM warranties without viable, cost-effective maintenance pathways leaves operators with little choice but to discard functional packs.
- **Market Economics:** Global price wars and manufacturing overcapacity make purchasing new units artificially cheaper than maintaining existing ones.
- **Regulatory Bottlenecks:** Insufficient frameworks fail to support or incentivise the safe, structured transition of reusable batteries into commercially effective second-life applications.



Fig. 1 - Linear vs Circular Battery Lifecycle

2. ENGINEERING SOLUTIONS: ADVANCED HEALTH DIAGNOSTICS

To combat premature retirement, the industry must shift from simplistic capacity tests and arbitrary warranty cut-offs to empirical, data-driven evaluations.

2.1 AI-Powered Electrochemical Impedance Spectroscopy (EIS)

The deployment of Artificial Intelligence-powered Electrochemical Impedance Spectroscopy (EIS) enables rapid, non-invasive “Health Checks”. This technology allows engineers to accurately assess:

- State of Health (SOH): Precise measurement of current capacity and internal resistance;
- Remaining Useful Life (RUL): Forecasting of operational runway before critical degradation;
- Hidden Safety Risks: Identification of internal micro-shorts and lithium plating that standard voltage checks miss.

By relying on this data, operators can confidently extend the service life of existing fleets and safely grade retired units for second-life use.

3. THE SAFETY-FIRST ECOSYSTEM AND SECOND-LIFE APPLICATIONS

Deploying second-life batteries in hyper-dense urban environments requires an uncompromising approach to fire-risk management through prevention, prediction, and protection.

3.1 The Prevention - Prediction - Protection Triad

- (a) Arc Fault Detection Devices (AFDD) - Prevention: Hardware-level protection to identify and isolate electrical arcing.
- (b) AI Monitoring - Prediction: Utilising advanced diagnostics to detect degradation before it leads to thermal events.

- (c) Thermal Management & Protocols - Protection: Physical and systemic fire-safety protocols tailored to urban constraints.

3.2 Validated Repurposing Pathways

Once safety is guaranteed, practical repurposing pathways suited to Hong Kong include:

- Data Centres: High-capacity UPS systems;
- Commercial Sites & Restaurants: Energy storage for peak-shaving and backup power;
- Construction Sites: Replacement of diesel generators with mobile battery storage;
- Grid Integration: Deployment in Vehicle-to-Grid (V2G) and Vehicle-to-Vehicle (V2V) networks.

4. SMARTER CHARGING INFRASTRUCTURE: REDUCING BATTERY MASS

An under-appreciated engineering lever is the expansion of convenient, high-density charging facilities. When charging points become ubiquitous - table-side chargers in restaurants, every parking space equipped for EVs - the need to carry large portable power banks or oversized vehicle batteries diminishes. Smaller battery packs mean lower material intensity, reduced fire load, and lower capital cost, while still delivering the required energy service. This “more chargers, smaller batteries” strategy complements second-life programmes and should be prioritised in urban planning.

5. ECONOMICS: REVERSE LOGISTICS AND CLOSING THE WARRANTY GAP

Technical viability must be matched with economic incentives to prevent viable batteries from being treated as waste.

5.1 The Hub-and-Spoke Reverse-Logistics Model

A localised hub-and-spoke reverse-logistics network enables efficient intake of retired batteries. Automated grading, powered by AI-EIS diagnostics, classifies packs into Grade A, B, or C for appropriate second-life or recycling pathways.



Fig. 2 - Hub-and-Spoke Reverse Logistics Flow

5.2 New Business Models and ESG Outcomes

To incentivise maintenance and refurbishment over premature scrapping, service-oriented models should be adopted:

- Energy Storage-as-a-Service (ESaaS): Leasing second-life batteries, lowering end-user capital expenditure;
- Data and Certification-as-a-Service: Monetising AI-certified health data.

These models close the warranty gap, create high-skilled green-collar jobs, drive GDP growth, and deliver robust Environmental, Social, and Governance (ESG) outcomes. ESG thinking further guides “smarter use”: encouraging battery deployment where it delivers clear system value while discouraging unnecessary proliferation.

6. ALTERNATIVE BATTERY CHEMISTRIES AND ENERGY-STORAGE MATERIALS

While lithium-ion technology currently dominates, a portfolio of alternative chemistries and non-battery storage options can reduce fire risk, material criticality, and long-term waste. Stakeholders across research, industry, and government are advancing these solutions. The comparison below summarises key attributes.

Technology	Cap. Cost	Fire Risk	Cycle Life	Efficiency	Key Advantage	Notes
Lead-acid	Low	Med-High	<350	70–80%	Low cost	Mature
Li-ion (generic)	Med-High	Medium	1,000+	90–95%	Energy density	Dominant
LFP (LiFePO ₄)	Medium	Low	2–5k	90–95%	Safety + life	Preferred stationary
NMC / NCA	Med-High	High	1–2k+	90–95%	High energy	EV dominant
LTO	High	Very Low	20–30k+	High	Ultra-safe long life	Premium
Sodium-ion	Medium	Low-Med	Improving	High	Abundant materials	Emerging
Flow batteries	High	Low	Very High	Medium	Long duration	Stationary
Solid-state	Very High	Very Low	Very High*	High*	Safety + density	*Emerging

Note: Rankings are relative. Exact figures vary by vendor, form factor, and application. Hydrogen and other chemical storage pathways also merit continued research as complementary or alternative long-duration solutions.

Table 1 - Comparative Overview of Battery and Storage Technologies

7. REGULATORY AND POLICY FRAMEWORKS

Systemic change requires HKSAR Government updates to legacy codes that reflect modern electrochemical realities. Recommended actions include:

- Building Code Updates: Revisions to EMSD and FSD regulations to safely accommodate secondary battery storage, aligned with the Waste Disposal

Ordinance (Cap. 354) and Chemical Waste regulations.

- Digital Battery Passports: Mandatory immutable, traceable records of lifecycle and health status via cost-effective IoT, blockchain, and AI analytics.
- Insurance Liability Models: Premiums and liability based on AI-certified health data rather than arbitrary age limits.
- Hardware Mandates: Consideration of AFDD installations for high-density stationary storage.
- Accountability & Reserve Funds: Clear ranking of responsibility across the supply chain for end-of-life management, with dedicated reserve funds to finance collection, grading, and safe disposal or reuse.

8. CALL FOR IMMEDIATE ACTION

The dual pressures of rising battery deployment and accumulating premature retirements demand coordinated, near-term action:

- Accelerate deployment of AI-EIS diagnostics and AFDD protection across fleets and stationary installations.
- Establish hub-and-spoke reverse-logistics capacity and Grade A/B/C certification schemes.
- Pilot Energy Storage-as-a-Service models with datacentres, commercial, and construction partners.
- Expand public and private charging infrastructure density to enable smaller battery packs.
- Advance regulatory reforms on battery passports, insurance, and second-life acceptance criteria.
- Invest in alternative chemistries (LFP, sodium-ion, LTO, flow, solid-state) and complementary storage pathways such as hydrogen to diversify the energy-storage portfolio and reduce rare-material dependency.

9. CONCLUSION

The premature retirement of lithium-ion batteries is a multifaceted problem that demands a multidisciplinary solution. By tackling the root technical, economic, infrastructural, and regulatory causes - and by embracing “smarter use” rather than unconstrained growth - this framework equips engineers, fleet operators, policymakers, and grid stakeholders with a practical roadmap.

Implementing these integrated solutions will allow Hong Kong to lead the region in converting an impending aged-battery crisis into a sustainable, high-value ecosystem that enhances urban energy security, reduces waste, mitigates fire-safety risks, and supports vital long-term decarbonisation goals.

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