THE HONG KONG
INSTITUTION OF ENGINEERS
ELECTRICAL DIVISION

The 43rd Annual Symposium
Thursday
23 October 2025

NEW QUALITY PRODUCTION FORCES IN ELECTRICAL ENGINEERING

Ballroom
Sheraton Hotel
Nathan Road
Kowloon
Hong Kong

SYMPOSIUM PROGRAMME

08.30 Registration and Coffee

09.00 Welcome Address
- Ir Tim CT Leung
  Chairman, Electrical Division, The HKIE

09.05 Opening Address
- Ir Alice KT Chow
  President
  The Hong Kong Institution of Engineers

09.20 Keynote Speech
- Dr. Lawrence CC Cheung
  Chief Technology Officer
  Hong Kong Productivity Council

1. Power Systems

09.50 The BVLOS Era: Reshaping Power Grid's Resilience and Reliability
- Ir Edward KS Chan
  Principal Manager - Logistics & Transport
- Mr. John LC Hung
  Business Support Manager
  CLP Power Hong Kong Limited

10.10 Engineering Demonstration of A Smart Microgrid for Source - Grid - Load - Storage Integration
- Dr. KK Gu, Deputy General Manager
- Professor R Gu, Researcher
- Professor X Zhang, Engineer
- Mr. YK Zhang, Engineer
- Mr. L Cao, Engineer
  Wuhan NARI Electrical New Materials Technology Centre
  Wuhan NARI Limited Liability Company
  State Grid Electric Power Research Institute

10.30 Enhancing Low Voltage System Safety, Sustainability and Power Resilience with Digital Electrification
- Ir Keith TM Wong, General Manager - Electrification & Automation
- Mr. Albert PH Leung, Senior Project Engineer
- Mr. Owen CP Woo, Project Engineer
- Ms. Christy KY Chan, Graduate Engineer
  Smart Infrastructure, Siemens Limited Hong Kong

10.50 Discussion

11.05 Coffee Break

2. Zero Carbon & Renewable

11.35 Zero Carbon EV Charging Infrastructure - A Smart Demand-Side Management Approach for Sustainable EV Integration
- Ir Professor Geoffrey L Chan
  Co-founder and Technical Director
  RadiansPlus Technologies Limited

11.55 Artificial Intelligence Based Automatic Fault Detection and Diagnosis for Photovoltaic Power Stations
- Dr. LW Zhang, Associate Professor
  South China University of Technology
- Ir Stanley KW Leung, General Manager
  GDEPRI Power Control Systems & Equipment (HK) Limited

12.15 Discussion

12.30 Lunch

3. ***AI Applications***

14.00 Empowering Engineers with AI: How EMSD's AI Agent Drives the New Quality Production Force

- Ir Patrick PM So, Senior E&M Engineer
- Mr. Morize KT Lau, E&M Engineer
- Mr. KF Leung, E&M Engineer
  Electrical and Mechanical Services Department
  The Government of the HKSAR
- Mr. Andy CY Tsang, Director
- Mr. Paul YH Tsoi, Data Scientist
  Capax Technology Limited

14.20 Building the Future: How AI Drives New Quality Production Forces in Railway Construction Delivery

- Mr. Auld Calum James
  Senior Engineering Manager
  MTR Corporation Limited

14.40 Making Your Electrical Switchboard AI Ready

- Mr. Cyrille Godinot, Product Owner
- Mr. Etienne Samain, Application Architect
- Mr. Kevin SH Hung, Power System Architect
- Ms. Jaya Mishra, Principal Technical Expert
  Schneider Electric Ltd.

15.00 Discussion

15.20 Coffee Break

4. Smart Technology

15.50 Smart Autonomous Development for Airfield Ground Lighting Maintenance in Hong Kong International Airport

- Ir Leslie KM Lee, Senior Manager, Airfield and Electronic Systems
- Ms. Pearl TP Ng, Manager, Electrical Services Maintenance
- Mr. Philip NM Chan, Assistant Engineer, Electrical & Mechanical Technical Services Systems Department, Airport Authority Hong Kong
- Ir David PK Leung, Senior Engineer/Airport Services
- Ir Vincent CW Ip, Engineer/Airport Services
  Electrical and Mechanical Services Department
  The Government of the HKSAR

16.10 Harnessing Big Data-Driven Pedestrian Traffic and Weather Insights for Smart Building Management

- Dr. Andrew HC Wu
  Lecturer
  Department of Electrical and Electronic Engineering
  University of Hong Kong

16.30 Discussion

16.45 Summing Up

- Ir Banson KC Lam
  Symposium Chairman
  Electrical Division, The HKIE

Closing Address

- Ir Dr. Wilton WT Fok
  Associate Dean (Student Enrichment)
  University of Hong Kong

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

Dr. Lawrence CC Cheung
Ir Dr. Wilton WT Fok
Ir Edward KS Chan
Mr. John LC Hung
Dr. KK Gu
Professor R Gu
Professor X Zhang
Mr. YK Zhang
Mr. L Cao
Ir Keith TM Wong
Mr. Albert PH Leung
Mr. Owen CP Woo
Ms. Christy KY Chan
Ir Professor Geoffrey L Chan
Dr. LW Zhang
Ir Stanley KW Leung
Ir Patrick PM So
Mr. Morize KT Lau
Mr. KF Leung
Mr. Andy CY Tsang
Mr. Paul YH Tsoi
Mr. Auld Calum James
Mr. Cyrille Godinot
Mr. Etienne Samain
Mr. Kevin SH Hung
Ms. Jaya Mishra
Ir Leslie KM Lee
Ms. Pearl TP Ng
Mr. Philip NM Chan
Ir David PK Leung
Ir Vincent CW Ip
Dr. Andrew HC Wu

Sponsors

Siemens Limited
CLP Power Hong Kong Limited
The Hongkong Electric Co. Limited
Dongguan Minxing Cables Co., Ltd.
GDEPRI Power Control Systems & Equipment (HK) Limited
The Jardine Engineering Corporation Limited
RadiansPlus Technologies Limited
Keystone Electric Wire & Cable Co. Limited
C&K Instrument (HK) Limited
Chat Horn Engineering Limited
Fed-Supremetech Limited
FSE Engineering Group Limited
Gammon E&M Limited
Green Energy Engineering Consultancy Limited
Greenland Engineering Co. Limited
Kum Shing Group
Mitsubishi Electric (Hong Kong) Limited
MTR Corporation Limited
Schneider Electric (Hong Kong) Limited
S.G.H. Electric Wire & Cable Co. Limited
SPL Lighting (Hong Kong) Co. Limited
TE Connectivity Hong Kong Limited
Hong Kong Electrical Contractors' Association Limited

43rd ANNUAL SYMPOSIUM ORGANIZING COMMITTEE

Symposium Chairman: **Ir Banson KC Lam**

Members:

Ir Tim CT Leung
Ir Ben CK Lam
Ir Andy KM Kwan
Ir Andrew KW Yan
Ir Dr. FC Chan
Ir Professor Henry SH Chung
Ir Hugo CY Chan
Ir Keith TM Wong
Ir Stanley KW Leung
Ir Ian YL Lee
Ir Vincent CT Leung
Ir Alex TH Fu
Ir TT Suen
Ir Eric MK Lun
Ir Raymond KM Sze
Ir Gloria CK Wong
Mr. Indi WF Wong

Hon. Secretary and Treasurer: **Ir YK Chu**

Paper No. 1

THE BVLOS ERA: RESHAPING POWER GRID'S RESILIENCE AND RELIABILITY

Authors/Speakers: Ir Edward KS Chan, Principal Manager - Logistics & Transport
Mr. John LC Hung, Business Support Manager
CLP Power Hong Kong Limited

THE BVLOS ERA: RESHAPING POWER GRID'S RESILIENCE AND RELIABILITY

Ir Edward KS Chan, Principal Manager - Logistics & Transport
Mr. John LC Hung, Business Support Manager
CLP Power Hong Kong Limited

ABSTRACT

CLP Power Hong Kong Limited (CLP Power) is advancing grid operations and supporting Hong Kong's emerging Low-altitude Economy (LAE) by incorporating Beyond Visual Line of Sight (BVLOS) drone technology into its inspection and maintenance of power facilities.

The company manages a vast network of over 17,000 kilometers, and overhead infrastructure is one of the major elements. This makes them more vulnerable to extreme weather conditions and environmental hazards, with external factors contributing to over 80% of voltage dips in recent years.

Through the Hong Kong SAR Government's LAE Regulatory Sandbox pilot project, CLP Power has commenced trials of BVLOS operations. This innovation allows drones to fly beyond the remote pilot's visual line of sight under controlled conditions. Trials conducted at selected locations, including 11kV distribution overhead lines and poles at Sai Wan in Sai Kung and 400kV transmission towers and overhead lines at Tai Mo Shan, have demonstrated significant enhancements in operational efficiency, situational awareness, and personnel safety. Initial results show that BVLOS drone operations have improved inspection efficiency by nearly four times, enabled earlier fault detection, and facilitated faster restoration works, ultimately enhancing the reliability of the power supply.

By integrating this advanced technology, CLP Power is not only modernizing its grid operations but also contributing to the development of Hong Kong's LAE while ensuring a reliable and resilient power supply for the community.

1. BACKGROUND

CLP Power has consistently invested in innovative technologies to enhance the performance and resilience of its power system. With extreme climate events becoming increasingly frequent and severe, the operational challenges faced by utilities have become more complex.

In Hong Kong, the convergence of mountainous terrain, dense urban corridors, and coastal exposure creates a particularly demanding environment. Some overhead lines and towers are situated at remote locations and are difficult to access. They are also more vulnerable to strong winds, heavy rain, and windborne debris.

Recognizing the potential of unmanned systems to address these challenges, CLP Power established its Small Unmanned Aircraft (SUA) team in 2018 to develop internal capabilities for aerial inspections. This team now comprises more than 60 professionally trained remote pilots, with over 20 holding Advanced Rating qualifications. Since its formation, the team has focused on training operators, developing standard operating procedures, and integrating aerial imagery into asset condition assessments. Starting with visual line of sight operations, the team has progressively advanced to more sophisticated capabilities, culminating in BVLOS operations.

Policy support has further accelerated the adoption of unmanned aircraft systems. In the 2024 Policy Address, the Hong Kong SAR Government introduced measures to promote LAE, recognizing the transformational potential of drones in enhancing public services and industrial efficiency. In alignment with this vision, CLP Power applied the first batch of LAE Regulatory Sandbox pilot projects.

CLP Power's proposal for BVLOS inspections was successfully selected, granting the company a controlled environment to test BVLOS operations on overhead lines and towers. This approval has allowed CLP Power to refine critical elements such as safety protocols, communication links, and data workflows.

2. THE CASE FOR BVLOS IN GRID OPERATIONS

The vast scale and diverse geography of CLP Power's network presents ongoing challenges for inspection and maintenance. Traditional ground patrols often require engineering staff to navigate rugged terrain on foot, limiting teams to inspect only around 5 kilometers per day. While helicopter patrols offer faster coverage in inspection, they are relatively costly and weather dependent. BVLOS operations transform this dynamic by decoupling a drone's range from the physical location of the pilot.

With validated communication and navigational systems, drones can fly extended routes over remote areas while streaming high-definition video, thermal imagery, and sensor data directly to control rooms in real-time. By monitoring asset health from a central facility, engineering staff can direct missions and make timely decisions in safe environments, especially during or after extreme weather events. This significantly improves safety and efficiency.

Sponsor of the proceedings: SIEMENS

This capability is particularly critical as external threats to grid reliability increase. CLP Power's transmission and distribution network consists of overhead lines that are exposed to environmental and external interference, including windborne debris, vegetation encroachment, lightning strikes, etc. These external factors have caused most recorded voltage dips in recent years.

BVLOS operations enable more frequent, standardized, and detailed inspections of these outdoor assets. Utilizing advanced imaging systems such as high-resolution cameras, infrared cameras, ultra-violet (UV) scanners, and light detection and ranging (LiDAR), drones can detect anomalies like hotspots, damaged insulators, frayed conductors, and vegetation interference before they escalate into potential faults or risks.

This shift from periodic, manually constrained inspections to high-frequency, data-rich patrols mark a significant advancement in CLP Power's operating model. By adopting predictive maintenance strategies powered by BVLOS technology, the company is building a more resilient and reliable grid.

3. PROGRAMME DESIGN & REGULATORY CONTEXT

CLP Power's BVLOS initiative operates within the LAE Regulatory Sandbox. This framework relaxes traditional restrictions, allowing BVLOS operations under controlled conditions to gather data on safety, reliability, and public benefit while gradually expanding the operational scope. CLP Power has adopted a carefully phased approach, starting with short, straightforward routes in relatively remote environments and progressing to longer, more complex missions.

Before deploying BVLOS operations, CLP Power conducted comprehensive route surveys using both helicopters and drones under visual-line-of-sight conditions. These surveys validated critical factors such as the mobile 5G network coverage, Global Positioning System (GPS) quality, and Global Navigation Satellite System (GNSS) signal strength. These preparatory steps ensured reliable command and control links, robust navigation, and the implementation of contingency measures, such as the fail-safe "Return to Home" function, to address any potential link degradation.

Safety management is the cornerstone of the entire programme. CLP Power has implemented detailed procedures for mission planning, airspace coordination, geofencing, and ground risk mitigation. Remote pilots and support staff undergo structured and professional training as well as competency assessments aligned with evolving regulatory standards to ensure operational excellence.

Clear communication protocols have been established to define roles and responsibilities among the team, manage escalation paths for potential anomalies, and conduct thorough post-flight debriefs to capture the lessons learned. To safeguard sensitive infrastructure information, data security measures include encryption of live video feeds and stored inspection records, alongside strict data access controls.

These efforts not only enhance inspection efficiency and grid reliability but also ensure that safety and data integrity remain at the forefront of innovation.

4. FIELD EXPERIENCE: SAI WAN & TAI MO SHAN

CLP Power's BVLOS pilot projects test advanced drone operations across four inspection routes that encompass both urban environments and sparsely populated terrain. A key milestone in this initiative was the installation of a fixed drone docking station on an 11kV distribution pole at Sai Wan (Figure 1). This installation followed an extensive site assessment to ensure safe technician access, stable power availability, and sufficient network connectivity for command links and data transmission. Also, meticulous logistics planning and staged work sequences were employed to minimize potential risks during installation.

The fixed docking station enables automated drone launching, landing, and charging, eliminating the need to dispatch field crews to the site for every inspection mission. This automation facilitates both scheduled and on-demand inspections, resulting in faster response time, more consistent data capture, and more effective utilization of resources.

Fig. 1 - A Drone Docking System installed in a 11kV Distribution Pole at Sai Wan

At the Tai Mo Shan routes, the programme conducted a range of mission types, including normal inspections, simulated emergency scenarios, and flights utilizing heavy or oversized SUA. These trials assessed the balance between payload capacity and endurance, while providing critical data on coverage rates, data quality, and operational reliability under diverse terrain and microclimate conditions.

The trials also validated the end-to-end data workflow, transmitting from onboard capture to CLP Power's smart management system - Grid-Visualisation (Grid-V). This facilitates future system integration to enable anomaly detection and equipment monitoring through Grid-V, enhancing the efficiency and responsiveness to potential hazards.

5. TECHNOLOGY STACK AND DATA PIPELINE

CLP Power's BVLOS operations leverage a carefully integrated suite of airframes, payloads, communications, and analytics to ensure precision, reliability, and efficiency. Drones are equipped with redundant communication links to maintain connectivity even across challenging terrain, while onboard autonomy and GNSS navigation enable precise waypoint tracking and smooth recovery in case of signal degradation.

The payloads deployed on these drones are designed to deliver a multimodal view of asset conditions, offering richer and more objective insights than traditional visual inspections. High-resolution cameras are used for detailed structural assessments, thermal cameras are also adapted to detect hotspots that may signal equipment stress or failure, UV scanners identify partial discharges (Figure 2), and LiDAR provides three-dimensional mapping of structures and surrounding vegetation. These advanced sensors work together to deliver comprehensive data, enabling a deeper understanding of asset conditions.

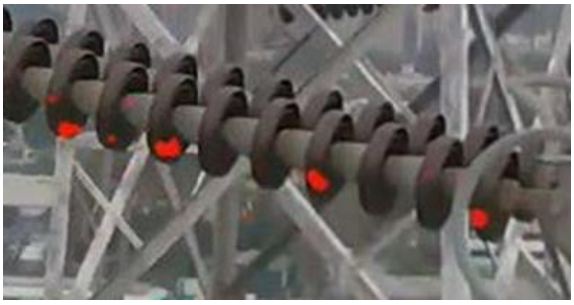


Fig. 2 - UV Scanner detecting Partial Discharge at Insulator Discs (Illustration Photo)

Equally critical is the management of such data. Video streams and sensor outputs are securely transmitted to Grid-V (Figure 3) for further analysis. Standardized, time-stamped, and georeferenced data models will support monitoring the asset and identifying the potential hazards with clear geographic details. Artificial Intelligence (AI) tools will be trained to detect condition issues, correlate with location-based information and trigger notification to engineers for follow-up actions. This reduces the time required for manual review of videos and thus enhances responsiveness to potential hazards.

Fig. 3 - CLP Power's Grid Visualisation (Grid-V) Control Centre for monitoring Critical Assets

6. OPERATIONAL BENEFITS & MEASURED OUTCOMES

The introduction of BVLOS drone operations by CLP Power is delivering substantial enhancement in performance, reliability, and safety. Traditionally, engineering staff inspecting remote corridors on foot could only cover 5 kilometres per day, making it difficult to maintain frequent inspections across the network. In contrast, drones can rapidly survey long spans of overhead lines and transmission towers, delivering consistent, high-quality imagery regardless of difficult ground access. Within the Regulatory Sandbox framework, CLP Power anticipates nearly a fourfold improvement in inspection efficiency for these assets.

This dramatic efficiency gain not only reduces inspection timelines but also enables more frequent inspections, thereby increasing the likelihood of detecting early-stage defects.

The reliability benefits of BVLOS technology are especially pronounced during and after extreme weather events like super typhoons and heavy rainstorms. When roads are blocked by landslides or fallen trees, drones can swiftly assess damage footprints, providing real-time aerial feeds that enhance situational awareness. This information supports precise triage and resource allocation, accelerating repairs and minimizing potential customer impact.

Equally significant are the safety improvements enabled by the programme. By allowing engineers to manage drone missions from safe, centralized locations, the risk of exposure to hazards such as heights, energized equipment, unstable terrain, and severe weather is significantly reduced. Additionally, replacing portions of helicopter patrols with unmanned drone flights further reduces operational costs.

7. RISK, SAFETY & COMPLIANCE

Operating BVLOS drones introduces new categories of risk, which CLP Power systematically manages through a robust, multilayered approach. This strategy ensures safety, regulatory compliance, and operational reliability while enabling continuous enhancement in drone operations.

Route design is carefully planned to minimize risks to both airspace and ground environments, while predefined geofences confine drone operations to safe corridors. Detect-and-avoid (DAA) procedures are implemented in alignment with sandbox parameters to ensure compliance with the Civil Aviation Department (CAD) standards. On the ground, stakeholder notifications and buffer zones are adopted to mitigate risks to people and property near flight paths.

Cybersecurity is a critical component of risk management. Command links and data at rest are protected through robust encryption measures, while audit trails and role-based access controls maintain accountability and prevent unauthorized access to sensitive data.

Continuous improvement is embedded in the BVLOS programme. For each test route, trial reports are submitted to the CAD, detailing objectives, flight data, identified issues, and lessons learned. This feedback loop facilitates update to procedures, training modules, and system configurations, ensuring that the programme evolves based on real-world experience.

Ongoing coordination with the CAD helps validate risk controls and ensure regulatory compliance, while also providing insights that guide approvals for future operational expansions. Progress is measured using defined performance metrics, including mission success rate, link availability, and report turnaround time. These metrics allow CLP Power to verify that procedural and technical changes deliver measurable benefits and enhance overall programme performance.

By proactively managing risks and fostering a culture of continuous learning, CLP Power is setting a strong foundation for safe and scalable BVLOS operations, enabling the company to unlock the full potential of drone technology in power grid management.

8. ROADMAP FOR SCALING

In the near term, the company plans to explore broadening route coverage and deploying additional docking stations in strategic locations to enable more widespread automated operations. These docking stations will support scheduled and on-demand inspections, reducing the need for dispatching field crews on site and enhancing response times. Simultaneously, AI models for defect detection will be refined as the dataset of labeled anomalies grows. Integrations with asset and outage management systems will also deepen, ensuring that actionable insights seamlessly inform work planning and execution.

Over the medium term, semi-autonomous mission planning will be explored to reduce the workload on human operators. This will allow drones to plan and execute missions with minimal intervention, increasing efficiency and scalability. Automated creation of maintenance tickets will further streamline operations, shortening the cycle from abnormality detection to repair and ensuring faster resolution of potential issues.
In the longer term, CLP Power sees significant potential in LAE development, envisioning coordinated fleet operations, where multiple drones operate synchronously across vast corridors. This capability will enable parallel inspections and persistent coverage during major events, such as extreme weather, with all operations managed from a central command platform. As drone autonomy continues to mature, drones will adapt flight paths in real-time based on detected conditions, enhancing both operational efficiency and network resilience.

9. CONCLUSION

BVLOS drone technology is revolutionizing how CLP Power monitors, maintains, and manages its power grid.

Early results from pilot projects at Sai Wan and Tai Mo Shan demonstrate that BVLOS operations can deliver significant enhancement in operational efficiency, reliability, and safety. These benefits are particularly evident during extreme weather events, where rapid assessments and real-time aerial insights enhance response times and minimize potential risk and impact.

Paper No. 2

ENGINEERING DEMONSTRATION OF A SMART MICROGRID FOR SOURCE - GRID - LOAD - STORAGE INTEGRATION

Authors/Speakers: Dr. KK Gu, Deputy General Manager
Professor R Gu, Researcher
Professor X Zhang, Engineer
Mr. YK Zhang, Engineer
Mr. L Cao, Engineer
Wuhan NARI Electrical New Materials Technology Centre
Wuhan NARI Limited Liability Company
State Grid Electric Power Research Institute

ENGINEERING DEMONSTRATION OF A SMART MICROGRID FOR SOURCE - GRID - LOAD - STORAGE INTEGRATION

Dr. KK Gu, Deputy General Manager
Professor R Gu, Researcher
Professor X Zhang, Engineer
Mr. YK Zhang, Engineer
Mr. L Cao, Engineer
Wuhan NARI Electrical New Materials Technology Centre
Wuhan NARI Limited Liability Company
State Grid Electric Power Research Institute

ABSTRACT

In the global context of proactive climate action and accelerated energy transition, building a clean, low-carbon, safe, and efficient energy system has become a consensus. With rapid advancements in renewable energy technologies, distributed energy sources now account for an increasing proportion in the energy supply structure [1][2]. However, the inherent volatility and intermittency of renewable energy pose significant challenges to the stable operation and effective integration of traditional power grids. Against this backdrop, the “source - grid - load - storage” integrated concept has emerged [3]. By deeply integrating and synergistically optimizing four key components - energy production (source), grid transmission (network), energy consumption (load), and energy storage (storage) - this approach leverages advanced intelligent control technologies and multi-energy complementary strategies to achieve efficient coordination across the entire energy process. This significantly enhances the stability and flexibility of energy systems, establishing it as a crucial pathway for constructing next-generation power systems [4].

As a key energy-consuming sector, the hotel industry is characterized by diverse energy demands and significant peak-valley load variations. Traditional hotel energy supply models not only incur high costs but also have substantial environmental impacts. Wuhan NARI Limited Liability Company of State Grid Electric Power Research Institute, actively responding to green development initiatives, pioneered the implementation of a “source-grid-load-storage” smart microgrid demonstration project at a hotel. The successful execution of this initiative has not only effectively reduced operational costs and carbon emissions but also provided an innovative model for energy management in the hospitality industry. This achievement holds significant practical implications for promoting regional energy structure optimization and sustainable development.

1. PROJECT BACKGROUND & OBJECTIVES

The project is located in a garden-style hotel integrating accommodation, catering, conference, entertainment and other functions. However, the daily operation of the hotel is accompanied by huge and complex energy consumption. Under the traditional energy supply mode, high electricity costs and potential environmental impact have become important issues for the sustainable development of the hotel.

To reduce operational costs, improve energy efficiency, and implement green development concepts, the hotel commissioned our company to execute a smart microgrid demonstration project integrating “source - grid - load - storage” systems. This initiative serves dual purposes: Firstly, it enables the hotel to fully utilize abundant local renewable energy resources, thereby reducing reliance on traditional fossil fuels, lowering carbon emissions, and fulfilling corporate social responsibility. Secondly, by establishing an autonomous energy management system, the hotel can better manage energy price fluctuations, enhance supply stability and reliability, and strengthen its market competitiveness [5].

2. RESEARCH ON CORE DEVICE OF THE PROJECT

2.1 Full Power Flexible Interconnection Device

The full-power flexible interconnected device, centred around fully controlled power electronic components, achieves bidirectional full-power conversion between AC and DC as well as across different voltage levels through AC/DC and DC/DC converter stages [6], as illustrated in Figure 1.

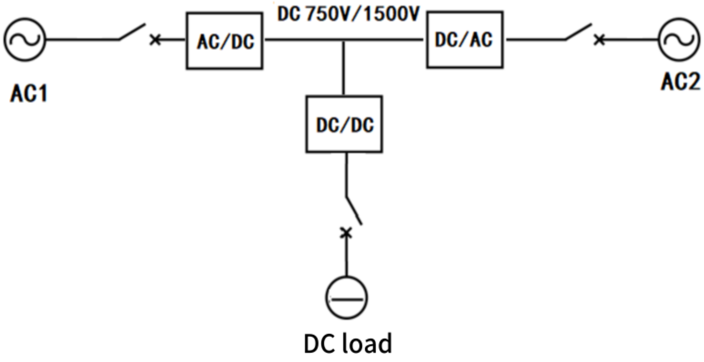


Fig. 1 - Topology of Full-power Flexible Interconnection Device

This device serves as a critical component in the energy internet's transition from "unidirectional power supply" to "bidirectional interaction". By utilizing fully controlled AC/DC bidirectional converters, the system connects two AC power sources through an internal DC bus, enabling zoned interconnection of AC grids and enhancing grid stability and operational flexibility.

2.2 Intensive AC Flexible Interconnection Device

The integrated AC flexible interconnection device operates on a back-to-back flexible AC/DC hybrid topology. While retaining the DC interconnection channel controlled by parallel control units, it introduces an additional AC interconnection channel managed by series control units. This configuration enables two AC power sources to be interconnected through both AC and DC channels, as illustrated in Figure 2. The system comprises two AC ports and one DC port. Core components include the Parallel Current Control Unit (PCM), Series Current Control Unit (SCM), Bypass Circuit (CRM), and Series Inverter (SIT). The SCM and SIT regulate voltage phase and amplitude across transformer terminals to achieve power flow adjustment between AC ports. The parallel current inverter control module (PCM) facilitates power flow conversion between AC and DC systems. The Bypass Current Limiting Unit (CRM) provides comprehensive protection for the entire system, ensuring uninterrupted power supply.

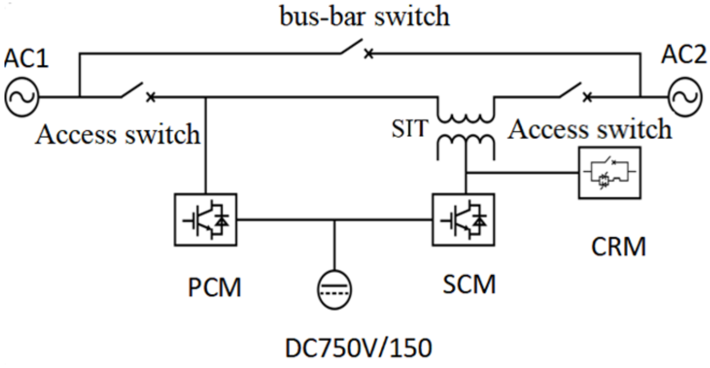


Fig. 2 - Topology of Intensive AC Flexible Interconnection Devices

3. PROJECT CONTENT

3.1 Construction Content

The project employs flexible interconnection technology to achieve flexible interconnection between the public transformer - 1, distribution transformer - 2, and distribution transformer - 3. By utilizing AC/DC interconnection networking and coordinated control technology, it fully utilizes existing transformer capacity resources to enable local photovoltaic power consumption, significantly enhancing the power supply reliability of the transformer district. The primary architecture diagram is shown in Figure 3, where boxes represent two flexible interconnection devices. Flexible Interconnection Device - 1 achieves flexible interconnection between the public transformer - 1 and distribution transformer - 2, featuring a built-in 750V DC bus with two DC ports configured for 67kW energy storage batteries and 280.5kW photovoltaic systems. Flexible Interconnection Device - 2 achieves flexible interconnection between the distribution transformer - 2 and distribution transformer - 3.

Under load conditions, the three transformers are configured as follows: The public transformer - 1 serves critical loads including the Chinese restaurant, guest reception building, and administrative office building. The distribution transformer - 2 handles load from the NIO battery swap station and eight 80kW DC charging piles. The distribution transformer - 3 manages eight 80kW DC charging piles along with residential loads.

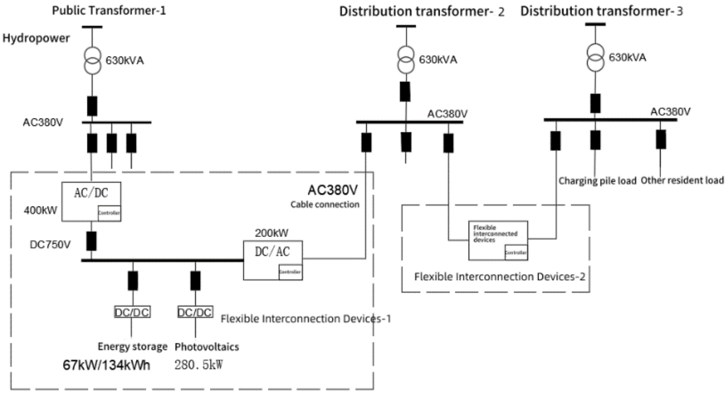


Fig. 3 - Three Transformers under Load

3.2 Control System Scheme

3.2.1 System architecture

The system architecture is divided into three layers: main station, converged terminal and terminal device.

Flexible interconnection modules are deployed on the main station layer, which mainly monitor data, issue policy control and manage operation of the power distribution station area where flexible interconnection devices are installed.

The flexible interconnection terminal integrates with the distribution layer to collect voltage, current, power, and switch status data within its substation area. It monitors and controls flexible interconnection devices while exchanging information via fibre optic cables with adjacent substations. This system enables centralized control of low-voltage DC flexible interconnection control strategies at the station control layer, while maintaining communication with the main substation.

The terminal device layer deploys flexible interconnection devices, consisting of low-voltage AC/DC flexible interface devices, local coordination control devices, and DC power distribution ports (optional as required). These components enable data acquisition and local control functions between substations, execute power and operation control commands, and achieve rapid control capabilities such as protection fault localization and isolation, as well as synchronous closing.

3.2.2 Communication network

By deploying intelligent integrated terminals in distribution transformer districts, we develop and expand flexible interconnection applications for low-voltage transformer districts. These terminals manage distribution parameters including voltage, current, and power within the district, while calculating critical metrics such as load factor, positive-sequence current, negative-sequence current, and zero-sequence current. The integrated terminals’ expanded flexible interconnection applications enable coordinated control in scenarios like load transfer during loop system overload, load balancing, source-load load transfer, and fault protection.

The three transformer fusion terminals communicate with the local coordination control device via Ethernet. The local coordination control device employs RS485 communication with port switches and flexible interconnection devices. These fusion terminals feature master-slave control capabilities, allowing one terminal to be designated as the master unit while others function as slave units. Fiber optic communication links the fusion terminals, with the primary terminal receiving operational data from subordinate units. All fusion terminals connect to the main station through wireless public network access.

3.2.3 System functions

The main functions include flexible interconnection of transformer districts, load balancing, source and load transfer, power protection in case of fault, etc., and fault isolation is the disposal function after abnormal conditions of the closed-loop system.

(a) Flexible interconnection of transformer districts:

Through the integration of terminals, the voltage, current, power and other distribution information of the transformer districts are managed, and the load rate of the transformer districts is calculated. The communication with the closed transformer district integration terminal is obtained to acquire the data information of the opposite transformer districts, and the coordinated control between transformer districts is comprehensively analysed and judged.

(b) Heavy load transfer:

By obtaining the distribution transformer load rate of each flexible interconnection area, the overload situation of the area, the available capacity of the distribution transformer in the remaining area and the available capacity of the low-voltage AC/DC flexible interface device can be calculated, so as to complete the calculation and control of power transfer between areas, realize power mutual aid between areas and distribution transformer overload management.

(c) Load balancing:

The master-slave integrated terminals communicate to obtain real-time load rates of distribution transformers across flexible interconnection zones. Based on control strategies issued by the main station, they regulate active power in low-voltage AC/DC flexible interface devices with the goal of balancing interface load rates. This achieves overall load balancing across interconnected zones, ensuring stable system operation.

(d) Source load transfer:

The master-slave integrated terminal acquires real-time load rates of distribution transformers across flexible interconnection zones through communication. It coordinates control of AC-side photovoltaic systems and loads within each interconnection zone, achieving source-load power balance both within and between zones. This dynamic mechanism supports the integration and local consumption of distributed energy sources and charging pile loads.

(e) Fault protection:

The fusion terminal detects the power failure in the station area, and the fault is not in the station area, or receives the supply guarantee instruction from the main station, jumps the low-voltage side total switch of the station area, starts the flexible interconnection device to provide power for the important load in the station area.

(f) Photovoltaic power generation monitoring:

The integrated terminal takes into account the characteristics of photovoltaic power generation and the source-load characteristics of energy storage, makes full use of peak, valley and normal periods, keeps the photovoltaic power generation in Maximum Power Point Tracking (MPPT) mode, and improves the revenue of photovoltaic power generation. At the same time, it solves the problem of high voltage in the terminal distribution network after distributed power supply is connected.

4. SUMMARY

The “Source - Grid - Load - Storage” Smart Microgrid Demonstration Project, developed by Wuhan NARI for hotel applications, represents an innovative power system implementation. This project integrates core components including 280.5kWphotovoltaic power generation, 67kW/134kWh energy storage systems, and 5-port flexible interconnection devices with centralized

AC flexible interconnection device. Utilizing a three-tier architecture of “central station-integrated terminals - terminal devices” and fibre-optic/wireless public network communication, the system achieves flexible interconnections between Public Transformer - 1 and Distribution Transformers - 2/3. Key functionalities implemented include platform area interconnection, load balancing, power protection during faults, and photovoltaic MPPT control.

Since its commissioning, the project has generated 490,200 kWh of electricity while saving approximately 160.78 tons of standard coal. It has reduced emissions by 488.72 tons of CO_2, 14.7 tons of SO_2, and 7.36 tons of NO_X. By implementing photovoltaic energy storage systems for peak shaving and valley filling, the initiative not only lowers hotel electricity costs and enhances power supply reliability but also provides replicable solutions for green energy transition in the hospitality sector and commercial buildings. This contributes to regional clean energy transformation and supports China’s “Dual Carbon” goals.

REFERENCES

1. Li Z S, Wu G, Cassandro R,et al. A Review of Resilience Metrics and Modelling Methods for Cyber-Physical Power Systems(cpps) [J]. IEEE Transactions on Reliability,2024,73(1):59-66.

2. Zou J, Qiu D, Liu D, et al. Optimal Control Strategy for Ac/Dc Hybrid Grid Based on Cpps [C]//2018 China International Conference on Electricity Distribution (CICED).2018:1778-1782.

3. Paul S, Ding F, Utkarsh K, [3] Paul S, Ding F, Utkarsh K, et al. On Vulnerability and Resilience of Cyber-Physical Power Systems: A Review[J]. IEEE Systems Journal, 2022, 16(2):2367-2378.

4. Oyewole PA, Jayaweera D. Power System Security with Cyber-Physical Power System Operation [J]. IEEE Access, 2020, 8:179970-179982.

5. Liu Z, Wang L. Leveraging Network Topology Optimization to Strengthen Power Grid Resilience Against Cyber-Physical Attacks [J]. IEEE Transactions on Smart Grid,2021,12(2):1552-1564.

6. Brun O, Yin Y. Random Neural Networks and Deep Learning for Attack Detection at the Edge[C] // 2019 IEEE International Conference on Fog Computing (ICFC). 2019:11-14.

Paper No. 3

ENHANCING LOW VOLTAGE SYSTEM SAFETY, SUSTAINABILITY, AND POWER RESILIENCE THROUGH DIGITAL ELECTRIFICATION

Authors/Speakers: Ir Keith TM Wong, General Manager - Electrification & Automation, Electrical Products
Mr. Albert PH Leung, Senior Project Engineer, Electrification & Automation, Electrical Products
Mr. Owen CP Woo, Project Engineer, Electrification & Automation
Ms. Christy KY Chan, Graduate Engineer, Electrification & Automation
Smart Infrastructure, Siemens Ltd. Hong Kong

ENHANCING LOW VOLTAGE SYSTEM SAFETY, SUSTAINABILITY, AND POWER RESILIENCE THROUGH DIGITAL ELECTRIFICATION

Ir Keith TM Wong, General Manager - Electrification & Automation, Electrical Products
Mr. Albert PH Leung, Senior Project Engineer, Electrification & Automation, Electrical Products
Mr. Owen CP Woo, Project Engineer, Electrification & Automation
Ms. Christy KY Chan, Graduate Engineer, Electrification & Automation
Smart Infrastructure, Siemens Ltd. Hong Kong

ABSTRACT

In the evolving landscape of electrical engineering, digital electrification stands as a pivotal innovation for enhancing safety, sustainability, and power resilience. This paper explores advanced digital technologies such as Arc Fault Detection Devices (AFDD), Smart Breakers for energy and condition monitoring, and Smart Substations. AFDD is a significant revolution in electrical safety by detecting and mitigating arc faults, which is a major cause of electrical fires. This is a pioneer technology which significantly reduces fire hazards, improves overall safety in residential, commercial, and industrial installation, i.e. protecting human lives and properties. The Smart Miniature Circuit Breaker (Smart MCB) contributes to sustainability through real-time monitoring and analytics, optimizing energy consumption and minimizing energy waste. It also facilitates preventive maintenance and energy efficiency, aligning with global sustainability goals. The integration of Smart Breakers and Smart Substations, leveraging internet of things (IoT), automation, and artificial intelligent (AI) enabling incipient fault detection, remote diagnostics, and predictive maintenance to enhance power resilience and reach sustainability goals.

This paper aims to provide a comprehensive analysis of these technologies in electrical installations. Through case studies and empirical data, we will discuss the benefits of implementing digital solutions to create safer, more sustainable, and resilient power systems.

1. ENHANCING ELECTRICAL SAFETY THROUGH DIGITAL EVOLUTION - ARC FAULT DETECTION TECHNOLOGIES

The safety of low voltage systems is of paramount importance, particularly in densely populated urban environments. Electrical fires, frequently triggered by arc faults, continue to pose significant risks to human life and property across residential, commercial, and industrial sectors. According to a study on electrical fire incidents in Shenzhen from 2014 to 2018, approximately 35% of all fires were attributed to electrical faults, with residential and dormitory buildings accounting for a substantial proportion of these cases [1]. This underscores the critical need for advanced protective technologies in cities with similar infrastructure, such as Hong Kong.

A recent and illustrative example is the CLP Yuen Long cable bridge fire accident in 2022. The incident, which was likely initiated by a fluorescent light installed on a transmission cable bridge, resulted in a large-scale blackout affecting approximately 175,000 customers [2]. Such an event highlights the vulnerability of electrical infrastructure to arc fault-related hazards and reinforces the necessity for proactive detection and mitigation strategies.

The statistics and real-world incidents demonstrate the urgent requirement for effective arc fault detection and prevention technologies. The low voltage Arc Fault Detection Devices (AFDDs) would be the pivotal solution, capable of identifying hazardous arc faults at an early stage and disconnecting affected circuits to prevent fires, thereby enhancing overall electrical safety.

1.1 Causes of Arc Fault and Limitations of Conventional Protection

Arc fault is predominantly caused by unintended current paths arising from damaged cable insulation, aging wiring, rodent activity, or poor electrical connections. These faults generate intense heat and sparks, which can easily ignite surrounding materials.

Figures 1 & 2 illustrate the variation in energy throughout the two carbonization phases as well as the ignition phase [3].

For Figure 1, most of the electrical energy is converted into heat and radiation, with only a small fraction forming an arc. The limited amount of energy is insufficient to sustain a stable arc capable of burning through the PVC insulation of the cable.

For Figure 2, the energy released during an arc event is sufficient to compromise PVC cable insulation and initiate fires. The arc stability rises to 90% within a short period of time and becomes very stable. Notably, arc faults frequently occur at load currents between 3A and 10A, a range typical of most domestic electrical appliances.

Traditional low voltage protection devices, such as Miniature Circuit Breakers (MCBs) and Residual Current Breakers with Overcurrent protection (RCBOs), are designed to operate only when current levels exceed their defined tripping curves. However, series arc faults often produce lower currents within the 3A to 10A range, which typically do not trigger these devices.

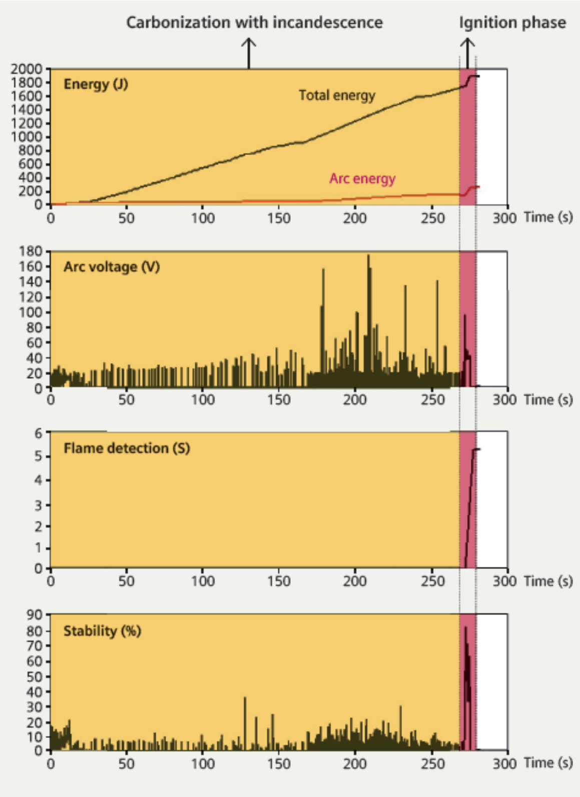


Fig. 1 - Fault Situation ranges up to 3A Arcing Current [3]

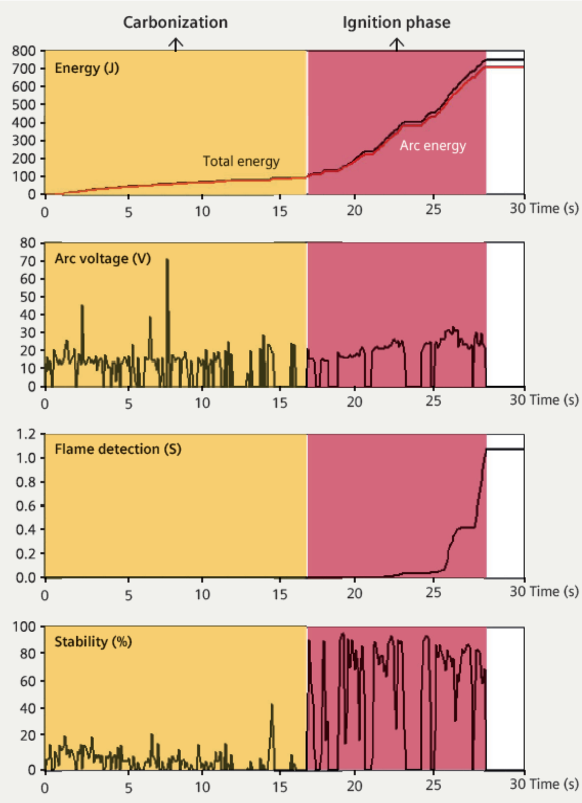


Fig. 2 - Fault Situation ranges from 3A to 10A Arcing Current [3]

Consequently, conventional protection methods are insufficient for detecting and mitigating the risks posed by series arc faults, leaving installations vulnerable to fire hazards.

Test arc current (r.m.s. values)	2,5 A	5 A	10 A	16 A	32 A	63 A
Maximum break time	1 s	0,5 s	0,25 s	0,15 s	0,12s	0,12 s

Table 1 - Maximum Break Time for Arcing Currents according to IEC 62606 [4]

1.2 Arc Fault Detection Devices and IEC 62606 Compliance

Arc Fault Detection Devices (AFDDs) represent a significant advancement in electrical safety by continuously monitoring current and voltage waveforms for distinctive arcing patterns. AFDDs are engineered to detect both series and parallel arc faults, offering comprehensive protection across various fault scenarios. Their performance is governed by the IEC 62606 standard, which stipulates maximum allowable tripping times based on the magnitude of the arc fault current. For instance, the standard mandates strict trip time limits for series arc faults at low current levels, ensuring prompt circuit disconnection and effective fire prevention.

1.3 Advanced Detection Methodology and Signal Processing

To reliably distinguish true arc fault signals from benign high-frequency noise generated by devices such as motors, drills, and vacuum cleaners, Siemens AFDDs utilize high-frequency sensors to capture the Received Signal Strength Indication (RSSI) from the electrical line.

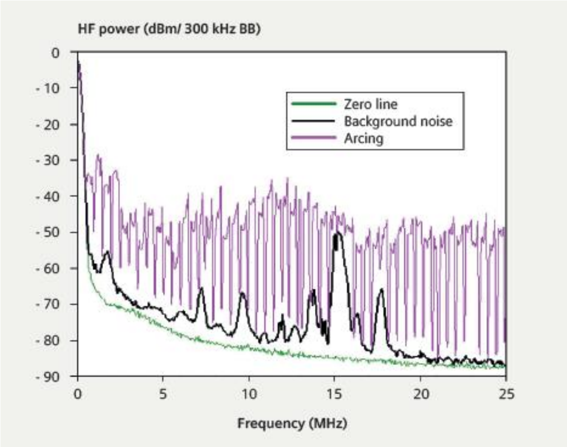


Fig. 3 - High-frequency Noise: Background Noise and Arcs [3]

As shown in Figure 3, the device performs advanced signal processing, scanning the 22-24 MHz frequency range where the distinction between arc fault signals and background noise is most pronounced, thereby achieving high immunity to interference and minimizing false tripping. Upon identifying the conditions for an arc fault, the microcontroller generates a trip signal that activates the switching mechanism via a shunt trip. In Siemens AFDDs, this triggers a mechanical coupling link to operate the attached MCB or RCBO, disconnecting the faulty circuit and isolating the hazard.

1.4 Detection of Serial Arcing Fault

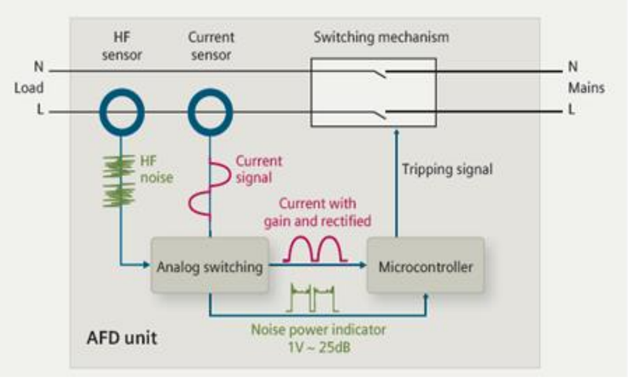


Fig. 4 - Design Example of AFDD [3]

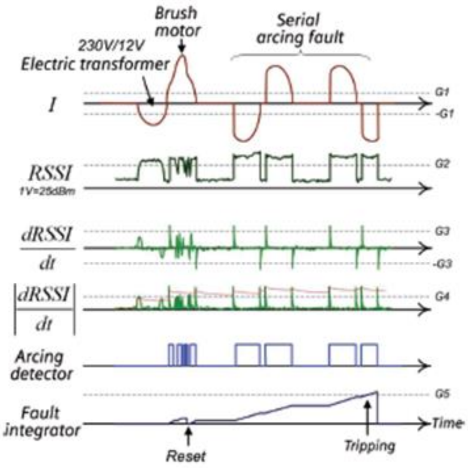


Fig. 5 - Signal Process for assessing Serial Arcing Faults [3]

Serial arcing faults in AFDDs are detected through a sophisticated signal analysis process that evaluates both current and high-frequency noise characteristics. The detection begins with sensors that monitor the line current and the broadband electromagnetic emissions produced by arcing [3]. A critical metric is the RSSI, which reflects the intensity of high-frequency noise. To confirm the presence of an arc, the system checks whether several conditions are met simultaneously:

(a) The current must exceed a minimum threshold (G1) to ensure sufficient energy for air ionization;

(b) The RSSI must surpass a defined level (G2) to indicate significant noise;

(c) The rate of change of RSSI (dRSSI/dt) must exceed thresholds (G3 and G4), capturing the rapid rise and fall typical of arc events.

These thresholds are derived from empirical data and are essential for distinguishing true faults from benign signals.

The detection algorithm then evaluates synchronization of RSSI and current signals - effectively counting the width of the resulting square wave pattern. If consecutive synchronized square waves are detected, they are accumulated in a fault integrator. Once the integrator exceeds a final threshold (G5), the AFDD issues a trip command to disconnect the circuit.

To avoid false tripping, the system resets the integrator when it detects patterns inconsistent with arcing, such as those generated by brush motors or switching devices. This multi-parameter approach ensures accurate detection of serial arcs while maintaining high immunity to operational noise.

1.5 Detection of Parallel Arcing Fault

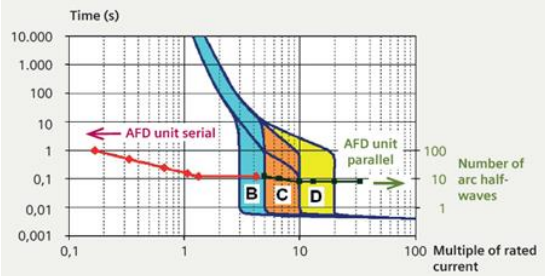


Fig. 6 - Protection by MCB [3]

If a fault occurs on the supply line upstream of the socket outlet, the circuit impedance is relatively low, resulting in a higher short-circuit current. This improves the likelihood of rapid disconnection by the MCB, enhancing protection. Conversely, faults occurring within extension cables typically encounter higher impedance, which significantly reduces the short-circuit current. In such cases, the current may fall below the magnetic tripping threshold of the MCB, rendering it ineffective for timely fault clearance and compromising fire protection.

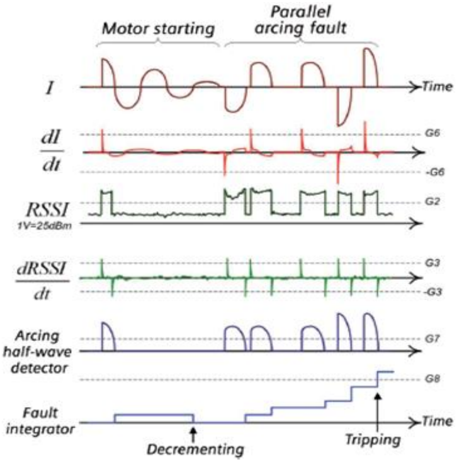


Fig. 7 - Signal Process for assessing Parallel Arching Faults [3]

In the case of parallel arcing faults, the arc typically initiates shortly after the zero-crossing of the line voltage. This delayed ignition results in a rapid and steep increase in current during each half-cycle. The AFDD leverages this behavior by monitoring the rate of change of current (derivative of dI/dt) which becomes significantly high during arc strike events. This steep current gradient serves as a key indicator for parallel arc detection, allowing the device to differentiate it from normal load transients or switching operations.

Maximum allowed number of arcing half-cycles within 0.5s (for AFDD at arc currents above 63A)						
Test arc current (r.m.s)	75A	100A	150A	200A	300A	500A
Number of half cycle at rated frequency	12	10	8	8	8	8

Table 2 - Limit Values of Operating Criteria for AFDD at High Arc Currents above 63A

The algorithm calculates the derivative of the current and activates the parallel arc detection logic when this rate exceeds a defined threshold (G6). If the RSSI also exceeds its threshold (G2) during the same half-wave, the system interprets it as an arcing event. Each qualifying half-wave contributes to a fault integrator, which accumulates one step in fault integrator. Unlike serial arc fault, according to IEC62606 [4], the requirement for detection of parallel arc is in number of half-cycles instead of time.

1.6 Intelligence and Data Communication in Next-Generation AFDD

The next generation of AFDD transcends traditional protection by integrating advanced data communication capabilities. These devices now function as IoT-enabled components, capable of transmitting operational and diagnostic data to centralized management platforms such as Building Management Systems (BMS). This connectivity empowers users with continuous remote monitoring of power quality, device status, and environmental conditions.

Intelligent AFDD can transmit real-time alerts for abnormal conditions, such as elevated temperatures or irregular electrical activity, facilitating rapid response and minimizing downtime. A key innovation is the ability to report the precise cause of a trip event, enabling targeted maintenance and optimizing asset management strategies.

This digital transformation is not limited to AFDD but extends across a suite of low voltage protection devices, marking a significant leap forward in data transparency and operational insight for facility management. The integration of IoT, automation, and artificial intelligence enables predictive maintenance, incipient fault detection, and enhanced power resilience - aligning with global sustainability and safety objectives.

2. SMART BREAKER MONITORING FOR A RESILIENT NETWORK

In conventional low-voltage (LV) electrical systems, monitoring and protection functions are typically performed by distinct devices. Circuit breakers serve to protect the system by interrupting current flow upon fault detection, whereas electric meters measure parameters such as current, voltage, active and reactive power, apparent power, power factor, frequency, and energy consumption. These measurements facilitate monitoring of circuit performance and energy usage.

Under the regulatory framework established by the Code of Practice for the Electricity (Wiring) Regulations and the Supply Rules of Hongkong Electric (HKE) and CLP Power, only circuit breakers are mandated for installation on every final circuit. Electric meters are required solely at the customer's main switchboard [5][6][7]. This arrangement limits visibility into the performance of individual final circuits, as multiple circuits are aggregated at the main switch, providing only an overall view of electricity consumption. Consequently, the granularity necessary for effective resource management and fault diagnosis is lacking.

Physical constraints within LV switch boards, where MCBs are installed, further restrict the integration of additional monitoring devices. This limitation has historically impeded the advancement of intelligent monitoring at the branch circuit level.

2.1 Emergence of Smart Circuit Breakers

Recent advancements in digitalization have led to the development of smart circuit breakers that integrate protection and monitoring functionalities within the compact footprint of traditional MCBs. Devices such as those in the Siemens Sentron COM series exemplify this trend by combining the roles of circuit breakers and electric meters, enabling detailed, branch-level electricity usage monitoring without requiring additional space or infrastructure modifications.

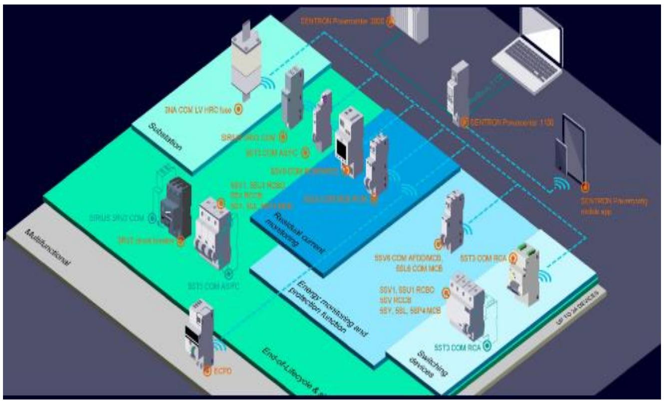


Fig. 8 - System Overview of one example in Siemens Smart Miniature Circuit Breaker [8]

Figure 8 illustrates a system overview of one such example in the Smart MCB. This innovation transforms each final circuit from a “black box” into a transparent, data-rich node within the power distribution network, fostering a more intelligent, responsive, and resilient electrical system.

2.2 Optimizing Resource Management and Energy Balancing

Smart circuit breakers provide a transformative capability in resource management and energy balancing by delivering granular visibility into energy consumption at the branch level. This detailed monitoring allows for comprehensive analysis and comparison of energy usage across circuits, supporting informed decisions in system design, operation, and maintenance.

As lighting accounts for a significant portion of energy consumption in office environments, one of applications involved a renovation office project where smart miniature circuit breakers played a crucial role. The customer aimed to analyze whether hot desk areas or dedicated desk zones used energy more efficiently. By monitoring lighting, socket, and air-conditioning loads, the smart circuit breakers provided detailed insights that enabled a strategic reconfiguration of the office layout, optimizing energy use and improving overall efficiency.

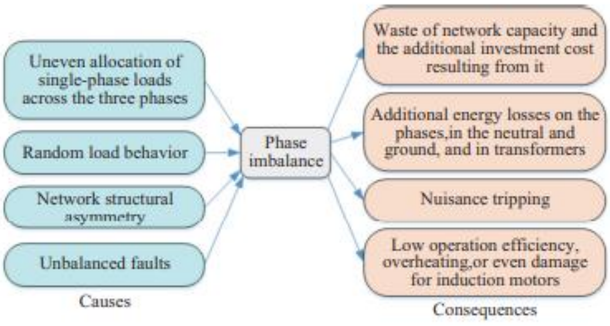


Fig. 9 - Causes for and Consequences of Phase Unbalance [9]

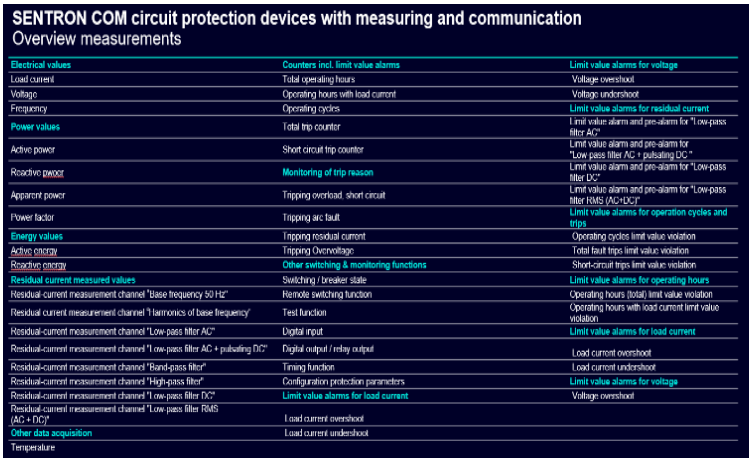
By collecting power quality data for each phase, the facility manager can aggregate load distribution across circuits in the distribution board. This balanced assignment reduces electrical losses, equipment stress, and unexpected shutdown, enhancing overall system performance and reliability. In office environments, phase imbalance can adversely affect three-phase motors in HVAC systems, causing overheating and premature wear. Transformers may experience uneven loading and increased heating [9], while sensitive electronics like computers and servers can suffer from voltage fluctuations and potential damage. Lighting systems with electronic ballasts or screens may also flicker or fail prematurely [10]. Correcting these imbalances extends the equipment lifespan and ensures stable, efficient operation throughout the facility.

In industrial contexts, similar monitoring capabilities enable operators to identify areas of excessive energy consumption, often attributable to aging or inefficient equipment. Targeted interventions, such as equipment upgrades or operational adjustments, can then be implemented to reduce waste and optimize system performance.

Ultimately, the integration of smart circuit breakers facilitates a more intelligent and adaptive power distribution system. By combining real-time monitoring with actionable insights, operators can achieve both operational efficiency and electrical stability, establishing a foundation for a resilient and sustainable energy infrastructure.

2.3 Condition-Based Maintenance and Fault Prediction

Traditional maintenance schedules are often time-based, leading to unnecessary servicing or missed faults. With real-time access to branch circuit parameters, such as temperature, residual current, maintenance can be scheduled based on actual circuit conditions.



SENTRON COM circuit protection devices with measuring and communication
Overview measurements

Electrical values	**Counters incl. limit value alarms**	**Limit value alarms for voltage**
Load current	Total operating hours	Voltage overshoot
Voltage	Operating hours with load current	Voltage undershoot
Frequency	Operating cycles	**Limit value alarms for residual current**
Power values	Total trip counter	Limit value alarm and pre-alarm for "Low-pass filter AC"
Active power	Short circuit trip counter	Limit value alarm and pre-alarm for "Low pass filter AC + pulsating DC"
Reactive pwoer	**Monitoring of trip reason**	Limit value alarm and pre-alarm for "Low-pass filter DC"
Apparent power	Tripping overload, short circuit	Limit value alarm and pre-alarm for "Low-pass filter RMS (AC+DC)"
Power factor	Tripping arc fault	**Limit value alarms for operation cycles and trips**
Energy values	Tripping residual current	Operating cycles limit value violation
Active energy	Tripping Overvoltage	Total fault trips limit value violation
Reactive energy	**Other switching & monitoring functions**	Short-circuit trips limit value violation
Residual current measured values	Switching / breaker state	**Limit value alarms for operating hours**
Residual-current measurement channel "Base frequency 50 Hz"	Remote switching function	Operating hours (total) limit value violation
Residual current measurement channel 'Harmonics of base frequency'	Test function	Operating hours with load current limit value violation
Residual-current measurement channel "Low-pass filter AC"	Digital input	**Limit value alarms for load current**
Residual-current measurement channel "Low-pass filter AC + pulsating DC"	Digital output / relay output	Load current overshoot
Residual-current measurement channel "Band-pass filter"	Timing function	Load current undershoot
Residual-current measurement channel "High-pass filter"	Configuration protection parameters	**Limit value alarms for voltage**
Residual-current measurement channel "Low-pass filter DC"	**Limit value alarms for load current**	Voltage overshoot
Residual-current measurement channel "Low-pass filter RMS (AC + DC)"	Load current overshoot	
Other data acquisition	Load current undershoot	
Temperature		

Fig. 10 - Sentron COM Circuit Protection with Measuring and Communication - Overview Measurements [11]

Figure 10 shows that the smart MCBs provide advanced monitoring features beyond basic protection. They measure key parameters such as power quality (voltage, current), leakage current, operating cycles, and temperature. Abnormal behaviours in final circuits, such as overheating, residual leakage [11], can be detected before they escalate into faults that trigger system trips. This predictive capability allows users to plan maintenance proactively, converting unplanned outages into scheduled interventions. As a result, system downtime is minimized, and maintenance resources are used more efficiently.

In addition, smart MCBs provide pre-alarms and real-time data, helping optimize energy management and ensure safer electrical installations, also enabling condition-based maintenance and early fault detection.

2.4 Research Towards Adaptive Protection and Intelligent Evaluation

A notable improvement in this area is the use of residual current monitoring miniature circuit breakers (RCM MCBs). Unlike traditional RCBOs that trip immediately upon detecting residual current, RCM MCBs allow continuous monitoring of leakage currents without interrupting the power supply. This enables early detection and diagnosis of insulation faults or leakage currents while maintaining uninterrupted operation, an essential feature for critical environments such as hospitals, data centres, refrigerated warehouses, and industrial facilities.

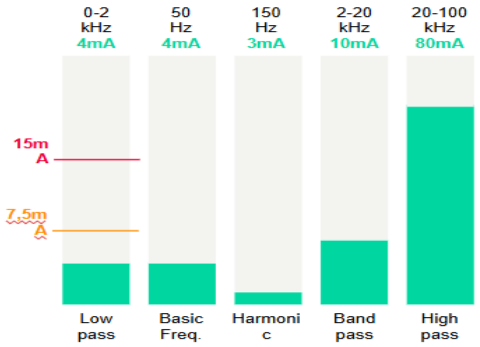


Fig. 11 - Simultaneous Monitoring of Residual Currents in Multiple Frequency Ranges [12]

Siemens Sentron RCM system allows users to set pre-alarms for leakage currents. When the leakage current exceeds a predefined threshold, an alert is triggered to notify the user. Additionally, the system can monitor leakage currents across five different frequency ranges, enabling more precise detection and diagnosis of various fault types. This multi-frequency monitoring enhances fault identification and helps prevent potential electrical hazards.

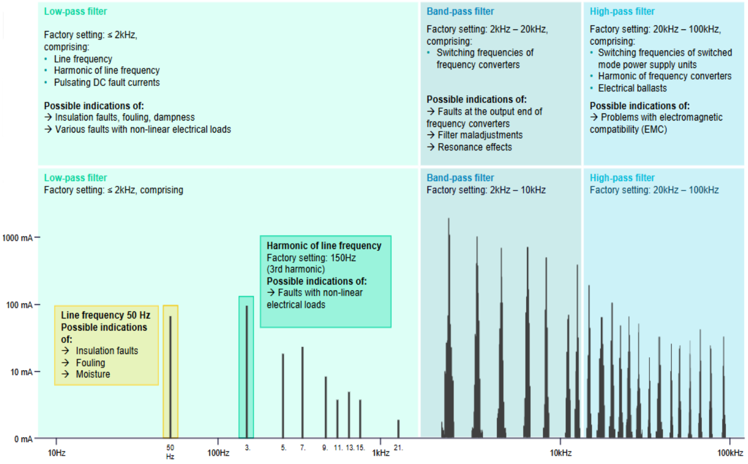


Fig. 12 - Fault Location based on Multiple Frequency [12]

This frequency-based analysis allows users to identify the nature and source of the fault, whether it is due to insulation degradation, moisture ingress, non-linear loads, or electromagnetic interference. By distinguishing between different fault types, operators can localize issues more accurately and respond with targeted maintenance actions.

By enabling fault detection without tripping and supporting detailed diagnostics, RCM-enabled smart breakers significantly enhance the power resilience of electrical systems. They allow operators to maintain continuous service, reduce testing costs, and improve safety through early intervention - making them a vital component in modern, intelligent power distribution networks.

3. DIGITAL ELECTRIFICATION & ITS ROLE IN SUSTAINABLE ENERGY SYSTEMS

To fully harness the data generated by smart circuit breakers, centralized systems are essential for collecting, visualizing, and managing this information effectively. The concept of the smart switch room serves this purpose by acting as the digital hub of a low-voltage distribution network. It aggregates real-time data from all connected breakers and presents it via an intuitive user interface (UI). This centralized platform enables operators to monitor circuit conditions, analyze energy consumption patterns, and perform remote control and diagnostics seamlessly. Beyond enhancing operational efficiency, smart switch rooms play a critical role in advancing sustainability objectives by identifying opportunities for energy savings, minimizing unnecessary consumption, and facilitating data-driven decision-making that supports greener building and infrastructure management.

Recent advances in artificial intelligence and data-driven technologies are revolutionizing the monitoring and management of energy systems. These innovations enhance the viability of decentralized renewable energy sources and facilitate smarter, more transparent energy trading. As these technologies continue to evolve, they provide operators and users with deeper insights into energy flows and overall system performance.

Central to this transformation is the smart switchroom system, a digitally enhanced hub designed for intelligent monitoring, real-time diagnostics, and predictive maintenance. The smart switchroom plays a pivotal role in collecting and analyzing operational data, supporting both immediate control actions and long-term strategic planning. By decoupling energy services from traditional infrastructure constraints, smart switchroom enables the development of digital twin ecosystems, fostering a more sustainable and resilient energy future.

Beyond improving operational visibility, these digital electrification infrastructures are critical to advancing carbon neutrality goals. The Government of the HKSAR has committed to reducing total carbon emissions relative to 2005 levels by 50%. Given that electricity generation accounts for approximately 66% of these emissions [13], real-time data logging provides essential benchmarking tools for stakeholders to assess and enhance their sustainability performance. Leveraging advanced data networks, these systems deliver detailed insights into energy consumption, system health, and emissions profiles. This transparency empowers informed decision-making, enabling organizations to reduce energy waste, optimize load distribution, and accelerate the adoption of low-carbon energy sources. Consequently, smart and digitalized electricity networks play a vital role in supporting measurable progress toward Hong Kong's climate objectives and contributing to a more sustainable future.

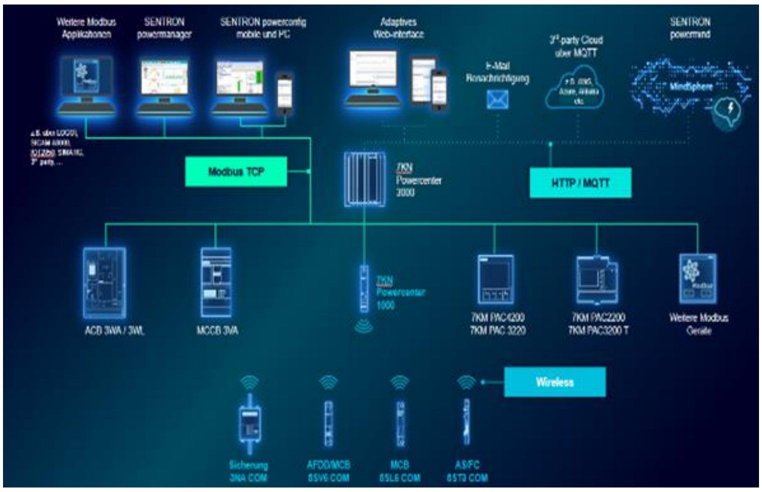


Fig. 13 - System Architecture of Smart MCB and Monitoring System

Digital electrification solutions such as smart switchroom also align with the United Nations Sustainable Development Goals (SDGs) outlined in the 2030 Agenda for Sustainable Development [14]. Specifically, they contribute to:

Goal 9: Industry, Innovation, and Infrastructure

- By modernizing electrical infrastructure through digital technologies and fostering innovation in energy monitoring and management.

Goal 11: Sustainable Cities and Communities

- By enabling smart city initiatives via real-time energy data, enhancing urban resilience, and promoting sustainable living environments.

Sustainability, commonly defined as meeting present needs without compromising the ability of future generations to meet theirs, can be further understood through three core objectives:

(a) Optimizing energy consumption,

(b) Extending the lifespan of infrastructure, and

(c) Minimizing environmental impact.

In the following section, this thesis will explore how digital electrification contributes to achieving these sustainability goals within low voltage electrical systems.

3.1 Optimizing Energy Consumption

Digital electrification is transforming energy management in commercial buildings by enabling granular monitoring and precise control of electrical infrastructure. Smart switchroom systems not only visualize the condition of the main switchboard [15] but also integrate branch circuits into a unified platform. This integration aligns with the requirements of Arc Fault Detection Devices (AFDD) and Smart Miniature Circuit Breakers (MCBs), allowing comprehensive monitoring of the entire electrical system within a building or facility.

With the support of digital twin technology, operations, monitoring, and measurement can be centralized and managed through a single platform. This holistic view empowers users to make informed decisions on energy-saving strategies tailored to specific office zones while enhancing power resilience by quickly identifying and responding to electrical faults. Moreover, smart switchroom systems can seamlessly integrate with existing Building Management Systems (BMS) using open protocols, ensuring interoperability and strengthening overall facility management.

By consolidating detailed electrical data and leveraging digital twin capabilities, facility managers gain real-time visibility and historical insights that support predictive maintenance, performance benchmarking, operational optimization, and improved power reliability, driving greater energy efficiency and resilience across commercial buildings.

3.2 Extending the Lifespan of Infrastructure

Environmental sensors that monitor parameters such as indoor air quality (IAQ), vibration, and noise are essential for maintaining optimal operating conditions in electrical systems. IAQ monitoring plays a vital role in enhancing the performance and safety of LV main switchrooms. By tracking airborne contaminants like dust, particulate matter, and volatile organic compounds (VOCs), IAQ sensors help prevent the accumulation of pollutants that can settle on switchgear surfaces, causing insulation degradation and increasing the risk of electrical faults. Additionally, maintaining good air quality supports proper cooling and reduces the likelihood of overheating. Among environmental factors, humidity remains critical to switchgear longevity and reliability - excess moisture can lead to corrosion of metallic components, insulation deterioration, and heightened risks of partial discharge or arc faults. Continuous monitoring of humidity and IAQ enables facility managers to optimize ventilation and implement dehumidification strategies, preserving equipment integrity, extending service life, and minimizing failure risks within the low voltage main switchroom.

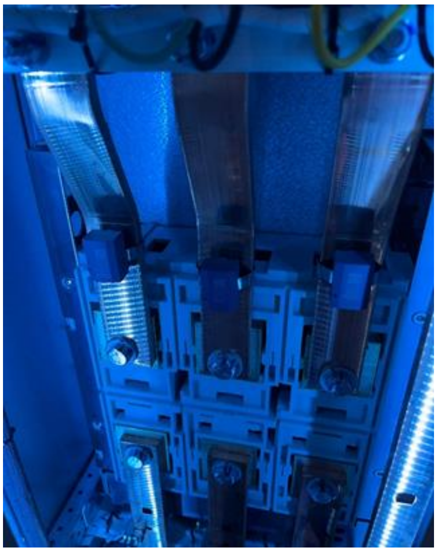


Fig. 14 - Siemens Wireless Busbar Temperature Sensor

Temperature extremes impose significant thermal stress specifically on the busbar temperature, which directly impacts switchgear performance [16]. Elevated busbar temperatures cause material expansion and contraction, leading to mechanical fatigue, loosening of connections, and accelerated insulation aging [17]. Fluctuations in busbar temperature can also impair the accuracy and reliability of protective relays and sensors. Wireless busbar temperature sensors provide continuous, precise monitoring of the busbar itself - rather than just ambient conditions - allowing early detection of thermal issues that affect electrical resistance and system efficiency. From Figure 14, these sensors are typically powered directly from the busbar, eliminating the need for separate power sources. The wireless technology also removes the requirement for extensive wiring and cable drilling, simplifying installation and reducing disruption. Effective thermal management focused on busbar temperature, combined with materials designed for high thermal tolerance, is critical to ensuring switchgear reliability under varying operating conditions.

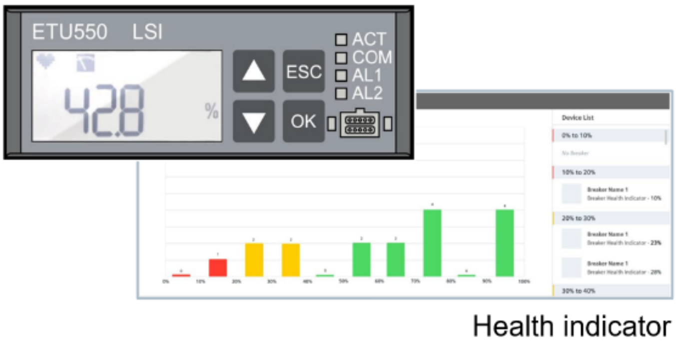


Fig. 15 - Health Indicator of Siemens Molded Case Circuit Breaker

Furthermore, modern Molded Case Circuit Breakers (MCCBs) and Air Circuit Breakers (ACBs) are equipped with health condition monitoring features. These devices provide a health indicator expressed as a percentage, accompanied by alerts and maintenance recommendations [15]. When the health indicator ranges between 30% and 100%, the breaker operates normally. A value between 1% and 30% signals the need for planned maintenance or replacement, while a 0% reading demands immediate replacement. This predictive maintenance approach ensures system reliability, minimizes downtime, and supports long-term asset management. Over time, this strategy contributes to reduced carbon emissions associated with transportation and promotes a more resource-efficient maintenance model.

3.3 Minimizing Environmental Impact

Minimizing environmental impact is an increasingly critical objective in modern electrical infrastructure, particularly within enclosed environments such as low-voltage (LV) switch rooms. Advanced environmental monitoring systems equipped with sensors capable of detecting a broad spectrum of pollutants - including particulate matter (PM10 and PM2.5), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), chlorine (Cl_2), ammonia (NH_3), and nitrogen dioxide (NO_2) - are essential tools in this effort. Real-time monitoring of these parameters enables facility managers to maintain air quality within safe limits, safeguarding both equipment and personnel [18].

Beyond air quality management, these sensors contribute to reducing carbon footprints by enabling remote diagnostics and monitoring. Engineers and technicians can assess switchroom conditions from off-site locations, reducing the need for frequent physical inspections. This practice lowers operational costs and decreases travel-related fuel consumption and emissions, fostering a more sustainable maintenance model aligned with global efforts to mitigate greenhouse gas emissions and protect ecosystems.

3.4 Example of Smart Switchroom Monitoring System

A smart switchroom monitoring system significantly advances sustainability objectives by providing real-time visibility into electrical system conditions. This system integrates Information Technology (IT) with Operational Technology (OT) through the deployment of smart devices such as wireless LoRa sensors and intelligent circuit breakers. A centralized software platform connects these devices, enabling users to monitor the condition of low voltage switchroom both on-site and remotely. An example of such a system is Siemens' Digital Electrification System, which exemplifies the integration of advanced monitoring technologies in modern electrical infrastructure. Figure 16 illustrates the sensors installed in low voltages switchroom.

Fig. 16 - Key Components of Smart Switchroom Monitoring

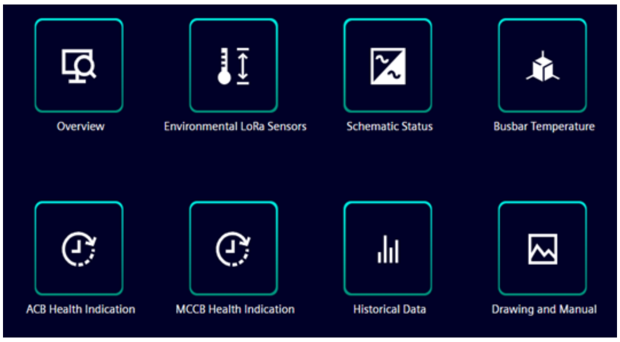


Fig. 17 - Elements in UI "Siepower"

The operational status (On, Off, and Trip) of ACBs and MCCBs within the low-voltage switchboard, along with power meter measurements, are collected via dry contacts or communication protocol networks. This data is transmitted to a data concentrator and subsequently relayed to the monitoring software platform, for example Figure 17. RFID wireless temperature sensors are installed on the incoming and outgoing busbars of the circuit breakers to continuously monitor their temperature, ensuring proactive maintenance and enhanced system reliability.

Implementing a smart switchroom monitoring system significantly enhances sustainability and power resilience within electrical infrastructure. By providing real-time visibility into energy consumption and equipment status, such systems enable facility managers to identify inefficiencies, reduce unnecessary energy use, and optimize operational schedules, thereby lowering overall carbon footprints [19]. The integration of wireless sensors and intelligent circuit breakers facilitates predictive maintenance, minimizing unplanned outages and extending equipment lifespan, which reduces waste and resource consumption. Furthermore, continuous monitoring supports rapid detection and response to faults, enhancing power resilience by preventing prolonged downtime and maintaining stable electrical supply to critical loads. This combination of energy efficiency, proactive asset management, and improved reliability aligns with broader sustainability goals and fosters a more resilient, eco-conscious facility operation [20].

4. CONCLUSION

The integration of Arc Fault Detection Devices (AFDDs) and smart circuit breakers marks a significant advancement in the safety, efficiency, and resilience of modern low-voltage electrical networks. AFDDs provide critical protection by detecting and mitigating arc faults, one of the leading causes of electrical fires—while smart breakers such as Smart MCB and MCCB enable real-time monitoring, predictive maintenance, and granular energy management at the branch level.

Centralized platforms, such as smart switchroom monitoring system, further enhance these capabilities by aggregating and visualizing data through intuitive user interfaces, supporting informed, data-driven decisions. Collectively, these innovations address the limitations of traditional systems and lay a robust foundation for safer, more reliable, and sustainable power distribution infrastructures.

REFERENCES

1. Li, Z., Qiu, F., Yang, H., Zhang, Y., Chen, H., & Du, Y. (2021, April). Residential Electrical Fire in Shenzhen: Data Analysis and Possible Solution. In 2021 IEEE/IAS 57th Industrial and Commercial Power Systems Technical Conference (I&CPS) (pp. 1–5). Las Vegas, NV, USA. https://doi.org/10.1109/ICPS51807.2021.94165

2. CLP Power Hong Kong Limited. (2022, August 26). Investigation Report on CLP Cable Bridge Fire Incident on 21 June 2022. https://www.clpgroup.com/content/dam/clp-group/channels/media/document/2022/20220826_en.pdf.coredownload.pdf

3. Siemens AG. (2016). 5SM6 arc fault detection unit primer (Document No. 109482288). Siemens Industry. https://cache.industry.siemens.com/dl/files/288/109482288/att_866515/v1/5SM6_AFDUnit_primer_EN_201601250858227805.pdf

4. International Electrotechnical Commission. (2013). IEC 62606: Arc fault detection devices (Edition 1.0, July 2013).

5. Electrical and Mechanical Services Department (EMSD). (2020). Code of Practice for the Electricity (Wiring) Regulations (2020 ed.). Hong Kong SAR Government. https://www.emsd.gov.hk/en/electricity_safety/code_of_practice/index.html

6. HK Electric. (2023). Guide to Connection of Supply (7th ed.) [PDF]. Hong Kong Electric Company.

https://www.hkelectric.com/documents/en/CustomerServices/CI/Documents/GCS_7th_en/GuidetoConnectionofSupply_Full_En.pdf

7. CLP Power Hong Kong Limited. (2023). Supply Rules (Version R3, August 26, 2023) [PDF]. CLP Power Hong Kong. https://e.clp.com.hk/supplyrules-en

8. Siemens AG. (2016). SENTRON Protection Devices for Modern Electrical Installations (Article No. EMLP-B10026-00-7600). Siemens AG Energy Management. https://cache.industry.siemens.com/dl/files/484/109745484/att_911404/v1/Protection-concept_Better-to-play-it-safe___6834_201701161459571550.pdf

9. Ma, K., Fang, L., & Kong, W. (2020). Review of Distribution Network Phase Unbalance: Scale, Causes, Consequences, Solutions, and Future Research Direction. CSEE Journal of Power and Energy Systems, 6(3), 479–488. https://doi.org/10.17775/CSEEJPES.2019.03280

10. Putz, Ł. (2019). Disturbances Generated by Lighting Systems with LED lamps and the Impact on Power Quality. *Applied Sciences*, *9*(22),4894. https://doi.org/10.3390/app9224894

11. Siemens AG. (2025). Residual Current Monitoring with the SENTRON COM system. https://info.siemens.com/viewer/8e05e4f69585ceb57d277c666a6a13fa

12. Siemens AG. (2023). 5SL6 COM RCM Miniature Circuit Breakers: Circuit Protection Devices with Communication and Measuring Functions https://assets.new.siemens.com/siemens/assets/api/uuid:3781b645-3ee4-482d-86da-725981516799/2023-06-19-sl-p310-com-en-web.pdf

13. Hong Kong Special Administrative Region Government. (2023). Hong Kong's Climate Action Plan 2050 [PDF]. https://cnsd.gov.hk/wp-content/uploads/2023/05/Climate-Target-of-HK_en.pdf

14. United Nations Office for Partnerships. Sustainable Development Goals Briefing Book 2023 [PDF]. https://unpartnerships.un.org/sites/default/files/publications/2024-01/SDG%20Briefing%20Book_2023.pdf

15. Wong, K. T. M., & So, C. Y. (2021). Energizing the New Normal through Digital Electrification Empowerment [Conference presentation]. The Hong Kong Institution of Engineers - Electrical Division, 39th Annual Symposium, Hong Kong. http://www.hkie.org.hk/docs/newsletter/uploading/sym21lef_online_final.pdf

16. IEEE Power & Energy Society. (2018). Thermal Management of Switchgear Components: Effects of Temperature on Electrical and Mechanical Performance. IEEE Transactions on Industry Applications, 54(3), 2345–2353. https://doi.org/10.1109/TIA.2018.2812345

17. Kumar, R., & Singh, M. (2019). Impact of Thermal Cycling on Switchgear Reliability and Insulation Aging. Journal of Electrical Engineering & Technology, 14(4), 1605–1613. https://doi.org/10.1007/s42835-019-00201-7

18. Water Supplies Department. (2021). E-11-01 LV Switchboard and Control Board (Rev. 10) [Technical specification]. Hong Kong Government. https://www.wsd.gov.hk/filemanager/en/content_1615/E-11-01%20LV%20Switchboard%20and%20Control%20Board%20Rev.10.pdf

19. SOK. (2024). Advancing Sustainability through Smart Switchroom Monitoring: A Comprehensive Guide. Sustainable Operations Knowledge.

20. Klatt, M. (2021). Enhancing Power Resilience with Intelligent Electrical Infrastructure. Journal of Sustainable Energy Systems, 15(3), 145–158. https://doi.org/10.1234/jses.2021.01503

Paper No. 4

ZERO CARBON EV CHARGING INFRASTRUCTURE - A SMART DEMAND-SIDE MANAGEMENT APPROACH FOR SUSTAINABLE EV INTEGRATION

Author/Speaker: Ir Professor Geoffrey L Chan
Co-Founder and Technical Director
RadiansPlus Technologies Limited

ZERO CARBON EV CHARGING INFRASTRUCTURE - A SMART DEMAND-SIDE MANAGEMENT APPROACH FOR SUSTAINABLE EV INTEGRATION

Ir Professor Geoffrey L Chan
Co-Founder and Technical Director
RadiansPlus Technologies Limited

ABSTRACT

As electric vehicles (EVs) proliferate globally, the challenge of integrating large-scale charging infrastructure without overloading existing electrical grids or increasing carbon emissions has become critical. This paper presents an innovative Zero Carbon EV Charging method, based on the Power System Neutral (PSN) principle and dynamic load management with dynamic set-point (DDLM), enabling widespread EV adoption without surpassing historical peak electrical demand or requiring costly infrastructure upgrades. Using real-time grid condition monitoring and a dynamic set-point algorithm, the system flexibly regulates EV charging loads, ensuring that operational and embedded carbon emissions are minimized. The algorithmic approach and showcase successful commercial deployments in Singapore's VivoCity mall and Housing & Development Board (HDB) public housing carparks will be detailed, demonstrating the technical feasibility, scalability, and sustainability of this solution.

1. INTRODUCTION

Decarbonizing transport is a centerpiece of global net-zero strategies, with electric vehicles (EVs) and solar photovoltaic (PV) systems at the forefront. While their environmental benefits are clear, the rapid deployment of EV charging infrastructure introduces new stresses to the power grid, particularly at peak times. Traditional grid expansion approaches require significant capital and time, and can result in increased carbon emissions from transmission and distribution to generation and customer installations. This often passes costs onto end-users, utilities, or governments, slowing adoption and undermining decarbonization goals. To address these challenges, a Power System Neutral (PSN) EV infrastructure approach, centred on dynamic load management with dynamic set-point (DDLM), has been developed. This technology maximizes existing grid utilization, avoids new peak demand, and delivers a win-win-win scenario for governments, utilities, and end-users.

2. CHALLENGES OF CONVENTIONAL EV CHARGING

Conventional EV charging methods, which allow vehicles to charge at full speed regardless of grid conditions, can quickly push facility or local grid demand past historical peaks, triggering several issues:

- Infrastructure Upgrades: Exceeding peak demand necessitates transformer, cable, and switch upgrades, which are costly and resource-intensive.
- Transformer Iron Losses: Distribution transformers added for increased peak demands incur iron losses, leading to raised operational carbon emissions.
- Generation Footprint: Extra generation capacity, from fossil or renewable sources, is required to meet new peak demand, undermining the carbon reduction promise of EVs.
- Low Asset Utilization: Investments in grid expansion for EVs result in asset utilization rates below 10%, far lower than the typical 25–45% for existing loads, hurting the power company's business case.

These factors create a deadlock among stakeholders, with the government caught between industry's calls for expansion and utilities being compelled to invest in low utilization assets.

3. PSN PRINCIPLE & DYNAMIC LOAD MANAGEMENT WITH DYNAMIC SET-POINT

3.1 PSN Infrastructure Concept

The PSN principle is built on two pillars:

(a) *Demand-Side Management for Flexible Loads:* EV charging, heat pumps, and other flexible loads are regulated so they only draw power when grid capacity is available.

(b) *Supply-Side Management for Flexible Generation:* PV systems and battery discharging are adjusted so that their output matches local demand or grid absorption limits.

This ensures that EV charging and PV generation have "no impact" on the power system infrastructure, maintaining grid stability and avoiding new peaks.

3.2 DLM vs DDLM

- *Dynamic Load Management with Fixed Set-point (DLM)*: This approach involves maintaining predetermined, fixed set-points for load parameters. The systems dynamically adjust load distribution to keep these fixed targets, regardless of variation in demand or supply conditions. The fixed set-point necessitated reserving capacity, which cannot be used for other applications, leading to potential underutilization of available resources.

- *Dynamic Load Management with Dynamic Set-point (DDLM)*: This method involves adjusting the set-points themselves based on real-time system conditions. The system modifies targets dynamically and adjusts load distribution accordingly, in response to changing system states. Since capacity does not need to be reserved for a fixed set-point, DDLM allows for much higher capacity utilization, especially during time of low demand or when other demands are minimal.

Fixed set-point systems are simpler to implement but limit total capacity that can be managed effectively. In contrast, dynamic set-point systems are more complex but enable significantly greater capacity utilization, adopting to real-time conditions for improved efficiency.

3.3 Deterministic vs Non-deterministic System

- *Deterministic System:* In deterministic systems, the capacity allocated to each device is fixed by a calculation algorithm. Once assigned, this capacity is reserved and remains unavailable for re-allocation, even if the device does not fully utilize it. The approach simplifies management but can lead to inefficient use of resources.

- *Non-Deterministic Systems:* Here, the capacity allocated to each device is dynamically adjusted based on real-time utilization, allowing the system to fully utilize available capacity. Capacity that is allocated but unused by a device can be re-allocated to others, ensuring higher efficiency and utilization rates.

Deterministic systems are easier to design but tend to be less flexible and less efficient in resource utilization. Non-deterministic systems are more complex to implement but are highly adaptable to changing conditions and can achieve near 100% utilization of available capacity.

DDLM inherently is non-deterministic because resource allocated to a device that is not used will be shown as surplus capacity that will then be re-allocated to other devices of the system.

3.4 Dynamic Load Management Algorithm: Dynamic Set-point Control (DDLM)

The PSN system employs a dynamic set-point algorithm, summarized as follows (based on US Patent US12119696B2):

- *Building/Grid Maximum Capacity (X):* The system establishes the facility's historical, contractual or technical maximum load limit.

- *Real-Time Monitoring (Y):* Total current and power are measured every few seconds at the main switchboard (MSB).

- *Set-points and Deadband:*
  - Curtailment Setting: Typically set at 80–85% of X.
  - Deadband: A 10-15% zone to avoid rapid cycling.

- *Control Logic:*
  - If Y < 0.85X, allow chargers to operate at maximum rate.
  - If Y > 0.85X, instruct chargers to reduce current step by step until Y < 0.8X.
  - If Y < 0.7X, instruct chargers to increase current step by step until Y < 0.75X.
  - If 0.75X < Y < 0.85X, maintain the current charging rate.

These are typical values for illustration purposes.

- *Fail-Safe Disconnection & Assertive Tripping:* If MSB current exceeds 90% of X for more than 1 minute, a fail-safe contactor will disconnect EV supply. If MSB current > 95%, an independent protective relay (Assertive Tripping Relay) will trip the MCCB of flexible loads (EV charging) before inflexible loads, ensuring building operations are not compromised.

This closed-loop (main switch current as feedback), non-deterministic (step by step change until sufficient) algorithm adjusts every 5 to 10 seconds based on real-time grid data. The process is local, hardware-based, and does not rely on internet connectivity, mitigating cyber-security risks.

3.5 Benefits of Dynamic Load Management with Dynamic Set-Point (DDLM)

- Maximizes "shadow power" (untapped grid capacity).

- Prevents new peak demand and associated infrastructure upgrades.

- Achieves 90%+ utilization of available capacity.

- Seamlessly integrates with existing charger management and building management systems.

- Ensures grid protection and operational reliability.

- Regulates both DC & AC Chargers.

4. CARBON EMISSION REDUCTION

The PSN approach directly reduces both embedded and operational carbon emissions of EV infra-structure:

- *Scope 2 (Operational):* By avoiding new transformer installations, iron losses are minimized. Each 1500kVA transformer avoided saves 1.75kW of iron loss, equivalent to the carbon absorption of 670 trees, or 202 tCO2e over 20 years.

- *Scope 3 (Embedded):* Grid expansion and power plant construction have high embodied carbon. Avoiding 1kW of grid capacity saves 0.38 tCO2e (grid) and 1.9 tCO2e (power plant), based on University of Reading's research.

Thus, the PSN method cuts carbon emissions from both the construction side (transformer rooms, cables and equipment) and operational side (generation losses, transformer losses). PSN EV charging infrastructure rides on infrastructures built for other purposes, hence the term "Zero Carbon EV Infrastructure."

5. IMPLEMENTATION: SUCCESS STORIES

5.1 VivoCity Mall, Singapore

5.1.1 Site overview

- Largest retail destination in Singapore, with 2,000 parking spaces. Only 20 medium EV charging points installed by end 2024.

- Contracted capacity : 12,500 kW and reached in weekends during noon and evening peak hours.

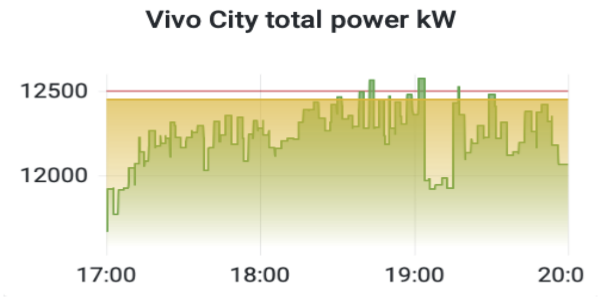


Fig. 1 - Consumption on weekend evening reaching Contracted Maximum of 12,500kW

5.1.2 PSN deployment

- March 2025: RadiansPlus PSN commissioned, enabling installation of 1x120kW DC (dual gun) + 2x60kW DC (dual gun) + 3x22kW, total 306kW of of 120/60kW DC plus 22kWAC charging capacity.

- Actual measurement revealed over 60,000 kWh of "shadow power" available daily, sufficient to fully charge 600 Tesla Model X or 150 double-decker electric buses.

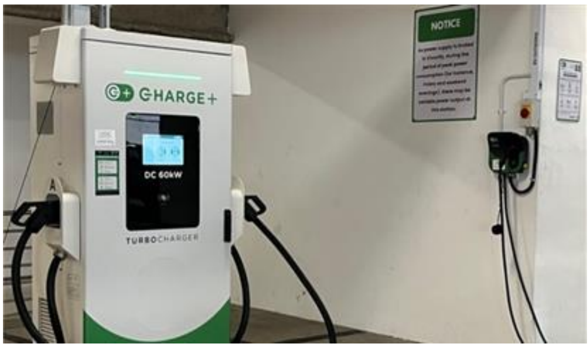


Fig. 2 - DC & AC Chargers using PSN

Fig. 3 - Daily Shadow Power Available

5.1.3 Dynamic load management in action

- Charging rates for each EVSE (EV Supply Equipment, i.e. EV chargers) were dynamically adjusted based on 10 second site consumption data from Building Management System.

- Once site consumption > 12,400kW, PSN instructs chargers to reduce charging rate until site consumption is below 12,400kW. Charging rates ramp up again when consumption drops below 12,200kW.

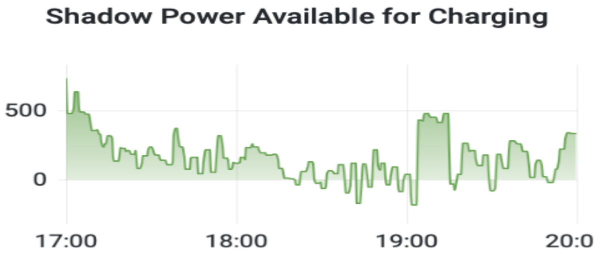


Fig. 4.1 - Shadow Power available for Charging on weekend evening

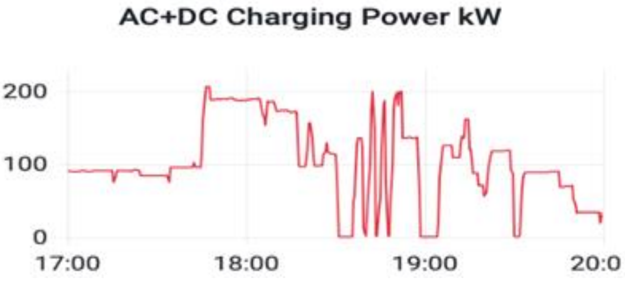


Fig. 4.2 - Actual EVs Power Drawn

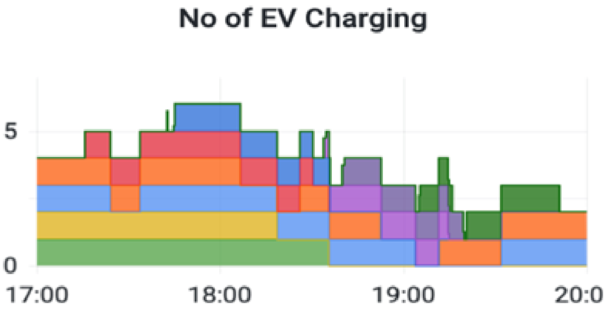


Fig. 4.3 - Number of EV Charged

- Notice is displayed on site to remind driver of variable power output. Drivers continue to use variable power chargers, which are otherwise not available without PSN principle.

NOTICE

As power supply is limited in Vivocity, during the period of peak power consumption (for instance, Friday and weekend evenings), there may be variable power output at this station.

5.1.4 Impact

- Demonstrated feasibility of scaling up EV charging infrastructure in any commercial building, without increasing peak power demand.

- Provided a model for other malls and large facilities.

- Driver acceptance of variable charging speed is confirmed.

- Win-win-win for power utility, building owners and shoppers with EV.

5.2 HDB Public Housing Carparks, Singapore

5.2.1 Site overview

- Government vows to install EV chargers to all 2,000 public housing carparks across Singapore by end 2025. Typical carpark supply is 100A three phases with 200+ parking spaces.

- 200 sites were perceived to be unable to install any chargers due to risk of overloading.

Fig. 5 - Singapore Public Housing Carpark CLRG (HDB Block 312 Multi-Storey Carpark) with PSN

5.2.2 PSN deployment

- November 2024: RadiansPlus PSN implemented, enabling installation of 3x7.4kW chargers with 6 charging guns at these sites. Expandable to 6x7.4kW.

- Existing Shadow Power can cover charging needs of 100 EV, 50% of all parking spaces.

- Installing roof top PV panels and can cater for 100% EV penetration in future.

5.2.3 Dynamic load management in action

- Real-time monitoring of carpark load, with EV charging rates throttled up or down based on MSB current.

- Once MSB current exceeds 60A, EV charging rate will be reduced. When MSB current exceeds 79A, a fail-safe contactor will disconnect the charger supply.

- Assertive tripping set at 85A to trip EV distribution board (EVDB) MCCB by a Definite Time Lag relay, ensuring inflexible loads (lighting, lifts, etc.) are never affected.

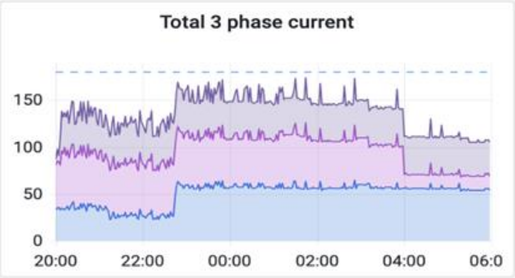


Fig. 6 - MSB Current Controlled below 60A per Phase (Max. 180A Total for Three Phases)

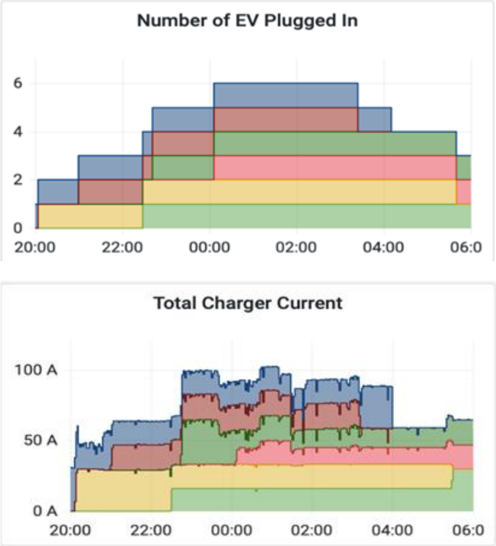


Fig. 7 - All Six Connectors charged at the same time, with Total Three Phase Current <100A

- Fully charged EVs are allowed to stay without an idle fee.

- Government adopted PSN principle, enabling charger rollout in carpark without power upgrade, public or utility funding. Costs incurred by operators are to be recovered over the 10-years concession period.

- Using one month of data from carpark CLRG in July 2025, the average current drawn from Singapore Power increased from 14A to 23A (a 64% increase).

- Only 14% of shadow power is used, allowing for a sixfold of EV population increase.

Fig. 8 - July 2025 Utilisation of Shadow Power in Carpark CLRG

5.2.4 Impact

- Enabled equitable access to EV charging for public housing residents. Equally applicable to other multi-tenant carparks with minimal supply.

- Removed grid or local switchboard constraints as a barrier to EV adoption.

- No idle fee for driver to leave their EV plugged in at the charge point overnights.

- Supported green transportation goals and offered a blueprint for rapid, cost-effective expansion of charging infrastructure.

6. DISCUSSION & CONCLUSION

6.1 Discussion

The implementation of the Power System Neutral (PSN) approach with Dynamic Load Management (DDLM) represents a transformative solution for integrating large-scale EV charging infrastructure without exacerbating grid stress or increasing carbon emissions. The success stories from VivoCity mall and HDB public housing carparks in Singapore underscore the practical viability of this method.

By leveraging real-time grid monitoring and dynamic set-point control, the system maximizes untapped "shadow power", ensuring efficient utilization of existing grid capacity while avoiding costly infrastructure upgrades.

Key insights from the deployments include:

(a) Scalability: The PSN system demonstrated its ability to scale EV charging infrastructure in diverse settings, from high-demand commercial malls to resource-constrained public housing carparks, without exceeding historical peak loads.

(b) Carbon Reduction: By minimizing Scope 2 (operational) and Scope 3 (embedded) carbon emissions, the PSN approach aligns with global decarbonization goals. The avoidance of new transformer installations alone translates to significant carbon savings, equivalent to the absorption capacity of hundreds of trees.

(c) User Acceptance: Drivers readily adapted to variable charging speeds, highlighting the importance of clear communication and the system's ability to balance convenience with grid stability.

(d) Economic Viability: The PSN principle eliminates the need for public or utility funding, enabling cost recovery through operational savings and long-term concessions.

6.2 Conclusion

The PSN principle with DDLM algorithm offers a sustainable, scalable, and economically feasible pathway for global EV adoption. By dynamically managing charging loads and integrating renewable energy sources, this approach addresses the dual challenges of grid stability and carbon neutrality. The successful application of the PSN principles with DDLM algorithm in Singapore for public commercial use serves as a blueprint for other regions, proving that widespread EV integration is achievable without overburdening existing infrastructure.

Policymakers, utilities and carpark owners are encouraged to adopt such demand-side management strategies to accelerate the transition to zero-carbon transportation while ensuring grid reliability and affordability.

In conclusion, the PSN principle not only bridges the gap between EV growth and grid capacity but also sets a new standard for sustainable infrastructure development, paving the way for a cleaner, smarter energy future.

REFERENCES

1. "More Electric Vehicle Charging Points to be Deployed in HDB Carparks", Singapore Land Transport Authority new releases, 2 November, 2022

2. Chan et al., “Method and Apparatus Performing Charging Modulation”, Patent No US 12119696B2

3. Geoffrey Chan, KW Ho, KH Chan,” Smart Electric Vehicle Charging with Dynamic Power and Load Management System”, 20th IET Power Symposium, 2022

4. Daniels, L., Coker, P. and Potter,B (2016), Embodied carbon dioxide of network assets in a decarbonised electricity grid. Applied Energy, 180. 142 - 154. ISSN 0306-2619

5. “National Grid: What are scope 1, 2 and 3 carbon emissions” https://www.nationalgrid.com/stories/energy-explained/what-are-scope-1-2-3-carbon-emissions

Paper No. 5

ARTIFICIAL INTELLIGENCE BASED AUTOMATIC FAULT DETECTION AND DIAGNOSIS FOR PHOTOVOLTAIC POWER STATION

Authors/Speakers: Dr. LW Zhang
Association Professor
South China University of Technology
Ir Stanley KW Leung
General Manager
GDEPRI Power Control Systems & Equipment (HK) Limited

ARTIFICIAL INTELLIGENCE BASED AUTOMATIC FAULT DETECTION AND DIAGNOSIS FOR PHOTOVOLTAIC POWER STATIONS

Dr. LW Zhang
Association Professor
South China University of Technology
Ir Stanley KW Leung
General Manager
GDEPRI Power Control Systems & Equipment (HK) Limited

ABSTRACT

Photovoltaic (PV) power generation is inherently volatile and highly susceptible to weather changes, leading to unstable power output and significant seasonal variations. Therefore, it is important to develop an intelligent monitoring and diagnosis scheme for distributed PV power stations. In this paper, we propose a power generation prediction method and a panel defect detection method to comprehensively evaluate the status of PV power stations. Learning-based intelligent prediction and fault warning is investigated for PV power generation. A PV panel defect detection model is developed based on the YOLOv8 framework, enabling timely diagnosis of panel defects. Utilizing automated inspection pan-tilt platforms or drones equipped with high-definition cameras and infrared thermal images, the system conducts comprehensive inspections of photovoltaic panels in automated mode. The high-definition cameras accurately identify surface issues such as cracks, dirt accumulation, and other physical defects, while the infrared thermal images detect and locate potential electrical faults like hot spots through temperature monitoring. The proposed method provides an artificial intelligence (AI) based automatic fault detection and diagnosis for PV power stations.

1. INTRODUCTION

With the rapid development of renewable energy, PV power stations have become a critical component of modern energy systems. However, their management and maintenance face significant technical challenges, including volatile power generation due to weather dependency, high equipment failure rates, and labour-intensive manual inspections. Existing approaches often struggle to achieve accurate power forecasting under dynamic environmental conditions and fail to detect subtle defects in PV panels promptly, which may escalate into severe safety hazards or efficiency losses.

The technical challenges of this work lie in two aspects: Firstly, traditional models often rely on limited historical data and simplistic correlations, leading to poor generalizability under rapidly changing weather conditions. Secondly, PV panels exhibit diverse defect types (e.g. cracks, hotspots, dust accumulation) and environmental interference (e.g. shadows, reflections) further complicate automated detection.

To address these challenges, our work builds a closed-loop operation and maintenance system featuring “intelligent perception - data analysis - precise handling”. Main contributions are: (1) Learning-based intelligent prediction and fault diagnosis is investigated for PV power generation. (2) A multi-modal YOLOv8-based defect detection system that integrates visible-light and infrared imaging is developed to achieve high-precision identification of defects. (3) A dataset collected from PV stations is used to comprehensively validate both the prediction stability and defect detection robustness.

2. INTELLIGENT POWER PREDICTION & FAULT DIAGNOSIS OF PV POWER GENERATION

The solar irradiance and temperature are generally used as input to forecast the future generated electricity. Back propagation neural network (BPNN) is used to deal with this problem since it is widely used in the field of data prediction. Prediction algorithm models trained by historical data are used by BPNN in the prediction and fault diagnosis section. A hidden layer BPNN structure is shown in Figure 1, which is divided into an input layer, a hidden layer, and an output layer.

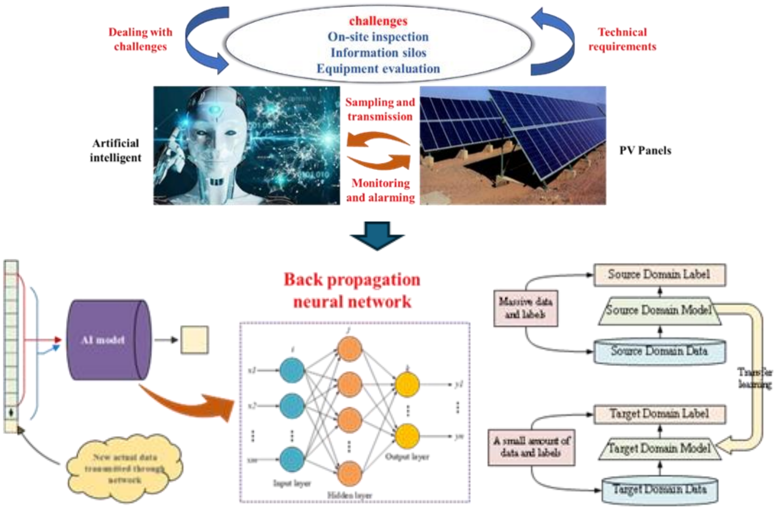


Fig. 1 - BPNN based Intelligent Power Prediction and Fault Diagnosis Structure of PV Power Generation

The input layer mainly receives external data. The hidden layer receives external information from the input layer. The output layer outputs the results of network computation to the outside. During the training process, the BPNN for solar PV power generation prediction continuously adjusts the weight threshold of each layer to make the network output close to the expected target.

This paper investigates the predictive performance of the following models: (a) a model using illuminance, temperature, and the past five historical time steps of electricity consumption as inputs, directly trained on institution-specific data; and (b) a model with identical input variables (illuminance, temperature, and five historical electricity consumption time steps), pre-trained on data from 101 institutions and subsequently fine-tuned via transfer learning. To this end, the pre-trained model based on BPNN is obtained. This work presents a model-based transfer learning technique. The network is trained by using a large amount of data and labels in the source domain, and then the trained network is saved for a new task domain. By learning knowledge from the source domain data, the network can better understand the data in the target domain. The neural networks can learn knowledge that can be applied to the target domain in related fields with large amounts of data by transfer learning. The pre-trained network model is loaded and the connection weight threshold from the input layer to the first layer of the hidden layer is frozen. The weight threshold of this layer is not updated in the following training process.

3. AI-BASED AUTOMATED DETECTION & DIAGNOSIS OF PV PANEL

This section employs a deep neural network model for intelligent defect detection in photovoltaic panels, which can be seen in Figure 2. By analyzing the collected image data, the model can identify common defects such as stains, cracks, and hot spots. The network leverages feature extraction and feature fusion techniques to enhance detection accuracy for complex defects, thereby improving the model’s robustness and precision.

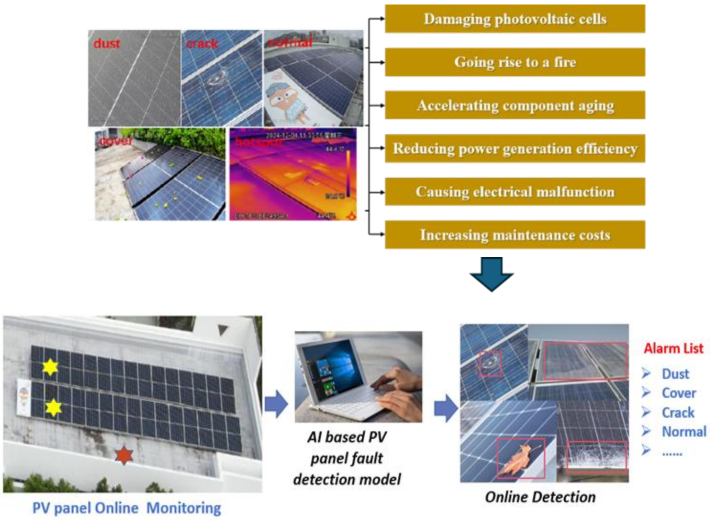


Fig. 2 - Schematic Diagram of Photovoltaic Panel Defect Detection Method

To inspect PV panels, we adopted the YOLOv8 model. YOLOv8 is a next-generation model in the YOLO series released by the Ultralytics team. Compared to its predecessors, YOLOv8 has made significant improvements in terms of accuracy, speed, and ease of use. It is a high-performance, modular object detection model that supports various vision tasks. We use PyTorch to implement YOLOv8 and train and test the model on a single RTX 4070 GPU. All training images are resized to 640×640 pixels, with data augmentation techniques such as random horizontal flip and random stretching applied. The batch size is set to 16, and the network is optimized using Stochastic Gradient Descent (SGD) with an initial learning rate of 0.001. The training process spans a total of 100 epochs.

4. EXPERIMENTS & VALIDATION

4.1 Data Source and Dataset Creation

4.1.1 Power generation prediction dataset

The dataset is collected from three schools: CPC Yao Dao Secondary School, Valtorta College, and DMHC Siu Ming Catholic Secondary School, which consists of operational data from PV power generation systems. The time periods and data volume for each school are detailed in Table 1. The data from PV power generation systems includes station name, data date, illuminance, temperature, humidity, voltage A-phase, voltage B-phase, voltage C-phase, current A-phase, current B-phase, current C-phase, total power, and electricity. The data of each station is maintained in an Excel spreadsheet, with each row corresponding to the photovoltaic power generation situation at a certain time. The time interval for each row of data is 15 minutes, which means there will be 96 data samples in a day. To select suitable input parameters for AI model, Pearce coefficient is a measure of the degree of rank correlation and is used for evaluating strength of input-output variables. The formula for calculating Pearson’s correlation coefficient under continuous variables:

$$\rho_{X,Y} = \frac{\operatorname{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{E\big((X-\mu_X)(Y-\mu_Y)\big)}{\sigma_X \sigma_Y} = \frac{E(XY) - E(X)E(Y)}{\sqrt{E(X^2) - E^2(X)}\sqrt{E(Y^2) - E^2(Y)}}$$

The coefficient describes the strength of the linear relationship between two random variables. It takes values ranging from -1 to 1, where -1 means perfect negative correlation, 1 means perfect positive correlation, and 0 means no correlation.

School	Time	Amount of data
CPC Yao Dao Secondary School (Phase II)	2022/5/13~2024/6/12	65996
Valtorta College (Phase II)	2023/7/28~2024/6/12	30224
DMHC Siu Ming Catholic Secondary School (Phase III)	2024/1/30~2024/6/12	12649

Table 1 - The Time Periods and Data Volume of each School

The Pierce’s coefficients for illuminance vs electricity, temperature vs electricity, and humidity vs electricity are calculated separately as in Table 2. The positively correlated data type, that is, illuminance and temperature are taken uniformly for prediction.

Data type	Pierce's coefficients
illuminance(W/m^2)	0.8875
temperature (℃)	0.5167
humidity (%)	-0.5375

Table 2 - Pierce's Coefficients for Different Data Type

4.1.2 Data of PV panel defects

A total of 3 thermal imaging cameras and 12 dome cameras were deployed across the three schools mentioned. Each school was equipped with one thermal imaging camera and four dome cameras. These 15 cameras were used to capture images at three different time periods each day - morning, noon, and evening - to obtain infrared and visible light images under various temperature and lighting conditions. The obtained images were combined with an open-source dataset to create an infrared dataset and a visible light dataset, respectively. To prevent overfitting due to insufficient data, the dataset was augmented using techniques such as random flipping, random stretching, and random cropping. The visible light dataset contained 6,166 images with annotated boxes for four categories: "normal", "cover", "crack", and "dust". The infrared dataset contained 2,265 images, all labelled under the "hotspot" category. The number of annotated boxes for each category is shown in Table 3.

Class	Number of annotated boxes
Normal	24569
Cover	11965
Crack	1280
Dust	2259
Hotspot	7689

Table 3 - Number of Annotated Boxes for the Visible Light and Infrared Datasets

4.2 Result Analysis and Performance Evaluation

4.2.1 Results of power generation prediction model

The performance of the prediction model is shown in Table 4. The performance of the power generation prediction model was evaluated using the Mean Squared Error (MSE). MSE amplifies the impact of larger deviations through squared computation, thereby measuring prediction stability.

School	MSE	σ value
CPC Yao Dao Secondary School (Phase II)	0.052	0.2214
Valtorta College (Phase II)	0.053	0.2263
DMHC Siu Ming Catholic Secondary School (Phase III)	0.046	0.2143

Table 4 - Performance of Prediction Results Infrared Datasets

The Inverter performance is judged according to how well (or bad) its output (kWh) compares to the AI model predicted values. The rating grade will be determined by the location of the "difference of predicted and measured kWh output" (referred as "Residual") to the normal or the respective probability distribution curve, in terms of standard distribution (or σ). The grades are listed as Table 5. The probability distribution curves for residuals are given as Figures 3 (a) and 3 (b), and Figure 4.

Distance from Normal	Grade
$<-3\sigma$	Poor
$-3\sigma \le x < -2\sigma$	Bad
$-2\sigma \le x < -1\sigma$	Minus
$-1\sigma \le x \le 1\sigma$	Normal
$2\sigma \ge x > 1\sigma$	Plus
$3\sigma \ge x > 2\sigma$	Good
$x > 3\sigma$	Excellent

Table 5 - Rating Grade based on Standard Distribution

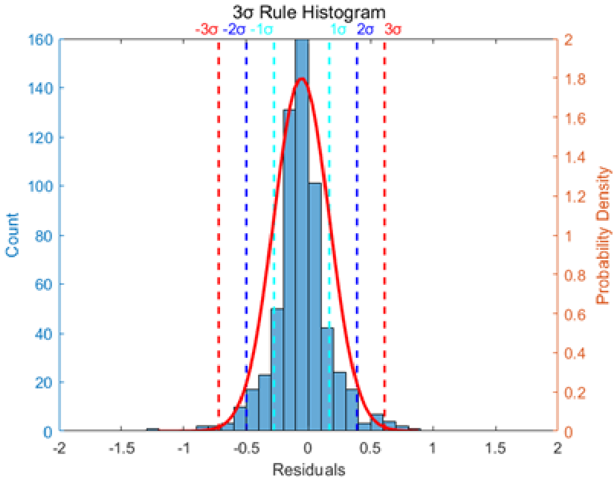


Fig. 3(a) - Probability Distribution of different Predicted and Measured Inverter's kWh Output of CPC Yao Dao Secondary School (Phase II)

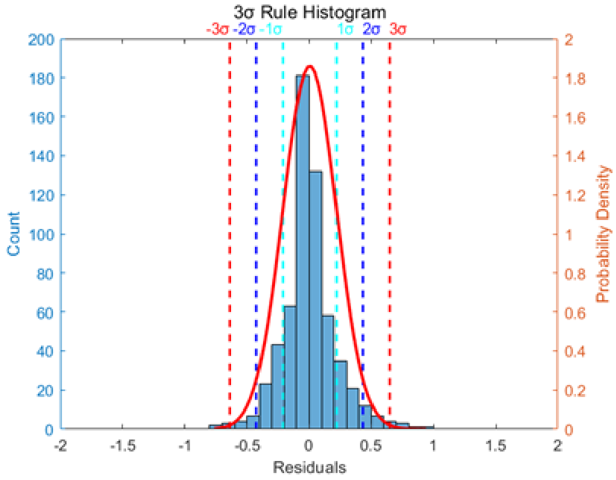


Fig. 3(b) - Probability Distribution of different Predicted and Measured Inverter's kWh Output of DMHC Siu Ming Catholic Secondary School (Phase III)

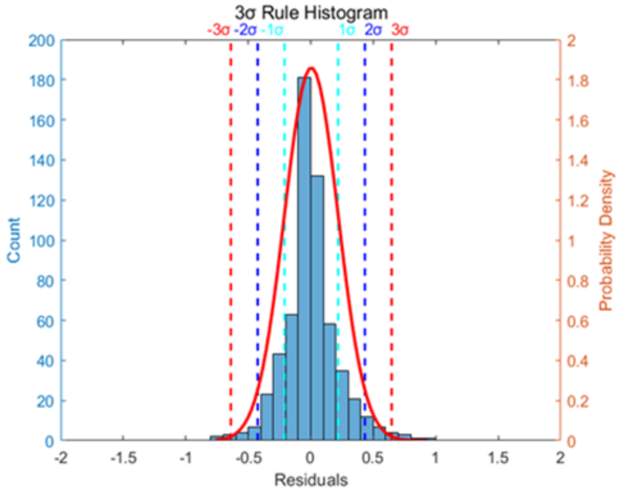


Fig. 4 - Probability Distribution of different Predicted and Measured Inverter's kWh Output of Valtorta College (Phase II)

4.2.2 Results of photovoltaic defect detection

After training, the detection performance of the visible light model in the actual deployment environment is shown in Figure 5 (top). It can be observed that the model accurately identifies defects on photovoltaic panels and demonstrates strong robustness under complex lighting conditions and varying weather. The detection performance of the infrared model is shown in Figure 5 (below). As can be seen from the figure, the infrared model can accurately capture temperature anomalies on the photovoltaic panels and demonstrate good stability.

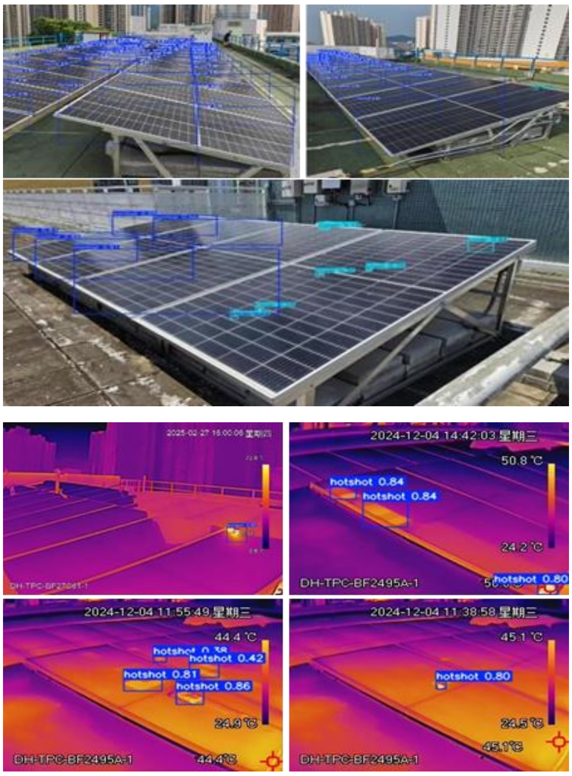


Fig. 5 - The Detection Effect of the Visible Light Model and Infrared Model

4.3 Research Results Application

The practical implementation of the proposed methodology, as depicted in Figure 6, involves utilizing either automated pan-tilt inspection platforms or drones equipped with high-resolution cameras and infrared thermal imaging sensors. The systems collect comprehensive video/image data, which is subsequently transmitted to our AI-based diagnostic system for automated fault detection and performance analysis of PV systems. The pan-tilt mounted inspection system offers high operational efficiency but has limited coverage range. Drone-based inspection enables rapid PV module imaging with AI analysis, featuring extensive coverage and superior real-time performance.

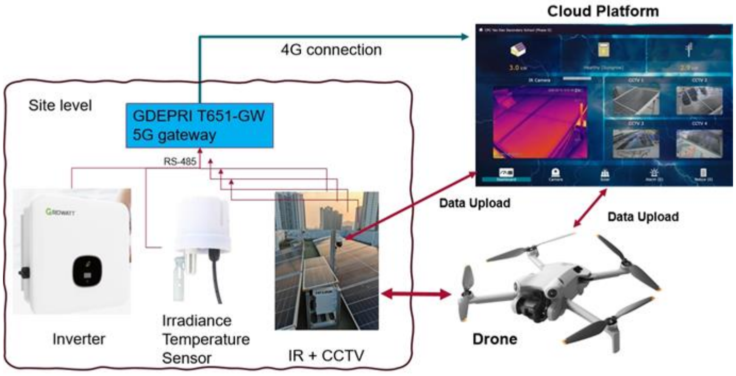


Fig. 6 - Research Results Application

The drone-based PV inspection system can achieve "automatic cruise + AI analysis + generation". The inspection range is set on the platform, and the drone automatically plans the route. The staff only need to click start, and the drone will fly according to the set route. The drone flies over the components and takes high-definition photos with a visible light camera and temperature distribution maps with an infrared thermal image. After the inspection is completed, the data is automatically transmitted back to the cloud, and the AI platform performs the analysis and automatically generates inspection reports. The application of the method described in this paper can greatly reduce the time and cost of traditional manual inspections, and lower the risks for maintenance personnel during high-altitude operations.

5. CONCLUSION

This paper develops advanced PV power generation prediction and intelligent panel defect detection technologies to addresses the challenges faced in the scientific management and maintenance of distributed PV power stations. We employ a BPNN for power generation prediction, which achieves promising results on the dataset, contributing to improved generation efficiency and stability, as well as optimized energy allocation. We utilize the YOLOv8 model to tackle the photovoltaic panel defect detection task, deploying 15 cameras at three sites to collect the dataset. The proposed AI models enable timely identification of anomalies before faults occur, enhancing the system’s safety and stability.

Paper No. 6

EMPOWERING ENGINEERS WITH AI: HOW EMSD’S AI AGENT DRIVES THE NEW QUALITY PRODUCTION FORCE

Authors/Speakers: Ir Patrick PM So, Senior E&M Engineer
Mr. Morize KT Lau, E&M Engineer
Mr. KF Leung, E&M Engineer
Electrical and Mechanical Services Department,
The Government of the HKSAR
Mr. Andy CY Tsang, Director
Mr. Paul YH Tsoi, Data Scientist
Capax Technology Limited

EMPOWERING ENGINEERS WITH AI: HOW EMSD'S AI AGENT DRIVES THE NEW QUALITY PRODUCTION FORCE

Ir Patrick PM So, Senior E&M Engineer
Mr. Morize KT Lau, E&M Engineer
Mr. KF Leung, E&M Engineer
Electrical and Mechanical Services Department, The Government of the HKSAR
Mr. Andy CY Tsang, Director
Mr. Paul YH Tsoi, Data Scientist
Capax Technology Limited

ABSTRACT

The growing complexity of building engineering systems demands intelligent system that enhances efficiency, reliability, and sustainability. While Large Language Model (LLM) have shown transformative potential across industries in recent year, their adoption in engineering remains constrained by the challenges of interoperability and integration with the physical world. To address this, we present in this paper Engentica, an AI-driven agentic framework developed by the Electrical and Mechanical Services Department (EMSD). Engentica bridges the digital and physical realms through semantic reasoning, Retrieval-Augmented Generation (RAG), semantic layer and a graph-based Model Context Protocol (MCP). Unlike conventional AI applications that lack decision-making capabilities and require manual intervention, Engentica actively interprets user intent, comprehends complex queries and system conditions, and delivers targeted recommendations accompanied by actionable plans. The framework achieves seamless data integration across diverse engineering systems and database, unifying live and historical operational data, maintenance record, supervisory analytics, and engineering knowledge. In parallel, the MCP enables seamless tool integration, allowing dynamic orchestration of decision-support, optimization, and analysis workflows. This proactive functionality improves real-time operational decision-making significantly, ultimately driving greater efficiency, reliability, and sustainability in building engineering system operations.

1. INTRODUCTION

The scale and complexity of modern building electrical and mechanical (E&M) engineering systems have grown dramatically, driven by expansive infrastructure and stringent performance goals. In fact, EMSD now oversees E&M operations for over 8,000 government-owned buildings in Hong Kong [1]. Managing such distributed systems, with thousands of sensors, controls, and equipment, far exceeds manual capabilities. Traditional on-site inspection and reactive maintenance for thousand of assets are slow, error-prone, and hard to coordinate. To address these challenges, Hong Kong's smart city strategy has emphasized digital transformation, including the deployment of regional control centres and internet of things (IoT) - based building management system to monitor energy use and system performance in real-time [2]. While these efforts enhance efficiency, reliability, and sustainability, they do not fully automate decision-making. Therefore, the scale and complexity of the building E&M engineering system demand AI-driven automation to optimize operations and maintenance (O&M) at scale.

Recent advances in generative AI and large language models (LLMs) have attracted interest in solving complex tasks across domains, particularly through agentic AI systems. These systems extend LLMs with semantic reasoning capabilities, enabling them to interpret user intent, set and pursue goals, maintain internal state or memory across interactions, retrieve information from external data source, and autonomously execute external tools without human intervention [3]. Such capabilities offer significant potential to support operation and maintenance of building E&M engineering systems, including monitoring equipment conditions, detecting anomalies, optimizing system performance, and coordinating real-time system response.

In this paper, we introduce Engentica, an AI-driven agentic framework designed to enhance engineering decision-making by unifying heterogeneous data sources and enabling seamless tool integration. These include live and historical operational data from the Integrated Building Management System (iBMS), historical maintenance records from the Digital Operation and Maintenance Systems (DOMS), supervisory analytics from the Regional Digital Control Centre (RDCC), and a comprehensive engineering knowledge database. The framework integrates a multi-agent system with a semantic layer, leveraging RAG for grounded reasoning and a graph-based Model Context Protocol (MCP) for seamless integration with both generic and engineering-specific tools (Figure 1). Unlike conventional systems that lack decision-making capabilities and require manual intervention, Engentica actively interprets user intent and dynamic system conditions to decompose complex queries, generate actionable plans, and orchestrate workflows, including the autonomous execution of tasks on building E&M systems. Through its core capabilities in decision support, predictive energy optimization, energy analysis, and sensor fault detection, Engentica facilitates a proactive approach to O&M, driving a shift toward smarter, more efficient, and reliable building management.

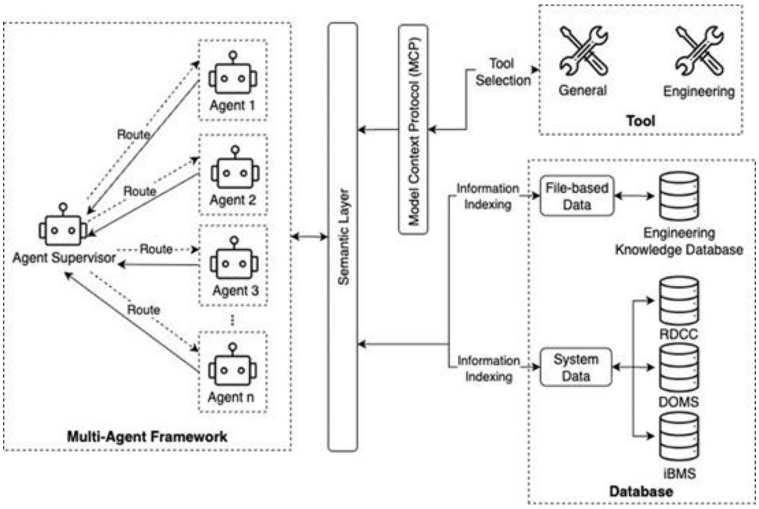


Fig. 1 - System Architecture of Engentica, showing the Layered Integration of Multi-agent Framework with DWO, Semantic Layer, MCP, Databases, and Tools

2. SYSTEM OVERVIEW

The Engineering Agent, Engentica, addresses the challenge of operating and maintaining complex building E&M systems by mediating interactions between authenticated users (technicians, engineers, and managers) and heterogeneous engineering infrastructures. At its foundation, a multi-agent framework is introduced which is composed of an agent supervisor and multiple role-specialized agents. Within the framework, the agent supervisor governs task delegation and communication flow, semantically analyzes user intents and select appropriate role-specialized agents based on contextual requirements. The supervisor also critiques agent outputs to enhance response quality and ensure higher task success rates. Apart from multi-agent framework, a semantic layer is introduced to transform engineering schematic into ontological representations, enabling machine-readable reasoning across diverse data sources, including system database (iBMS, DOMS, RDCC) and the engineering knowledge database. The graph-based MCP provides seamless integration with general-purpose and engineering-specific tools. This layered architecture supports contextualized planning, tool orchestration, traceability, and resilient execution, making Engentica suitable for on-premises, safety-critical deployment.

3. SYSTEM ARCHITECTURE

3.1 Core Components

The architecture is composed of the following key components:

(a) Multi-tenant Workspaces with User Authentication:

Engentica offers secure, browser-based access through isolated digital workspaces for each organization. User authentication ensures that only verified users can access the platform, supporting organizational privacy and scalable deployment across diverse environments.

(b) Multi-Agent Framework:

The multi-agent framework equips with the Dynamic Workflow Orchestrator (DWO), which semantically interprets natural-language queries, classifies engineering problems, and assembles tailored task pipelines. The DWO decomposes intents into structured workflows, schedules parallel subtasks, and delegates them to role-specialized agents for functions such as real-time sensor analysis, fault diagnosis, data visualization and control of engineering systems. Central to this framework is RAG, which allows agents to ground their reasoning on live and historical operational data, maintenance records, supervisory analytics, and domain-specific knowledge, thereby reducing hallucinations and enhancing explainability. The Agent Supervisor oversees inter-agent interactions, evaluates agent output, and provides corrective feedback to resolve inconsistencies or errors, ensuring robust and contextually accurate results. Through iterative critique and refinement under supervisory oversight, the framework establishes a feedback loop to enhance workflow reliability, adaptability, and the overall trustworthiness of decision-making.

(c) Semantic Layer:

The semantic layer serves as a foundational component that enables machine-readable reasoning over engineering data. Although LLMs exhibit strong capabilities in processing general engineering knowledges, they lack the ability to efficiently interpret heterogenous data formats of real-world building engineering systems, which often include schematic diagrams, operation and maintenance manuals, and other multimodal records that lacking the structured semantics required for automated reasoning. To address this challenge, ontology-based approaches such as Brick [4] and Project Haystack [5] have been widely adopted to formalize engineering relationships into standardized, machine-interpretable vocabularies. These initiatives have demonstrated the value of semantic modelling in enabling interoperability across diverse platforms and data sources. Building on these principles, Engentica introduces a semantic layer that is lightweight, LLM-native, and designed for seamless integration with RAG. The semantic layer leverages established semantic models from prior research to provide a structured foundation for contextual reasoning [6], while additionally incorporating a semantic model to transform engineering schematics into machine-readable representations, enabling integration of unstructured diagrams into ontology-based workflows.

As illustrated in Figure 2, the model implements a two-phase approach for converting engineering schematic into machine-readable semantic representation. First, E&M schematics are transformed into textual representations using an image-to-text model, capturing component characteristics and interconnections. Second, an instruction-tuned LLM with RAG extracts entity classes and relationships according to an engineering ontology standard, leveraging external metadata to enhance accuracy without retraining. This process transforms unstructured engineering schematics into structured semantic representation that are natively compatible with LLM.

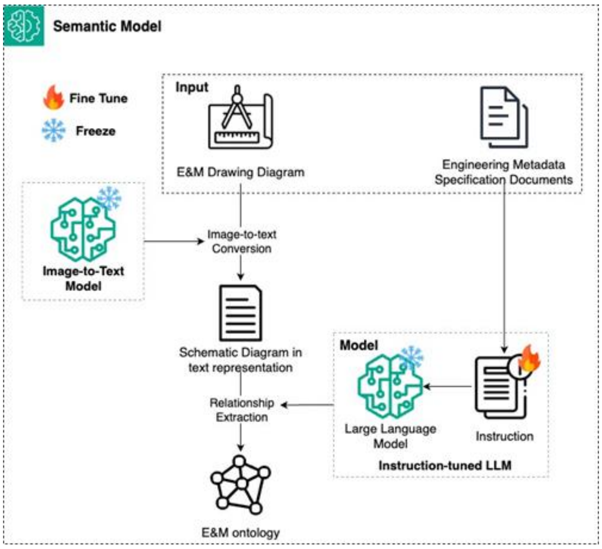
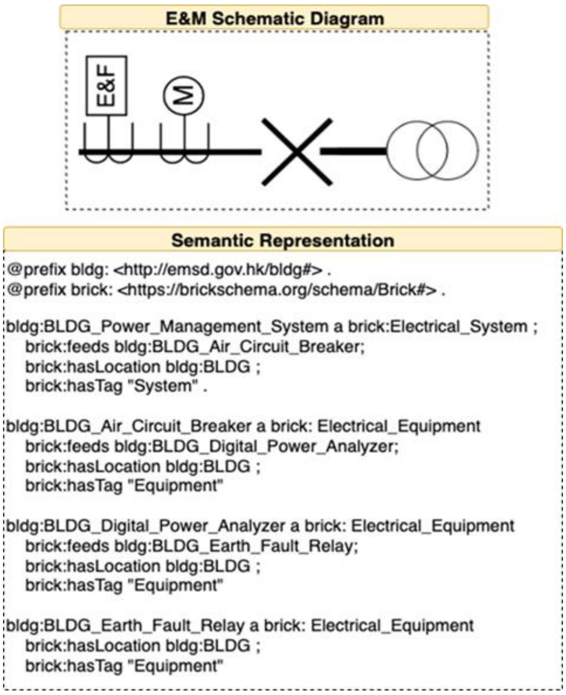


Fig. 2 - Design of the Semantic Model, illustrating the Conversion of Engineering Schematics into Machine-readable Ontologies through Image-to-Text and Entity-relationship Extraction

For clarity, Figure 3 presents an example E&M schematic alongside its corresponding semantic representation generated by the model.



```
@prefix bldg: <http://emsd.gov.hk/bldg#> .
@prefix brick: <https://brickschema.org/schema/Brick#> .

bldg:BLDG_Power_Management_System a brick:Electrical_System ;
   brick:feeds bldg:BLDG_Air_Circuit_Breaker;
   brick:hasLocation bldg:BLDG ;
   brick:hasTag "System" .

bldg:BLDG_Air_Circuit_Breaker a brick: Electrical_Equipment
   brick:feeds bldg:BLDG_Digital_Power_Analyzer;
   brick:hasLocation bldg:BLDG ;
   brick:hasTag "Equipment"

bldg:BLDG_Digital_Power_Analyzer a brick: Electrical_Equipment
   brick:feeds bldg:BLDG_Earth_Fault_Relay;
   brick:hasLocation bldg:BLDG ;
   brick:hasTag "Equipment"

bldg:BLDG_Earth_Fault_Relay a brick: Electrical_Equipment
   brick:hasLocation bldg:BLDG ;
   brick:hasTag "Equipment"
```

Fig. 3 - Example Schematic Diagram and its Semantic Representation

By combining vector indices and semantic enrichment, the semantic layer support RAG grounding, ensure the outputs from LLM are explainable, auditable, and interoperable across heterogeneous data sources. This representation further enables domain-specific semantics to be embedded into decision-making workflows, thereby supporting advanced capabilities such as explainable recommendations, cross-system integration, and tool interoperability.

The importance of semantic modelling is increasingly recognized internationally. For example, the recently published ASHRAE Standard 223P establishes a unified semantic data model for building systems, aligning with Brick and Project Haystack to support interoperable, machine-readable metadata [7]. Regulatory initiatives, such as Practice Notes for AI-ready Building Informatics of EMSD, provide practical guidance for implementation [8]. Engentica's semantic layer aligns with these standards by mapping extracted entities and relations to standardized ontologies. This alignment reduces adoption effort, improves interoperability with external systems, and enables verifiable, standards-aligned LLM-driven reasoning and multi-agent operation.

(d) Model Context Protocol (MCP):

A graph-based MCP is designed as a structured mechanism for organizing both generic and engineering-specific tools, where nodes represent tools and edges encode their functional relationships and capabilities. Unlike traditional approaches that require loading all tools prior to understanding user needs, the MCP performs a semantic analysis of user intent and dynamically retrieves a compact, contextually relevant sub-graph of candidate tools, following the principles of the GraphRAG approach [9]. The pre-selection process enables the system to reason over structured relationships in the graph, pass only the most relevant tools to the LLM for binding and execution, and thereby reduce hallucinations arising from improper tool selection and misuse (Figure 4).

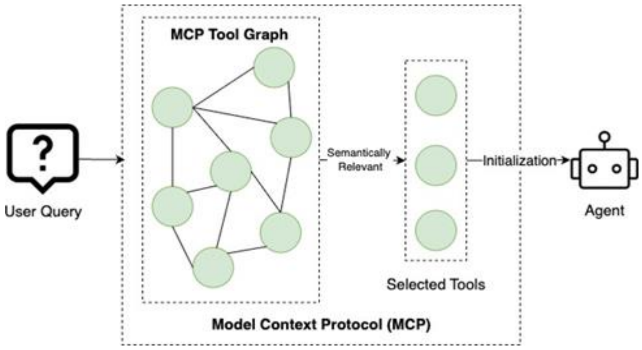


Fig. 4 - Design of the Graph-based MCP, representing tools as a graph for Semantic Retrieval, Contextual Selection, and Workflow Execution

Moreover, the framework of Engentica is designed to allow external tools to connect seamlessly through the

MCP, promoting collaboration with agentic tools developed by other parties. This integration eliminates the need for complex data connection processes, significantly lowering the investment cost of deploying new applications. This capability not only enhances scalability, interpretability, and reliable grounding in engineering workflows, but also accelerates the development of diverse applications, thereby fostering the growth of the New Quality Production Force.

(e) Databases:

The architecture integrates heterogeneous data sources to provide comprehensive system context. The iBMS collects live and historical sensor data from operating electrical and mechanical systems, enabling real-time monitoring and long-term performance analysis.

The DOMS documents maintenance activities of engineering machinery, capturing multimodal information such as text, images, and schematics describing fault events and corrective actions. The RDCC operates as a unified digital platform that monitor critical E&M equipment, including photovoltaic and chiller systems, through a real-time IoT infrastructure to enhance operational efficiency and environmental performance. The Engineering Knowledge Database, serve as a manifest, consolidates file-based resources such as drawing, O&M manuals, photo records, and project documents. Collectively, these data bases unify operational, maintenance, diagnostic, and knowledge-based information, forming the foundation for robust and data-driven decision-making.

(f) Generic and Engineering Tools:

Engentica integrates generic tools (e.g. web access, chat memory, analysis & visualization) and engineering-specific tools (e.g. optimization, fault detection, energy & cost analysis) (Figure 5). These tools extend the reasoning capabilities of agents by enabling them to retrieve contextual knowledge, analyze system behaviour, simulate outcomes, and execute corrective actions. In this manner, they bridge abstract reasoning with actionable engineering workflows, ensuring outputs remain explainable, verifiable and operationally relevant.

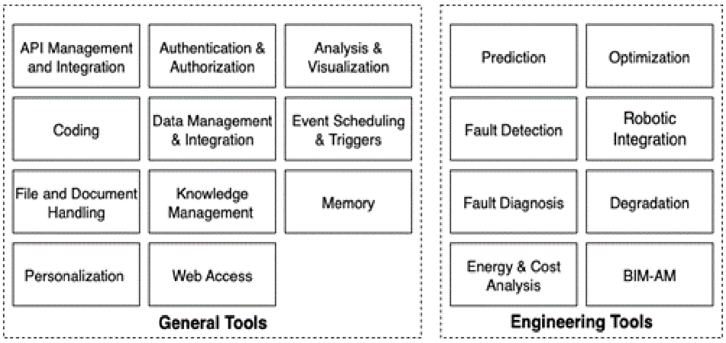


Fig. 5 - Generic and Engineering-specific Tools available within Engentica

3.2 Workflow Mechanism

The workflow is initiated by either user queries or event triggers. The agent supervisor interprets user query and dynamically assembles workflows, while the DWO route and assigns role-specialized agents to execute subtasks such as sensor data analytics, fault diagnosis, data visualization, simulation, and engineering system control. Subtasks are supported either by retrieving contextual evidence from system databases, using information indexing to enrich LLM prompts, or by leveraging general-purpose and engineering-specific tools through the MCP to enable reasoning, simulation, and actionable execution. The agent supervisor continuously monitors inter-agent communication flows by criticizing agent response to resolve inconsistencies, enhance response quality, and improve task success rates, thereby establishing a feedback loop that ensures reliability, adaptability, and contextual accuracy. The output response from agent or tools are recorded in memory and audit logs, ensuring reproducibility, human oversight, and resilient execution across interactive and automated workflows (Figure 6).

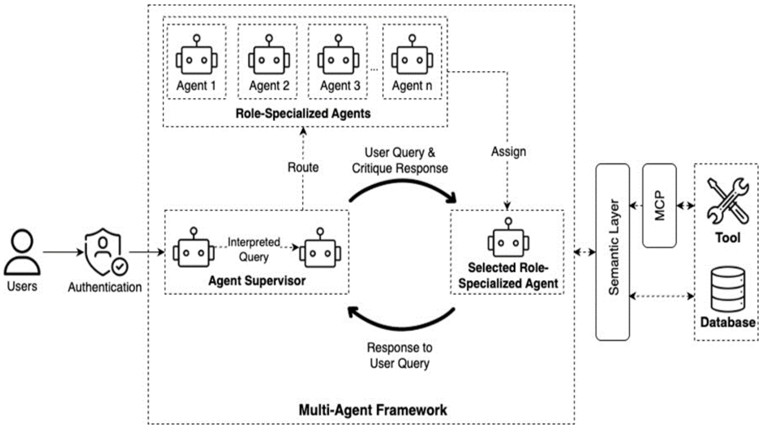


Fig. 6 - Workflow Mechanism of Engentica, illustrating how User Queries or Event Triggers are interpreted by the Agent Supervisor, decomposed into Subtasks by the DWO, and executed through Role-specialized Agents with Contextual Grounding from Databases and Tools via the MCP

3.3 Core Features

Engentica delivers a comprehensive suite of functionalities for electrical and mechanical operation and maintenance, combining real-time intelligence, predictive analytics, compliance-aware automation. By leveraging multi-agent reasoning, semantic retrieval, and tool usage, it streamlines engineering workflows to enable efficient decision-making, optimized system performance, and adaptive management across complex infrastructures. The system incorporates compliance-aware workflow composition with regulatory checkpoints and supports incremental integration of third-party AI services and legacy tools through standardized interfaces. Containerized, on-premises deployment ensures operational safety, low latency, and data sovereignty, making Engentica suitable for mission-critical infrastructure environments.

4. USE CASE

This section presents a streamlined end-to-end use case illustrating Engentica’s effectiveness in chiller plant optimization, energy analysis, and sensor fault detection (Figure 7). The scenario highlights how Engentica could facilitate intelligent decision-making, rapid anomaly detection, and automated control through integrated data access, LLM reasoning, and coordinated multi-agent workflows.

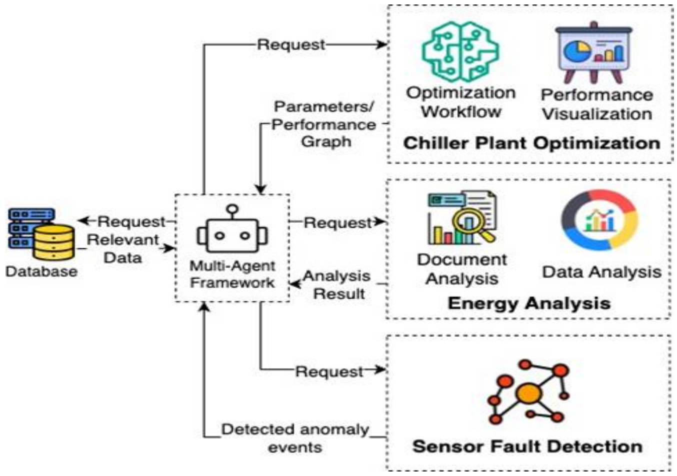
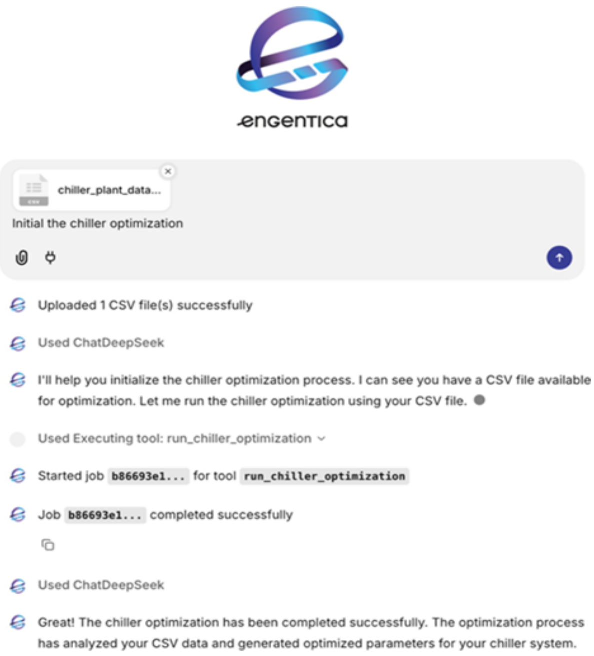


Fig. 7 - Case Study Overview of Engentica, demonstrating its application in Chiller Plant Optimization, Energy Analysis, and Sensor Fault Detection

4.1 Chiller Plant Optimization

In the chiller plant optimization scenario, Engentica provides an interactive interface that initializes the optimization process by loading live or historical operational data from the iBMS (Figure 8).



Initial the chiller optimization

Uploaded 1 CSV file(s) successfully

Used ChatDeepSeek

I'll help you initialize the chiller optimization process. I can see you have a CSV file available for optimization. Let me run the chiller optimization using your CSV file.

Used Executing tool: run_chiller_optimization

Started job `b86693e1...` for tool `run_chiller_optimization`

Job `b86693e1...` completed successfully

Used ChatDeepSeek

Great! The chiller optimization has been completed successfully. The optimization process has analyzed your CSV data and generated optimized parameters for your chiller system.

Fig. 8 - Engentica Interface for initiating Chiller Plant Optimization. The System loads Live iBMS Sensor Data and supports Optimization Requests through User Queries or Automated Event Triggers

Upon receiving user query or automated event trigger, the agent supervisor invokes the chiller plant optimization service through MCP. The agent then ingests the operational data from the iBMS or user-provided data file, including the chiller and water pump running status, chilled water temperature, water pump flow rate, cooling load produced, plant energy consumption and ambient condition.

Following published methodologies [10], the chiller plant optimization process employs a partially observable reinforcement learning algorithm combined with multi-objective Bayesian optimization to dynamically optimize water-side operation. This framework identifies trade-off between minimizing energy consumption and maintaining adequate cooling by efficiently exploring the parameter space. Through continuous interaction with a machine learning model derived simulated environment, the reinforcement learning agent iteratively refine its control strategies, enabling adaptation to diverse load profiles and environmental conditions, thereby achieving energy savings, cost reduction, and sustainability improvements.

Please provide the optimized control parameter for the chiller plant

Used ChatDeepSeek

I'll get the optimized control parameters for the chiller plant for you.

Used Executing tool: get_chiller_optimized_control_parameters

Started job `a65adae0...` for tool `get_chiller_optimized_control_parameters`

Job `a65adae0...` completed successfully

Data Display

record	CHR-01-S	CHR-02-S	CHR-03-S	CHR-01-CHWSWT	CHR-02-CHWSWT	CHR-03-CHWSWT	CHWP-01-S	CH 02-
0	On	Off	Off	6.56	0	0	On	Off
1	On	Off	Off	6.5	0	0	On	Off
2	On	Off	On	6.78	0	6.79	On	Off
3	On	Off	Off	6.96	0	0	On	Off

Please provide the comparison graph before and after chiller optimization

Used ChatDeepSeek

I'll get the COP comparison graph for you to show the before and after optimization results.

Used Executing tool: get_cop_comparison_graph

Started job `fe198b45...` for tool `get_cop_comparison_graph`

Job `fe198b45...` completed successfully

Images

Fig. 9 - Comparative Performance Visualization of the Chiller Plant, including a table of Opimized Control Parameters and a Plot of the COP before and after Optimization

The optimized control parameter is delivered as actionable recommendations or executed directly on the iBMS when authorized. Engentica also supports post-optimization analysis by visualizing efficiency improvements, including comparative plots of the coefficient of performance (COP) before and after optimization (Figure 9). This enables operators to assess the impact of optimization decisions and monitor long-term system performance.

4.2 Energy Analysis

In the energy analysis scenario, Engentica enables comprehensive building energy analysis through MCP server by integrating live and historical operational data, maintenance record, and engineering knowledge into a structured workflow. Upon a user query or automated trigger, the agent supervisor activates the energy analysis service through the MCP, retrieving relevant building information and energy data to construct a complete analysis profile, which includes foundational elements such as regulatory compliance analysis and energy use intensity (EUI) calculation, as illustrated in Figure 10.

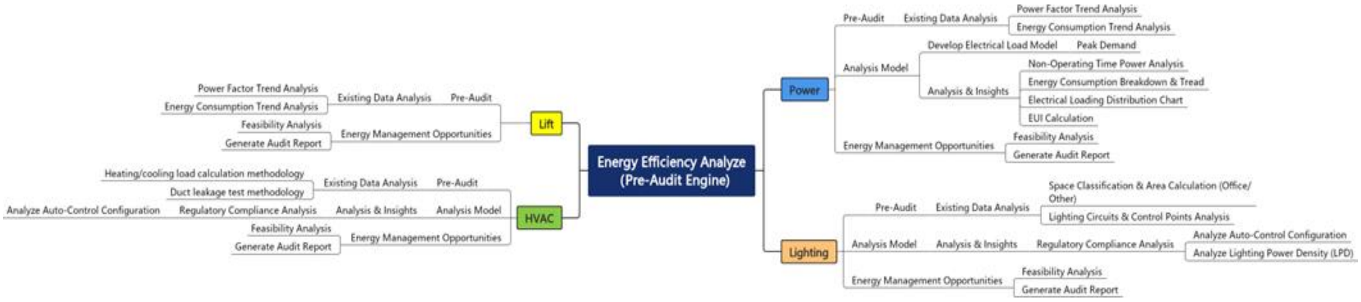


Fig. 10 - Workflow of Energy Efficiency Analysis for Lift, HVAC, Power, and Lighting subsystems, covering Pre-audit, Optional Analysis Models identification of Energy Management opportunities, and Audit Reporting

The analysis is structured around a detailed evaluation of the building's core energy-consuming systems. For the general power profile, the server constructs a detailed electrical load model, analyzing power factor trends and conducting non-operating time power analysis to identify phantom loads and inefficiencies. The Heating, Ventilation, and Air Conditioning (HVAC) analysis focuses on calculating EUI and evaluating fuel demand patterns to assess the heating and cooling plants efficiency. For lighting systems, the server performs a lighting circuit and control points analysis, calculates Lighting Power Density (LPD), and assesses control strategies against regulatory baselines. Finally, specialized loads such as lift systems are characterized by their duty cycles and integrated into the overall load distribution model to understand their contribution to peak demand.

Through this subsystem-level breakdown, Engentica automatically aggregates data, generates visualizations like consumption trend analyses and load distribution charts, and produces actionable reports. The agent identifies specific inefficiencies within each domain and recommends targeted energy management opportunities, such as power factor correction, HVAC operational adjustments, lighting retrofits, or schedule optimization.

By unifying data retrieval, analysis, and decision support, Engentica enhances operational efficiency, reduces energy waste, and supports sustainability objectives. The agent leverages semantic data integration, energy modelling tools, and RAG-enabled reasoning to interrogate its knowledge base of technical standards, ensuring that audit outcomes are actionable, explainable, and verifiable against established engineering benchmarks, enabling informed decision-making for building management.

4.3 Sensor Fault Detection

In the sensor fault detection scenario, Engentica utilizes a MCP server that equipped with knowledge graph-guided graph neural network to monitor anomalies in building sensor data. Upon a user query or automated trigger, the agent supervisor engages the fault detection service via MCP, retrieving the anomaly detected from the building sensor fault detection system.

Adapting the methodology from [11], the service employs the BuildKnow framework, which enhances incomplete smart metering data in sustainable buildings by leveraging building knowledge graphs (BKGs) to guide graph neural network (GNN) models. BuildKnow refines BKGs to identify meter dependencies, learns hierarchical representations of building entities, and fuses this structural knowledge with temporal patterns in metering data to generate accurate predictions for missing values.

These techniques enable anomaly detection by extending data enhancement to reconstruction-based monitoring: the BKG-guided GNN predicts expected meter readings based on dependence meters and temporal patterns. Anomalies are flagged when actual readings deviate significantly from predictions, such as exceeding a Coefficient of Variation of the Root Mean Square Error (CV-RMSE) threshold, indicating faults like sensor failures. This approach improves detection accuracy by incorporating domain-specific building knowledge, reducing false positives through context-aware reasoning, and facilitating root-cause analysis via

BKG correlations, thereby supporting proactive maintenance and enhanced E&M system reliability.

Engentica achieves sensor anomaly detection by integrating the sensor fault detection service into its multi-agent workflow through MCP. Role-specialized agents apply the service to return detected anomaly events, which can be extended to incorporate potential root-cause analysis and actionable recommendations, for example, scheduling preventive maintenance through DOMS. This integration ensures a seamless pipeline from anomaly detection to remediation, enabling proactive management, improving E&M system reliability, and promoting sustainable building operations.

5. CONCLUSION

This paper presents Engentica, an AI agent framework designed to manage the operational complexity of modern building engineering systems. Its architecture integrates a multi-agent system, RAG, and a graph-based MCP to unify heterogeneous data sources and interface with generic and engineering-specific tools. This enables the framework to interpret complex user intents and autonomously execute tasks. Use cases in chiller plant optimization, energy analysis, and sensor fault detection demonstrate Engentica's effectiveness in improving operational efficiency and system reliability. By equipping engineers with intelligent tools that reason, plan, and act, this work marks a significant advancement from passive system intervention to active system management, contributing to the development of a more efficient and sustainable smart infrastructure.

REFERENCES

1. HK Green Finance Association "Decarbonising Hong Kong Buildings: Policy Recommendations and Next Steps", 2020.

2. C. K. Lee et al., "Digital Transformation for a Smart City" in Proceedings IET Management Symposium 2023 - Digital Management in the Post-Pandemic Era, Hong Kong, May 2023.

3. Z. Xi et al., "The rise and potential of large language model based agents: A survey", Science China Information Sciences, vol. 68, no. 2, p. 121101, 2025.

4. B. Balaji et al., 'Brick: Metadata schema for portable smart building applications', Applied energy, vol. 226, pp. 1273-1292, 2018.

5. J. John and Others, 'Project haystack data standards', in Energy and Analytics, River Publishers, 2020, pp. 237-243.

6. M. Li, Z. Wang, G. Fierro, C. H. C. Man, P. M. P. So, and K. F. C. Leung, 'Developing an Automatic Approach to Generate Brick Model from Building Information Modelling', Available at SSRN 4759342.

7. O. Vyshnevskyy and L. Zhuravchak, 'Semantic models for buildings energy management', in 2023 IEEE 18th International Conference on Computer Science and Information Technologies (CSIT), 2023, pp. 1-4.

8. Electrical and Mechanical Services Department, "Practice Note for AI- ready Building Informatics - Semantic Modelling", 2025

9. H. Han et al., "Retrieval-augmented generation with graphs (graphrag)", arXiv preprint arXiv:2501. 00309, 2024.

10. C. H. C. Li et al., "Chiller Plant Replacement by MiMEP and Optimization with Reinforcement Learning Algorithm," The International Council on Electrical Engineering (ICEE) 2024, 2024.

11. F. He, J. Fan, Y. Deng, X. Zhang, K. T. Lau, and D. Wang, "Smart metering data enhancement in sustainable buildings via knowledge graph-guided graph neural networks", Knowledge-Based Systems, p. 114016, 2025.

Paper No. 7

BUILDING THE FUTURE: HOW AI DRIVES NEW QUALITY PRODUCTION FORCES IN RAILWAY CONSTRUCTION DELIVER

Author/Speaker: Mr. Auld Calum James
Senior Engineering Manager
MTR Corporation Limited

BUILDING THE FUTURE: HOW AI DRIVES NEW QUALITY PRODUCTION FORCES IN RAILWAY CONSTRUCTION DELIVERY

Mr. Auld Calum James
Senior Engineering Manager
MTR Corporation Limited

ABSTRACT

The integration of artificial intelligence (AI) technologies as new quality production forces in infrastructure project delivery such as railway represents a fundamental transformation in how construction projects are planned, executed, and managed. This paper examines four specific AI applications that are reshaping infrastructure construction delivery:

- AI assistant knowledge management systems;
- Agentic AI safety assistant systems;
- Outcome-based documentation generation systems and;
- Automated documentation checking and requirement management systems.

These solutions address critical challenges in knowledge accessibility, safety oversight, documentation efficiency, and compliance validation while creating foundations for continued innovation in construction delivery. The evidence demonstrates that strategic implementation of these technologies enables construction organisations to achieve new levels of efficiency, quality, and compliance that were previously unattainable, positioning the industry for continued advancement toward more automated and optimised construction processes.

1. INTRODUCTION

The infrastructure industry stands at a transformative juncture where AI technologies are emerging as new quality production forces that fundamentally reshape how construction projects are delivered. The integration of AI capabilities across different aspects of construction delivery - from knowledge management and safety oversight to documentation generation and compliance validation -represents more than incremental improvement; it constitutes a paradigm shift toward more intelligent, efficient, and reliable construction processes [1].

The concept of AI as a new quality production force recognises that these technologies do not merely automate existing processes but create entirely new capabilities that enable construction organisations to achieve levels of performance, quality, and compliance that were previously challenging and time consuming through traditional approaches. This transformation is particularly significant in infrastructure projects, where the complexity of regulatory requirements, safety considerations, and technical specifications creates unique challenges that benefit substantially from AI-powered solutions [2].

The current landscape of AI adoption in infrastructure construction delivery demonstrates significant momentum, with industry leaders recognising the strategic importance of these technologies for maintaining competitive advantage and meeting increasingly demanding project requirements. The convergence of advanced AI capabilities with construction domain expertise is creating opportunities for fundamental improvements in how construction projects are conceived, planned, executed, delivered, and operated [3].

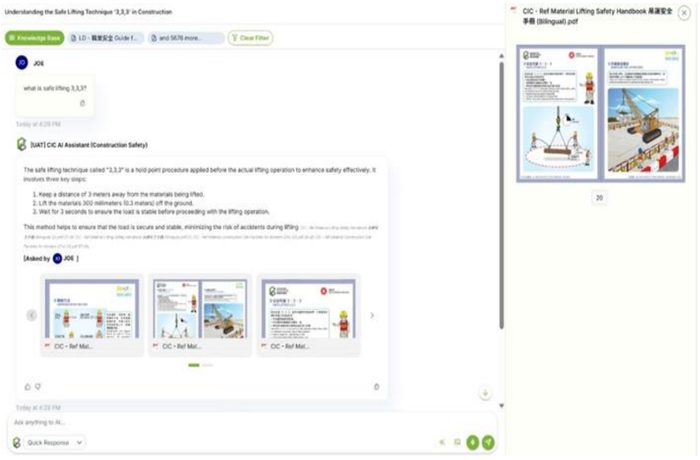
This paper examines four AI applications that represent the current state-of-the-art in construction delivery: AI assistant knowledge management systems that democratise access to institutional knowledge, agentic AI safety assistant systems that provide proactive safety support, outcome-based documentation generation systems that automate complex document creation, and automated documentation checking and requirement management systems that ensure comprehensive compliance validation. These applications demonstrate how AI technologies are creating new quality production forces that enable construction organisations to achieve unprecedented levels of efficiency, quality, and compliance.

2. AI ASSISTANT KNOWLEDGE MANAGEMENT SYSTEMS

Infrastructure projects generate and require access to vast amounts of information spanning regulatory requirements, technical specifications, best practices, and institutional knowledge that is distributed across multiple departments, systems, and documentation repositories. Traditional approaches to information management rely on keyword-based search systems and manual knowledge retrieval processes that are time-consuming, often incomplete, and frequently fail to provide users with the specific information needed for decision-making in construction delivery contexts [4]. The fragmentation of information across different work departments, document management systems, and knowledge repositories creates significant challenges for construction professionals who need immediate access to relevant information to support project delivery activities. Traditional search approaches require users to know specific keywords or document titles, limiting their effectiveness when users need information but are uncertain about exact terminology or document locations [5].

The complexity of systems and volume of information required for infrastructure projects often exceed human capacity for comprehensive knowledge management, creating risks of oversight, misinterpretation, or incomplete information that can impact project quality, compliance, and delivery timelines. The need for specialised domain knowledge across multiple disciplines further complicates information access and interpretation [6]. AI assistant knowledge management systems address these fundamental challenges by enabling natural language querying across thousands of documents and information sources, providing construction professionals with immediate access to relevant information through conversational interfaces that understand context and intent rather than relying solely on keyword matching [7].

To address this challenge, a government body has successfully implemented such an AI assistant knowledge management system to consolidate regulatory guidance, technical standards, and compliance requirements across multiple construction frameworks. The system enables teams to query complex regulatory requirements using natural language, receiving comprehensive responses that include relevant clauses, compliance pathways, and supporting documentation from thousands of regulatory documents and technical standards. The system leverages natural language processing capabilities to understand user queries in context, search across comprehensive knowledge bases that span multiple departments and information sources, and provide relevant responses that include specific references, citations, and supporting documentation. The AI system can process complex queries that involve multiple concepts, relationships, and requirements while providing comprehensive responses that address user needs [8].



what is safe lifting 3,3,3?

The safe lifting technique called "3,3,3" is a hold point procedure applied before the actual lifting operation to enhance safety effectively. It involves three key steps:

1. Keep a distance of 3 meters away from the materials being lifted.
2. Lift the materials 300 millimeters (0.3 meters) off the ground.
3. Wait for 3 seconds to ensure the load is stable before proceeding with the lifting operation.

This method helps to ensure that the load is secure and stable, minimizing the risk of accidents during lifting

[Asked by JOE]

Fig. 1 - The AI Assistant Knowledge Management System

The consolidation of knowledge from multiple sources into unified, searchable repositories enables construction professionals to access information that would otherwise require extensive manual searching across different systems and departments. The AI system’s ability to understand relationships between different types of information enables more comprehensive and contextually relevant responses to user queries [9]. The implementation of AI assistant knowledge management systems provides substantial benefits that directly contribute to enhanced productivity and quality outcomes in construction projects. The time savings achieved through natural language querying and comprehensive response generation are immediate and measurable, with users able to obtain relevant information in minutes rather than hours of manual searching and validation [10]. Knowledge accessibility improvements enable better decision-making throughout the construction delivery process by ensuring that relevant information is available when and where it is needed. The system’s ability to extract relevant pages and clauses provides users with specific references and citations that support compliance validation and regulatory adherence, reducing the risk of oversight or misinterpretation [11].

The knowledge gap reduction benefits are particularly significant for new workers entering the industry, who can leverage the AI system to access institutional knowledge and best practices that would otherwise require years of experience to accumulate. This democratisation of knowledge enables more consistent performance across different experience levels while supporting professional development and skill building [12], as summarized below:

- Quality assurance benefits include improved consistency in information access and interpretation, reduced risk of missing critical requirements, and enhanced ability to validate compliance across complex regulatory frameworks. The AI system’s comprehensive knowledge base ensures that users have access to current and accurate information while providing confidence in the completeness and relevance of search results [13].
- Improved knowledge accessibility through the system’s ability to extract specific references enhances decision-making and ensures compliance, reducing misinterpretation risks. This system also bridges the knowledge gap, especially for new workers, by providing access to institutional knowledge, promoting consistent performance and skill development.
- Quality assurance is improved through consistent information access, reduced risk of missed requirements, and enhanced compliance validation. The AI system’s comprehensive

knowledge base ensures accurate and complete search results.

3. AGENTIC AI SAFETY ASSISTANT SYSTEMS (WHATSAPP AI SAFETY ASSISTANT)

Safety management in construction has traditionally relied on reactive technology approaches where safety deficiencies are identified and addressed after incidents occur, often through machine learning video analysis systems that highlight safety issues post-event. This reactive approach, while valuable for learning and improvement, does not provide the proactive safety support that construction workers need to prevent incidents before they occur [14].

The complexity, and dynamic nature of construction sites create numerous safety challenges that require immediate attention and expert guidance. Construction workers, supervisors, and other professionals often encounter safety situations that require specialised knowledge or expert consultation, but traditional safety support systems are not readily accessible in real-time field conditions. The need for immediate safety guidance, hazard identification, and risk mitigation advice creates significant challenges for maintaining consistent safety performance across diverse construction activities [15]. Safety training and support approaches rely on periodic training sessions, written safety procedures, and human supervision that may not be available when and where safety decisions must be made. The gap between formal safety training and real-world application creates risks that can result in incidents, injuries, and project delays that impact both human welfare and project performance [16].

Agentic AI safety assistant systems address these as fundamental safety challenges by providing every construction professional with immediate access to AI-powered safety expertise through familiar communication platforms such as WhatsApp. These systems represent a paradigm shift from reactive safety management toward proactive safety support that is available in workers' pockets whenever and wherever safety decisions must be made [17].

This initiative demonstrates how AI assistants can serve as knowledge multipliers, capturing and disseminating safety expertise across the industry while continuously learning from field experiences and safety interactions. The multimodal capabilities of these AI safety assistants enable users to take photographs of construction conditions and receive immediate AI analysis that identifies potential risks and hazards while providing specific guidance on mitigation strategies. The AI system leverages comprehensive safety knowledge bases and extracts relevant safety standards and method statements to provide contextual advice that is specific to the observed conditions [18].

A Hong Kong surveying contractor has deployed a WhatsApp AI Safety Assistant System across a few of their construction projects, enabling field surveyors and construction teams to receive immediate safety guidance through their mobile devices. The system allows workers to photograph potential hazards or unsafe conditions and receive instant AI-powered analysis with specific recommendations for risk mitigation, creating a proactive safety culture that prevents incidents before they occur. The proactive nature of these systems enables safety intervention before incidents occur, with the AI assistant providing real-time guidance on safe work practices, hazard recognition, and risk mitigation strategies. The system's ability to analyse visual information and provide immediate feedback creates opportunities for preventing safety incidents that might otherwise occur due to lack of immediate expert guidance [19].

The photo depicts a construction site where a worker is seen kneeling on a temporary wooden walkway/platform that is elevate...

現場安全檢查報告

專案名稱:		專案類別:	
現場位置:		合約:	
陪同檢查人員:	Joe Wong	簽發人:	
檢查週期:	27.07.25 - 03.08.25	承包商:	
報告日期:	Sun 03 Aug, 23:30	報告參考ID:	WN17B4LB

總結

危害評級	描述
A	存在嚴重傷害的緊迫風險。建議立即糾正。
B	中度傷害或損壞風險。建議在24小時內採取行動。
C	低級別危害。在72小時內解決。

觀察

照片ID	觀察總結	拍攝日期
0		30.07.25

- 高空墮落危險: 工人於棚架上工作，已佩戴安全帶
  風險等級: B
  補救建議: 確保安全帶正確使用並固定於獨立生命線或安全錨點
- 物體打擊風險: 工人正在處理金屬棚架構件，若未妥善固定可能造成危險
  風險等級: B
  補救建議: 確保所有棚架構件均已牢固固定，並由合資格人員進行監督

Fig. 2 - The AI Safety Assistant System

The system also provides automated reporting capabilities enabling the AI safety assistant to generate comprehensive safety reports based on observed conditions and interactions, providing documentation that supports safety management and regulatory compliance. The system can also generate automated toolbox talks for site teams, ensuring that safety information and lessons learned are communicated effectively to the workforce [20].

Agentic AI safety assistant systems offer substantial and measurable benefits in construction, directly improving safety performance, reducing incident rates, and fostering a stronger safety culture. By providing expert-level safety guidance through familiar communication platforms, these systems ensure safety support is accessible precisely when and where it is most needed [21].

Key benefits include:

- Incident Prevention: The systems proactively identify potential hazards, offer real-time guidance on safe work practices, and provide immediate access to expert safety advice, thereby preventing accidents and injuries. Their ability to analyze visual information and deliver contextual safety recommendations creates opportunities to avert incidents that might otherwise occur [22].

- Knowledge Transfer: These systems democratize safety expertise, allowing less experienced workers to access expert-level guidance and supporting the overall development of safety knowledge and skills. The immediate feedback and guidance capabilities foster continuous learning, significantly enhancing overall safety competence [23].

- Automated Documentation and Reporting: Administrative overhead is reduced through automated documentation and reporting, ensuring safety interactions and observations are accurately recorded for regulatory compliance and continuous improvement. The systems also generate automated toolbox talks and safety communications, ensuring effective dissemination of critical safety information to the workforce [24].

4. OUTCOME-BASED DOCUMENTATION GENERATION SYSTEMS

Documentation in construction projects consume around 10% of project costs to develop key artifacts such as design reports, progress reports, tender documents, method statements and commercial risk management documents that must comply with local building regulations, contract requirements, and client specifications. Traditional approaches to document creation rely on manual processes that are time-consuming, prone to inconsistency, and often struggle to maintain compliance with complex and evolving regulatory requirements [25].

The complexity of compliance requirements across different regulatory frameworks, contract specifications, and client requirements creates significant challenges for construction professionals who must ensure that all documentation meets applicable standards while maintaining technical accuracy and completeness. Manual document creation processes often result in inconsistencies between different documents, gaps in compliance coverage, and significant time investment required for review and approval cycles [26]. Traditional document creation workflows involve multiple iterations, extensive review processes, and frequent delays due to ambiguous clauses, incomplete information, or compliance gaps that are identified late in the approval process. These inefficiencies create project delays, increase costs, and can result in compliance risks that impact project delivery and regulatory adherence. The challenge of maintaining consistency and quality across large volumes of documentation while ensuring compliance with multiple regulatory and contractual requirements creates significant resource demands that can impact project schedules and budgets. The need for specialised expertise in regulatory compliance, technical writing, and contract management further complicates the document creation process.

Outcome-based documentation generation systems address these fundamental challenges by leveraging AI technologies to automatically generate compliant documents including method statements, design reports, progress reports, and tender documents in seconds rather than days or weeks, while ensuring compliance with applicable regulatory and contractual requirements. The AI-powered document generation capabilities enable construction professionals to specify desired outcomes and requirements, with the system automatically generating comprehensive documents that incorporate relevant regulatory requirements, contract specifications, and best practices from approved historical documents. The system can generate multiple document types simultaneously while maintaining consistency and compliance across all generated materials.

Auto-generation and rewriting capabilities enable the system to create compliant documents based on best practices from past artifacts that have been approved by users, ensuring that new documents benefit from proven approaches while adapting to specific project requirements. The system can automatically rewrite and improve existing documents to enhance compliance, clarity, and completeness. Enabling real-time collaboration and change management capabilities allows project teams to provide feedback instantly, with AI assistance that expedites the approval process by identifying and resolving ambiguous clauses that typically delay approval cycles. The system can challenge users on unclear or incomplete information, ensuring that documents are comprehensive and ready for approval before they enter formal review processes.

The benefits provided by outcome-based documentation generation systems are substantial and immediate, contributing directly to improved efficiency, quality, and compliance in construction projects, as summarized below. The time savings achieved through automated document generation are significant, with documents that traditionally require days or weeks to create being generated in seconds while maintaining or improving quality and compliance standards.

- Significant Time Savings: Documents that traditionally take days or weeks can be generated in seconds, without compromising quality or compliance.

- Improved Quality: These systems ensure enhanced consistency across various document types, better compliance coverage, and a reduced risk of errors or omissions that could create project risks. By incorporating best practices from approved documents, new documents benefit from proven approaches while being adaptable to specific project requirements.

- Assured Compliance: Current regulatory requirements, contract specifications, and client standards are automatically integrated into generated documents, minimizing the risk of compliance gaps or violations. The system's ability to stay updated on regulatory changes ensures ongoing compliance.

- Enhanced Collaboration Efficiency: Review and approval processes are streamlined, feedback incorporation time is reduced, and ambiguities are resolved before documents enter formal approval cycles. This leads to fewer project delays and faster decision-making throughout the construction delivery process.

5. AUTOMATED DOCUMENTATION CHECKING & REQUIREMENT MANAGEMENT SYSTEMS

Infrastructure construction delivery such as complicated railway services must comply with thousands of performance requirements specified in contracts, regulations, and client specifications, requiring extensive manual review processes that consume hundreds of hours and create significant risks of oversight or misinterpretation. Traditional approaches to requirement validation rely on human reviewers who must manually compare contractor submissions against performance specifications while maintaining detailed records of compliance status throughout the project lifecycle.

The scale and complexity of requirement management creates particular challenges due to the volume of requirements that must be tracked, validated, and maintained throughout the construction process. Projects may involve up to 10,000 or more individual performance requirements that span multiple disciplines, regulatory frameworks, and contractual obligations, creating management challenges that exceed human capacity for comprehensive oversight.

Manual review processes are inherently limited by human capacity for processing large volumes of detailed information while maintaining accuracy and consistency. The time required for comprehensive requirement validation often creates project bottlenecks, while the risk of human error or oversight can result in compliance gaps that are discovered late in the project lifecycle when they are expensive and time-consuming to address. The challenge of maintaining current and accurate records of compliance status across thousands of requirements while ensuring that all contractor submissions are properly validated against applicable specifications creates significant administrative overhead that can impact project schedules and budgets. The need for specialised expertise in requirement interpretation and compliance validation further complicates the management process.

Automated documentation checking and requirement management systems address these fundamental challenges by leveraging AI technologies to automatically review and validate up to 10,000 performance requirements within specifications and contracts, providing comprehensive compliance validation throughout the project lifecycle while ensuring that assets meet client performance specifications. The automated comparison capabilities of these systems enable comprehensive validation of contractor submissions against client performance specifications and contemporaneous records, ensuring that all requirements are fulfilled while maintaining detailed documentation of compliance status. The AI system can process vast amounts of documentation and data to identify compliance gaps, inconsistencies, or areas requiring attention. Enabling impartial analysis capabilities provides objective assessment of compliance status with detailed explanations and confidence scores that help users focus on items that genuinely require attention rather than spending time on requirements that are clearly satisfied. This prioritisation capability enables more efficient use of human expertise while ensuring that critical compliance issues receive appropriate attention.

The interactive guidance capabilities enable users to engage with the AI system to obtain insight on how to resolve ambiguities or address compliance gaps, providing expert-level guidance on requirement interpretation and compliance strategies. The system can recommend specific actions or approaches for addressing identified issues while maintaining comprehensive documentation of resolution strategies. Capturing all of the capabilities within one solution provides a single source of readiness with automated readiness assessment capabilities to provide clients with comprehensive readiness risk reports that determine overall operational readiness based on compliance status across all applicable requirements. These reports provide executive-level visibility into project compliance status while identifying specific areas that require attention before project completion.

The benefits provided by automated documentation checking and requirement management systems are substantial and measurable, contributing directly to improved compliance assurance, reduced project risks, and enhanced efficiency in infrastructure construction projects, as summarized below. The time savings achieved through automated requirement validation are significant, with processes that traditionally require hundreds of hours being completed in minutes while maintaining or improving accuracy and completeness.

- Compliance assurance benefits include comprehensive validation of all applicable requirements, reduced risk of oversight or misinterpretation, and enhanced ability to demonstrate compliance to clients and regulatory authorities. The system's ability to maintain detailed records of compliance status throughout the project lifecycle provides comprehensive audit trails, and a single source of truth for change management that support regulatory compliance and client satisfaction.

- Risk reduction benefits include early identification of compliance gaps or issues that can be addressed proactively rather than reactively, reduced risk of late-stage compliance discoveries that can create project delays or cost overruns, and enhanced ability to maintain compliance throughout the construction process. The system's prioritisation capabilities ensure that critical issues receive immediate attention while routine compliance matters are handled efficiently.

- Efficiency improvements include optimised use of human expertise through intelligent prioritisation of issues requiring attention, streamlined compliance validation processes, and enhanced ability to provide clients with current and accurate compliance status information. These improvements enable faster decision-making and more effective project management throughout the construction delivery process.

6. INTEGRATION & FUTURE DIRECTIONS

The successful implementation of AI solutions in infrastructure construction delivery such as complicated railway services requires careful attention to integration across different construction activities and stakeholder organisations. The AI assistant knowledge management system provides the foundational information infrastructure that enriches project teams access to knowledge, while the safety assistant, documentation generation, and requirement checking systems create a comprehensive AI ecosystem that addresses critical aspects of construction delivery.

The integration of these solutions creates synergistic effects that amplify the benefits of individual applications. Knowledge management systems provide the information foundation that enables more effective safety assistance, while documentation generation systems benefit from the compliance validation capabilities of requirement checking systems. This integrated approach enables construction teams to achieve levels of coordination and optimisation that would be impossible through individual solutions.

Looking toward the future, the trajectory of AI adoption in infrastructure construction delivery presents significant opportunities for continued advancement toward automated building processes that extend from automated document creation to robotic construction sites. The foundation provided by current AI solutions creates the information infrastructure and process optimisation capabilities that will enable more advanced automation in future construction delivery.

The next 3 to 5 years will likely witness continued advancement in AI capabilities, reduced implementation costs, and better integration between different AI systems. The convergence of AI with other emerging technologies such as robotics, internet of things (IoT) sensors, and augmented reality (AR) will create new possibilities for construction delivery that build upon the foundation established by current AI solutions.

7. CONCLUSION

The integration of AI technologies as new quality production forces in infrastructure construction delivery such as railway represents a fundamental transformation that addresses critical challenges in knowledge management, safety oversight, documentation generation, and compliance validation. Through AI assistant knowledge management systems, agentic AI safety assistants, outcome-based documentation generation, and automated requirement checking systems, AI is enabling new levels of efficiency, quality, and compliance that were previously unattainable.

The evidence presented demonstrates that these specific AI applications are already providing measurable benefits in projects while creating foundations for continued innovation and advancement toward more automated construction delivery processes. The most successful implementations are those that recognise these AI solutions as enhancements to human expertise rather than replacements for it. The industry-wide implications of AI adoption infrastructure construction delivery are substantial and will continue to evolve as these technologies mature and become more widely adopted. Organisations that can effectively integrate these AI capabilities with traditional construction expertise while maintaining high standards of safety, quality, and compliance will be positioned to thrive in an increasingly competitive and demanding construction environment.

The call to action for the industry is clear: the time for strategic implementation of these proven AI solutions has arrived. Success will require thoughtful planning, systematic capability development, and collaborative approaches that leverage the collective expertise of the industry while embracing the transformative potential of AI technologies as new quality production forces in construction delivery.

REFERENCES

1. McKinsey & Company. (2024). "The journey toward AI-enabled railway companies." McKinsey Infrastructure Insights.

https://www.mckinsey.com/industries/infrastructure/our-insights/the-journey-toward-ai-enabled-railway-companies

2. Boston Consulting Group. (2025). “The Route to a Fully Digitized Rail System.” BCG Publications. https://www.bcg.com/publications/2025/route-to-a-fully-digitized-rail-system

3. Phusakulkajorn, W., Núñez, A., Wang, H., & Dollevoet, R. (2023). “Artificial intelligence in railway infrastructure: Current research, challenges, and future opportunities.” Intelligent Transportation Infrastructure, 2(1), 1-25. https://academic.oup.com/iti/article/doi/10.1093/iti/liad016/7264159

4. Construction Today. (2024). “The Rise of Artificial Intelligence in Construction.” Construction Industry News. https://construction-today.com/news/the-rise-of-artificial-intelligence-in-construction/

5. Real KM. (2022). “Using artificial intelligence to improve knowledge management in the construction industry.” Knowledge Management Research. https://realkm.com/2022/12/19/using-artificial-intelligence-to-improve-knowledge-management-in-the-construction-industry/

6. Forbes. (2024). “AI-Powered Design And Construction.” Technology Innovation. https://www.forbes.com/sites/heatherwishartsmith/2024/06/10/ai-powered-design-and-construction/

7. ScienceDirect. (2021). “Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges.” Automation in Construction. https://www.sciencedirect.com/science/article/pii/S2352710221011578

8. Construction Today. (2024). “Top 8 AI Platforms Enhancing Safety and Efficiency in Construction.” Construction Technology News. https://construction-today.com/news/top-8-ai-platforms-enhancing-safety-and-efficiency-in-construction/

9. Oracle. (2025). “AI in Construction: Benefits and Opportunities.” Enterprise Technology. https://www.oracle.com/construction-engineering/ai-construction/

10. AvidXchange. (2024). “9 AI Applications in Construction.” Financial Technology. https://www.avidxchange.com/blog/ai-applications-in-construction/

11. Autodesk Construction Cloud. (2024). “AI for Construction.” Construction Technology. https://construction.autodesk.com/workflows/artificial-intelligence-construction/

12. Lumenalta. (2024). “AI in construction: Practical applications, safety, and industry trends.” Technology Consulting. https://lumenalta.com/insights/how-can-ai-be-used-in-construction

13. ABC RMC. (2025). “AI in Construction: Transforming Projects and Safety.” Construction Industry Association. https://www.abcrmc.org/ai-in-construction-transforming-projects-and-safety/

14. Epsilla. (2024). “Revolutionizing Construction Safety with Epsilla AI Agent.” AI Safety Solutions. https://www.epsilla.com/verticals/construction

15. Pelco. (2024). “AI in Construction Safety: Latest Innovations and Trends.” Security Technology. https://www.pelco.com/blog/ai-in-construction-safety

16. MIT Technology Review. (2025). “How generative AI could help make construction sites safer.” Technology Research. https://www.technologyreview.com/2025/07/02/1119607/how-generative-ai-could-help-make-construction-sites-safer/

17. OpenSpace. (2024). “Reality Capture & Construction Site Documentation.” Construction Technology. https://www.openspace.ai/

18. Project Safety Journal. (2025). “Artificial intelligence - your new assistant.” Safety Technology. https://projectsafetyjournal.com/artificial-intelligence-your-new-assistant/

19. ScienceDirect. (2024). “AI integration in construction safety: Current state, challenges, and future directions.” Safety Science. https://www.sciencedirect.com/science/article/abs/pii/S0926580524001791

20. SWAPP. (2024). “AI-powered documentation and modeling automation for architects.” Construction AI. https://swapp.ai/

21. Datagrid. (2025). “How AI Automates Document Management in Construction.” Data Management. https://www.datagrid.com/blog/automate-document-management-construction

22. Document Crunch. (2024). “AI Construction Contract Analysis & Management.” Legal Technology. https://www.documentcrunch.com/

23. Inncircles. (2025). “Generate construction documents with AI.” Construction Technology.

https://inncircles.com/resources/blogs/681c9d7951f6475fc0b4e4e6/

24. Windward Studios. (2024). “Construction Document Automation.” Document Automation Solutions. https://www.windwardstudios.com/blog/construction-document-automation

25. Jama Software. (2024). “Leveraging AI in Requirements Management.” Software Engineering. https://www.jamasoftware.com/blog/leveraging-artificial-intelligence-in-requirements-management/

26. IBM Watson IoT. (2024). “AI driven requirements management.” Enterprise Solutions. https://www.ibm.com/internet-of-things/learn/requirements-management-ai/

Paper No. 8

MAKING YOUR ELECTRICAL SWITCHBOARD AI READY

Authors/Speakers: Mr. Cyrille Godinot, Product Owner
Mr. Etienne Samain, Application Architect
Mr. Kevin SH Hung, Power System Architect
Ms. Jaya Mishra, Principal Technical Expert
Schneider Electric Ltd.

MAKING YOUR ELECTRICAL SWITCHBOARD AI READY

Mr. Cyrille Godinot, Product Owner
Mr. Etienne Samain, Application Architect
Mr. Kevin SH Hung, Power System Architect
Ms. Jaya Mishra, Principal Technical Expert
Schneider Electric Ltd.

ABSTRACT

The evolution of electrical switchboards has accelerated with the rise of smart panels, now embedded with internet of things (IoT) sensors and intelligent components that enable real-time communication and data sharing. This digitalization has become the driving force of modern electrical systems, transforming panels from passive infrastructure into active, data-rich platforms that support smarter decision-making and operational efficiency.

Global standards are shaping this transformation by defining frameworks for digitalizing low-voltage switchgears. These standards support the development of a complete digital architecture that overlays traditional electrical systems, enabling seamless integration across building systems and ensuring interoperability.

At the heart of this shift is a unified digital ecosystem - a single, simple and cybersecure framework that connects not only the switchboard but also HVAC, lighting, access control, UPS, and more. This convergence enhances visibility, control, and performance across the entire building, aligning with the equation: Digital + Electric = Safe, Available and Sustainable.

With this interconnected infrastructure generating vast amounts of data, artificial intelligence (AI) becomes the natural next step. By analyzing big data, AI can optimize energy use, predict maintenance, and improve building performance - driving greater sustainability, safety, and availability in the built environment.

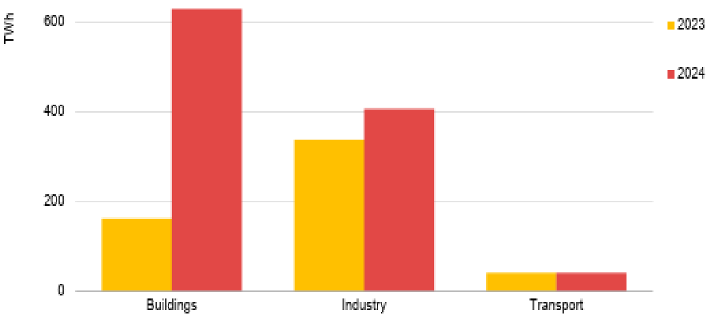
1. INTRODUCTION

In October 1879, when Thomas Edison lit the first incandescent light bulb with a continuous source of electricity, he might have been far from guessing how much the world would be transformed by his invention.

In turn, electricity has become a cornerstone of humanity industrialization and modernization along the twentieth century; bringing light in almost every home, enabling expansion of motorized applications like lifts, pumps and many other industrial applications, just to name a few.

Along the century, many developments were brought forth to resolve various challenges like safety and availability; and the arrival of circuit breaker technologies have significantly enhanced safety for people and properties, unlocking further growth and progress.

With the expansion of applications and improved availability and safety, the quantity of electricity consumed in the world has increased years on years exceeding 31.000 TWh in 2024.



IEA. CC BY 4.0.

Fig. 1 - IEA Global Annual Change in Electricity Consumption by Sectors

As a result, cost of electricity has taken a larger share of the total expenses for building operations, and fluctuations in electricity prices have motivated building owners to seek out solutions for better control of their consumption and to optimize usage. For instance, Thomas Edison’s incandescent light bulb with filament has been replaced almost everywhere with LEDs thanks to the huge jump in technology enabling a significant reduction of consumption while ensuring similar light comfort in most applications.

Meanwhile, the pressure on CO_2 based energy (in heat or transportation for instance) has created new acceleration for expansion of electricity usages, as consumers are seeking low-carbon energy to continue their operations.

Nowadays, our world has become highly dependent on availability of electricity, and any outage at local level, or even worse, at regional or country level represents huge exposure.

On the electricity production front, renewables sources like solar and wind farms have reshuffled the way electricity is produced; from a centralized model strictly controlled by utilities, to an extremely decentralized production where each building owner can turn their building into a prosumer, with not just the ability to produce electricity for self-usage but can also re-inject electricity into the grid if local demands are met. This opens the opportunity for some building owners to store energy locally and become operators of microgrids to optimize further their electricity bill and CO_2 impact.

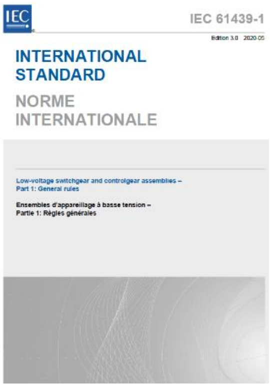
All of these transformations compound into and result in a more complex system where management of safety, availability and sustainability have to be achieved simultaneously.

The purpose of this paper is to discuss the opportunities and challenges of bridging the two worlds of Digital and Electrical in what we call Electricity 5.0 - The Electrical system empowered by AI.

2. STANDARDS

William Thomson, born 200 years ago, was a pioneer of international standardization and the first president of International Electrotechnical Commission which is more widely seen as IEC; the body that helps electrical engineer and electrical equipment manufacturers to speak the same language and prepare this industry for the future.

IEC has continuously updated their Standards to reflect the state-of-the-art of technology and align progress to reality. For instance, electrical panels are extensively described in the Standard, IEC 61439 [1] (Figure 2), which is an evolution of IEC 60439 that came before and now replaced.



IEC 61439-1

Edition 3.0 2020-05

INTERNATIONAL
STANDARD

NORME
INTERNATIONALE

Low-voltage switchgear and controlgear assemblies –
Part 1: General rules

Ensembles d'appareillage à basse tension –
Partie 1: Règles générales

Fig. 2 - Front Cover of IEC 61439-1

Industry has taken the challenge to complement the traditional electrical distribution panel with a new set of sensors and solutions to continue the pursue of providing safer, available and sustainable electricity.

2.1 Availability

Naturally, the observation of breakers and the maintenance of switchboard have been done year after year to ensure safe and reliable operations of the electrical system, mostly based on the recommendations of electrical device original equipment manufacturers (OEMs) (e.g. Power Story for Availability [2]).

IEC TR 63482 [3] on Maintenance of LV Switchgear, and Circuit Breakers described in IEC 60947-2 [4], and their assemblies provide guidance and recommendation for the specification and selection of maintenance approach and for the planning and execution of the maintenance calls for moving from scheduled maintenance to condition-based maintenance and predictive maintenance.

2.2 Digitalization

With the increasing number of sensors and IoT solution added to switchboards, it became obvious that some harmonization was needed to define and simplify the design, assembly, installation and usage of switchboards while ensuring the continuation of delivering safe solutions.

The latest IEC TS 63290 “Intelligent assemblies” [5] describes the complementary requirements to install digital equipment in electrotechnical assembly for the purpose of achieving higher level of service in electrical switchboards.

2.3 Safety

Several risks are present in electrical systems which may typically lead to electrical fire, electrical injury or arc fault. Even if switchboards to IEC 61439 are designed to be arc resistant, there is still a risk to have an arc fault situation, and there is a need to mitigate the impact of such event, specifically for critical applications where electricity availability is crucial for operations (e.g. Power Story for Safety [6]).

IEC/TR 61641 [7] on internal arc fault in an assembly is considering moving from passive solution with arc containment to an active solution with an arc mitigation system. Linked with IEC 60364-4-42 [8], this is expected for publication July 2026.

2.4 Sustainability

Of course, energy measurement is not new, and many solutions are available on the market. However now IEC 61439 is taking the challenge to enhance switchboards to become more reliable, to extend their life cycles and help reduce energy consumption thanks to the standardization of the data collected along the usage of the switchboard on all its devices and sensors.

Describing wired & wireless digital architectures in switchboard to enable monitoring and control at edge or cloud level is the confirmation that IEC standards are paving the way our switchboards will enable deployment of AI solutions for a safer, reliable and sustainable future.

Interesting fact, William Thomson was also the first scientist to be elevated to Britain House of Lords as Lord Kelvin, well known for inventing the international system for absolute temperature, a unit typically not perceived as part of an electrical unit, but clearly high temperature is an outcome of electrical losses and one of the main reasons for electrical fire. We should not forget that.

3. DIGITALIZATION TRANSFORMATION

At the heart of this shift is a unified digital ecosystem - a single, simple and cybersecure framework that connects not only the switchboard but also HVAC, lighting, access control, UPS, and more. This convergence enhances visibility, control, and performance across the entire building, enabling AI to deliver on the value of the equation: Digital + Electric = more Sustainable, Safer and higher Availability.

3.1 Electrical Safety Benefits from Digitalization

In all electrical system, Safety is the main purpose. Breakers, for instance, trip to protect people and property and to help avoid electrical problems escalating into a disaster.

Over time, the solution has improved to provide even more safety in other electrical distribution networks such as TT or TN for instance. A breaker now may trip for different reasons, and many settings are required to make sure there will be no undesired trip.

Breakers are becoming smarter and incorporate many digital functions, leaving their electromechanical wheels to digital screens, and they are also becoming part of a digital ecosystem able to interact and to communicate information like their own status (Open/Close/Trip) and for which reason they tripped which is very useful for the maintenance staff.

Safety is however also expanded beyond the product and looking at its own system. For instance, the ability to monitor temperature of bolted connection on busbar is critical to identify if some bolts might not have been properly tightened to the expected torque. Some of these sensors are wireless and battery-less, enabling a very simple installation in greenfield as well as in brownfield. Thus, by pairing such type of sensors installed at all critical connection points, you have now a permanent view of potential hotspot without having to wait for the next IR inspection. See Figure 3 on such type of sensors.

Additionally, these temperature data are sent to a digital edge able to compare temperature between phases, to calculate trends, and to contextualize the temperature information with the actual current going through each phase, leveraging the best of digital for your safety.

Fig. 3 - PowerLogic^{TM} TH110 “EMS59440”

Similarly, if the hotspot is related to a loose cable connection, then the first signal of this problem will be volatile organic compounds (VoCs) that can be detected by an electronic “nose” (Figure 4).

Any old electrician will tell you that an electrical panel overheating will first be detected by its characteristic smell of “melted plastics”. From there you can start your investigation.

However, thanks to continuous monitoring, you will receive alarms when things are going wrong even before the electrical fire starts.

Fig. 4 - PowerLogic^{TM} HeatTag “SMT10020”

Therefore, digitalization is bringing new opportunities to improve safety by introducing new sensors into the digital ecosystem of the electrician or facility manager. Other opportunities with insulation monitoring or digital arc flash mitigation solution are leveraging digitalization too.

3.2 Digitalization Improves Availability

The purpose of electricity is to serve a load, which can be a simple light to a very critical equipment in an intensive care room in a hospital. So, depending on the application, it is required to adapt the level of digitalization to the level of criticality of the application.

What you want is to avoid failure of your critical equipment by avoiding electrical equipment tripping or even worse, fail to trip. Nowadays, another risk is rising due to the spread of distributed energy that can be produced and stored next to buildings and then consumed in high power for recharging electric vehicles.

What you should monitor first is the electrical flow itself (voltage, current) but also all the “micro faults” that are often invisible but can be the source of many problems for the loads. Things like harmonics (voltage and/or current), unbalance phases or various distortion can eventually lead to faulty equipment, as newer equipment contains more and more electronic components which, even if they passed various tests to be certified, can be exposed to level of distortions far beyond what the standards are admitting.

Electrical equipment sees all those perturbations, and sometimes, they may interpret such a situation as a tripping condition, because their purpose is to avoid the worst situations. Hence, it is specifically interesting to access the breaker’s internal data because often faults are predictable. Indeed, the conditions for a breaker to trip are mostly due to a slow degradation of some conditions, like damaged cable, loose connection, or other degradation modes.

Both IEC and NFPA standards have evolved to recommend the tracking of maintenance activities and ensure that maintenance is done as needed per manufacturer recommendations. This means that tracking the usage of an asset can provide valuable information about its ageing. Take for instance a simple contactor, even if it can usually sustain a very large number of operations, the conditions under which it operates can significantly affect its life expectancy. Also, electromechanical equipment very often uses grease to enable the movement of mechanical parts, but in hot outdoor or dusty conditions, this grease may not last as long as in clean indoor switchboards. A breaker that might not be able to operate at its expected speed may lead to more serious damage to the electrical installation and loads as well, so it is always worth to keep a fresh eye and monitor the conditions in which it is operated.

Looking at the transformation we are living in today, where each building is becoming a “prosumer” and can generate its own source of electricity thanks to photovoltaics mostly and store this energy in fixed battery systems. Buildings also have new consumers of electricity like heat pumps and electric vehicle charging stations on the premise. To keep control of this new context, strict and robust monitoring, and a control system must be put in place to avoid potential overcurrent situations when demand exceeds the capability of the system to supply electricity.

Therefore, it becomes clear that in all cases, the monitoring of the electrical flow, the electrical equipment, the sources and loads, and an appropriate maintenance management is required to deliver the full availability of electricity in a building.

3.3 Improve Sustainability Thanks to Digitalization

While electricity is one of the energy sources available, it has become clear that, since it can be produced from renewable sources, it is nowadays the most efficient to produce, store and consume. Its adoption is accelerating in new fields like transportation and expanding in industrial applications.

In Hong Kong, for instance, the priority to improve sustainability is to work on efficiency of commercial and residential buildings because since 2012, this pair has represented more than 93% of total energy consumption as per Figure 5.

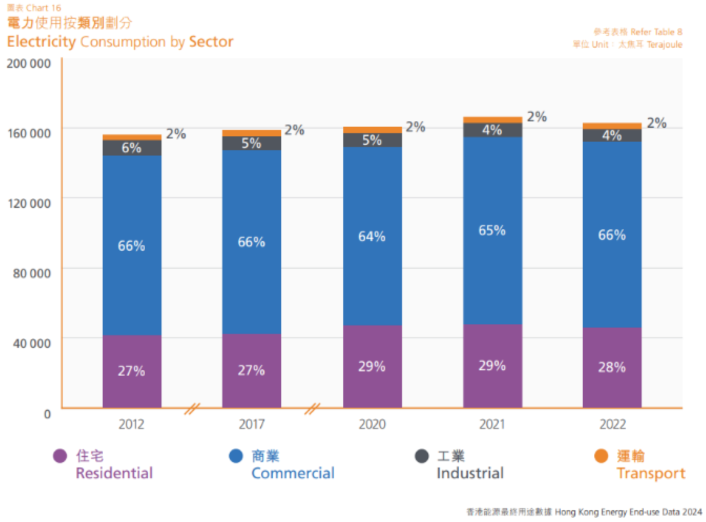


Fig. 5 - HK Electricity Consumption by Sectors

It is our responsibility to increase effort for managing electricity in the most efficient way possible and this starts with measurement. Having a clear and granular understanding of electricity consumption is the number one success factor in improving the way you manage electricity.

While everyone pays their electrical bill based on utility meter, for identifying opportunities for savings, additional measurement devices are required. Several options are available.

Wireless sensors attached to breakers are the cheapest solution if they are considered from design phase. They offer consistency and ease of installation while enabling us to build good granularity from day one. Moreover, when additional devices are needed during the operation phase, these wireless sensors are well appreciated and simpler to implement. Since ratings can be quite different, it is required to select a vendor that has a wide range of wireless sensors.

For ease of data collection, wireless gateways have to offer simple aggregation of sensors specifically at the commissioning phase, and also during operation where you may have to do diagnostics. Gateways offering web pages for instance are quite useful since all information is available in the same location.

Obviously, our purpose of collecting sensor data is to visualize energy consumption and help identify which saving opportunities can be achieved. While reading direct measurements on some sensors was the norm, the gateway with webpages is a very good local alternative at the electrical switchboard level if it offers some data aggregation and storage capabilities.

Leveraging data at site level is even more interesting since it enables us to analyze data consumption on a wider level. This supervision software solution can either be hosted locally or cloud base solution can be leveraged.

These tools start to offer valuable insights to help identify potential sources of savings, analyzing data patterns and inconsistency over time.

Combining data from multiple sites is an additional opportunity to identify savings. For instance, a restaurant chain operator may help each restaurant to make the right choice based on shared experiences and analytics. Additionally, combining data with external sources like meteorological information enables us to identify additional sources of savings.

So far, we have focused mainly on energy consumption, but sustainability is enabled by the fact that each electricity consumer can also become a producer. Photovoltaics have become very popular with retail chains covering car parks with solar panels to improve customer experience and enable them to reduce their CO_2 impact. This production of energy requires the facility to have its own measurement capability as it is extremely variable.

Along with such local sources of electricity comes the opportunity to have a local storage solution which will further enable energy consumption optimization according to various criteria. A typical choice is to optimize based on cost of electricity, which offers a superior return on investment if, and only if, your system can make the right decision at the right moment thanks to a proper design of your digitalized system.

3.4 Digitalization Unification

Value of Digitalization comes when a complete electrical ecosystem can merge into one digital system. While this brings many opportunities, it may in some cases bring also its own set of challenges that have to be identified and addressed ahead.

Usually, the design of a digital electrical system will focus on convergence of protocols as a starting point. For instance, serial protocols (like Modbus Serial) or Ethernet based protocols (like Modbus TCP) are selected. This is a good base, but it is not enough. Indeed, data must converge through gateways and aggregate to a central system. This is where data is visualized and where the operator or maintenance personnel can access all information by an electrical SCADA, a building management system (BMS) or an energy monitoring system.

Many parameters in data models have to be considered. Beyond product specific address tables, one should consider the data collection rates but also the uniformity of data collected (same unit, same format for same information etc.). Unification of digital ecosystems is required to bring all information at once and enable scaling of digital adoption in electrical systems.

The design of the digital ecosystem, the selection of the gateways and the organization of the data to make them meaningful can be significantly time consuming. To significantly reduce system integration effort, you may decide to select a preconfigured solution that enables data to flow naturally between the edge and cloud systems. This is where AI can make best use of the data; for example, optimization of energy usage taking into account local energy storage, solar panel production forecast, grid energy cost, and so on.

3.5 Segments Specific Situations

The flexibility and diversity of these IoT assets allow us to build a digital architecture overlaying the usual power architecture adapted to the customer needs.

For example, retail industry deals with higher energy expenses and labor challenges. It is clear that a sustainable approach is vital for long-term success. With a lack of workers in stores, retailers need innovative ways to improve operations and customer experiences. Decarbonization is now a top priority, leading to the demand for energy-efficient and eco-friendly solutions. To tackle these challenges, integrating smart solutions in retail spaces and panels is crucial, offering opportunities to save energy, streamline operations, and cut costs.

The digital layer usually integrates energy, temperature, humidity and motion sensors for loads and HVAC management, and also, solar panels and battery management for some sites. All these data are centralized in a local BMS that could also be connected to the cloud to take advantage of AI for energy management optimization and benchmark.

Concerning hotels, managers and staff face the dual challenge of enhancing guest comfort while improving operational and environmental performance. They must ensure high levels of guest satisfaction to foster loyalty and revenue, while also boosting staff productivity to focus on service quality and maintenance. At the same time, hotels have an opportunity to become more sustainable by reducing energy consumption, minimizing carbon emissions, and ensuring compliance with legal and customer expectations. Achieving energy efficiency and maintaining reliable power availability are essential to avoid costly disruptions. By simplifying the journey toward sustainability, hotels can move toward net-zero operations while delivering a positive impact and an exceptional guest experience.

To answer these challenges, a digital layer with intelligent circuit breakers, energy meters, and sensors offer simple connectivity options to remotely collect the data needed to understand where and how hotel uses energy. Having these devices in place will also earn points toward certifications. Then, onsite or cloud-based apps automate data collection from connected devices and turn that data into insights needed (e.g. IoT based facility management by Planon [9]) to uncover saving opportunities and make data-driven decisions on improving energy efficiency while reducing emissions.

Continuous building performance scoring is provided by reporting tools that saves time and effort during re-certification. With connected devices securely sharing data with the cloud, advisory services help to push hotel sustainability further and gain points toward higher levels of green certification.

In office buildings, rooms and offices are not used continuously. Therefore, it is really important to adapt HVAC and lighting to each spaces' occupancy level. Decision process is based on knowing where people are in the office location-wise and time-wise.

Similar digital architectures linked to onsite BMS or cloud-based advisors with AI can be deployed depending on the segment and customer's needs.

3.6 Challenges in Digital Transformation

While we have been focusing so far on discussing opportunities a digital electrical system brings to end users thank to unification and artificial intelligence, we will now explore the consequences to the ecosystem of partners involved in the deployment of smart panels.

Historically, panel builder's role was related to the building and wiring of electrical equipment in workshops, while system integrators were mostly working at customer sites to add sensors and communication wires after Panels were installed. The convergence of digital and electrical is dramatically impacting this traditional breakdown. Let us explore the why first and then discuss the benefits and challenges.

As electrical equipment gains communication capabilities, the need for separate sensors is reducing. As an example, low voltage breakers which had current sensors for only protection purpose previously are now capable to communicate information on energy consumption in a digital format (e.g. MicroLogic E on ComPacT NSX or MicroLogic X on MasterPacT MTZ by Schneider Electric includes energy measurements).

This brings more integrated solutions right at panel builder's workshop where previously belong to system integrators. In some cases, also, communication can be done through wireless communication devices which reduces cable installation time and enables higher density (e.g. PowerTag Energy range of wireless sensors compatible with any device up to 2,000 A). It also enables leveraging a uniform digital electrical system that becomes part of panel builder's scope from the communication capability standpoint. In other words, the electrical panel is not only an electrical protection and cabling system, but also a digital communication system.

To digitally enable all the functions, some communication "commissioning" steps are now needed and must be mastered by the panel builder since his responsibility has increased. His role has evolved, and traditional technicians need to step-up and acquire new digital competencies. Since this is a transformation process, it is important that electrical equipment vendors provide not only cyber-secure products complying with IEC 62443, but also all the tools and digital ecosystem that enable the set-up of the communication system.

The role of the system integrator has simultaneously increased, but on a different level. Since more data is available, his role is to make all data configured to the purpose of the end client. The value provided has increased, and he should not be worried anymore by the low-level communication topic which, in a unified system, is already resolved between the electrical vendor manufacturer and the panel builder.

The system integrator becomes the last step to make data available to the cyber-secure edge and cloud solutions and ready for AI to use while encompassing the data protection regulations.

4. INTERCONNECTED DIGITAL ECOSYSTEM BENEFITS

Electrical switchboards are operating with a purpose to feed electrical energy to the downstream loads (or applications), but they are also receiving energy from upstream incomers, either directly from the low voltage grid for instance in residential or small commercial buildings or through a transformer where medium voltage is supplied for higher energy demanding applications.

Therefore, it is necessary to consider also the digital ecosystem that surrounds the switchboard.

a) Upstream

The energy being supplied through the upstream system might come from various sources; traditionally, the utility is playing this role, and sometimes, customers have secured their supply with a local generator as a backup.

With the emergence of renewables sources of energy due to significant cost reductions, every building may become also a producer of electricity leveraging solar panels, batteries or small windmills. We can consider now clients as "prosumers" since they are both producer and consumer of electricity.

The optimization of the use of those new resources can only be leveraged when considering external data sources like meteorological data (current and forecasted temperature typically) and electricity price, which may vary over time either based on pre-established scheduled, or sometime even dynamic pricing. Those external sources are critical to be part of achieving an impact.

b) Downstream

Loads are the purpose of the supply of energy, but not all loads are similar. Some can be very critical (IT infrastructure or payment terminals for instance) while others are less (external car park lighting) subject to each application. However, microgrids are now appearing and opening new sources of energy, like local photovoltaic panels, local battery storage, Combined Heat and Power (CHP) generation and others. The microgrids system brings also its own set of challenges as “control” of electrical loads is becoming much more common.

Let us look at how these new interconnected ecosystems bring also new opportunities for a safer, more reliable and more sustainable future.

4.1 Predictive Maintenance

Historically, electrical equipment and switchboards maintenance activities have been performed according to recommendations coming from the original electrical equipment manufacturer (OEEMs) and often based on a very simple time-based schedule.

As per other industries, end clients may not have performed those maintenance tasks, partly because OEEMs were asking for high frequency of maintenance (to be on the safer side) sometimes or partly because of costs constraints. As a result, we have observed various sorts of issues leading to outages with both more and less serious consequences.

OEEMs have decided to address this issue and propose to their clients to improve the quality and efficiency of the maintenance activities and have developed a framework within NFPA70-B in US and IEC TR 63482:2024 to enable flexible maintenance schedules and achieve the highest level of availability and safety. This basically means that according to standards, it is now possible to shift maintenance activities from time-based schedule to condition-based, which is providing higher flexibility and improved accuracy. But how did they achieve this?

Obviously, digitalization is at the heart of this transformation, because going through data collection coming from various sensors, it is now possible to simulate the actual behavior and the ageing of equipment in their real context. What it means is that beyond monitoring only voltage and current (and sometimes harmonics and other distortions), it is required to add sensors to monitor temperature at various locations or humidity because those parameters are also important to estimate the ageing of an electromechanical device.

As an outcome, you can decide to delay your maintenance schedule to save costs and by having enriched data, you can also detect that one specific switchboard or breaker that requires early intervention to prevent an outage. This is why sensors like CL110 have been developed for instance.

What is amazing about this sensor is that it is wireless and can fit almost everywhere in any electrical switchboard, so that it can be used both in greenfield application but also can be deployed in brownfield to upgrade existing equipment.

Fig. 6 - P PowerLogic^{TM} CL110 “EMS59443”

Indeed, often predictive maintenance does not come as a concern in the early part of the life cycle of the equipment while it becomes a necessity after several years of operations. However, this is not the best approach anymore. Fitting sensors in electrical switchboards by the panel builders while he is doing the assembly will enable the capture of all data along the full life cycle of the equipment.

Data has to be pushed to the cloud or at least remote servers’ solution to be able to compute long historical data sets. Analytics are generating recommendations from the OEEM to the client. A solution like Asset Advisor for Electrical Distribution [10] is already an existing application of AI leveraging electrical switchboard sensors data to provide real value for predictive maintenance.

4.2 Energy Efficiency

As we have discussed earlier, measurement of energy consumption is the cornerstone of an energy saving approach. It enables us to select where efforts should be focused to have the biggest impact.

Often the solution may be simpler than we thought, and quick wins identified. For instance, connecting energy measurement with building management system enables various savings on the HVAC systems when it is made sure that heating and cooling systems are not in “competition” simultaneously.

Additionally, while you might detect some systems requiring external heating while others expect external cooling, you can identify optimization of your own resources also at lower costs.

Focusing on electrical switchboards, tapping into an example of a wastewater treatment plant, the ability to measure and control which breaker/feeder supply to which pump (pumping-in vs pumping out) you can optimize the thermal management of your switchboard since both pumps will never work simultaneously. The thermal surveillance of the switchboard becomes a necessity since, based on the pure design, you may exceed temperature if automation system is not operating properly.

As a result, energy efficiency can be significantly improved if more data are provided to represent in real time how the electrical system is being operated and this new set of data coming from various sensors is enabling the development of AI solutions to identify pocket of energy savings.

4.3 Facility Management

The maintenance of electrical switchboard is typically operated by facility management companies providing resources to end-users to schedule and track maintenance activities and work orders.

Since electrical switchboards are becoming smarter, it is possible to identify what maintenance is required and enable remote diagnostics so that when a maintenance technician is getting on site, he/she is fully prepared for the task scheduled, and much less time is wasted. Additionally, digitalization of electrical equipment enables easier decision process and reporting of maintenance activities with factual data inputs based on sensors and analytics.

As a result, facility management companies can leverage digital information from electrical switchboards and implement AI strategies to optimize their resources and costs while operating a better service for their end clients.

5. CONCLUSION

In this paper, we have analyzed the impact of IEC Standards and working groups for Electrical Switchboard in preparation for a more digitalized future.

Focusing on digitalization of switchboard, we believe that with digitalization, we can now leverage AI to help clients reduce energy consumption.

By combining different sets of information, connected switchboards are able to provide more accurate data that AI can compute and provide predictive models for maintenance.

Enriched switchboards with variety of sensors like light and current transducers and in combination with fast digital architectures enable smarter decision-making for mitigating arc fault situation, reducing risk of fire and injury and enabling faster restart of operation.

We have established the importance of IEC Standards in its ability to influence the industry and accelerate adoption of digital solution to have an impact on energy consumption, safer electrical operations and improved availability of electrical switchboard and even grid when the ecosystem will be fully interconnected. IEC Standards are creating the foundation for Electricity 4.0 where Digital + Electrical = Safe, Reliable and Sustainable.

REFERENCES

1. IEC 61439 Series: Low-voltage switchgear and controlgear assemblies

2. Power Story for Availability [https://download.schneider-electric.com/files?p_enDocType=User+guide&p_File_Name=998-21359052_GMA_ Power Availability-Guide_REV1.pdf&p_Doc_Ref=998-21359052_GMA]

3. IEC TR 63482:2024 Maintenance of low voltage switchgear and controlgear and their assemblies

4. IEC 60947-2 Low-voltage switchgear and controlgear - Part 2: Circuit-breakers

5. IEC TS 63290 (Nov 2024) Supplement requirement for Intelligent Assembly

6. Power Story for Safety [https://cloud.go.se.com/_WW_201907_Electrical-Fire-Prevention-Guide-Content.EA-LP-EN.633116_?source=Content&sDetail=Electrical-Fire-Prevention-Guide_WW]

7. IEC/TR 61641:2014 Enclosed low-voltage switchgear and controlgear assemblies - Guide for testing under conditions of arcing due to internal fault

8. IEC 60364-4-42 Low-voltage electrical installations - Part 4-42: Protection for safety - Protection against thermal effects

9. Planon predictive maintenance with IoT Sensors [https://planonsoftware.com/uk/software/iwms/asset-maintenance-management/]

10. EcoStruxure^{TM} Asset Advisor [https://www.se.com/hk/en/product-range/64477-ecostruxure-asset-advisor/#overview]

Paper No. 9

SMART AUTONOMOUS DEVELOPMENT FOR AIRFIELD GRUND LIGHTING MAINTENANCE IN HONG KONG INTERNATIONAL AIRPORT

Authors/Speakers: Ir Leslie KM Lee, Senior Manager, Airfield and Electronic Systems
Ms. Pearl TP Ng, Manager, Electrical Services Maintenance
Mr. Philip NM Chan, Assistant Engineer, Electrical & Mechanical
Technical Services Systems Department,
Airport Authority Hong Kong
Ir David PK Leung, Senior Engineer/Airport Services
Ir Vincent CW Ip, Engineer/Airport Services
Electrical and Mechanical Services Department,
The Government of the HKSAR

SMART AUTONOMOUS DEVELOPMENT FOR AIRFIELD GRUND LIGHTING MAINTENANCE IN HONG KONG INTERNATIONAL AIRPORT

Ir Leslie KM Lee, Senior Manager, Airfield and Electronic Systems
Ms. Pearl TP Ng, Manager, Electrical Services Maintenance
Mr. Philip NM Chan, Assistant Engineer, Electrical & Mechanical
Technical Services Systems Department, Airport Authority Hong Kong
Ir David PK Leung, Senior Engineer/Airport Services
Ir Vincent CW Ip, Engineer/Airport Services
Electrical and Mechanical Services Department, The Government of the HKSAR

ABSTRACT

To strengthen Hong Kong's position as a global aviation hub and accommodate long-term growth in air traffic demand, Hong Kong International Airport (HKIA) commissioned the Three Runway System (3RS) in November 2024. The airport now operates with three active runways, supported by state-of-the-art airfield operation systems, including the aerodrome safety - critical Airfield Ground Lighting (AGL) system.

The AGL system plays a vital role in aviation safety by providing visual guidance to pilots during take-offs, landings and ground movements - especially under low visibility conditions. In response to increasing maintenance demands for the additional assets, reduction in maintenance window and the need to enhance manpower efficiency, HKIA has partnered with technology companies to develop innovative solutions that enhance maintenance operations. These advancements include the use of artificial intelligence (AI) image analysis, autonomous vehicles, robotic technologies, and more to build the Airfield Ground Lighting Scanning and Inspection System, as well as the Autonomous Airfield Ground Lighting Cleaning and Inspection Robot.

This paper outlines the development roadmap and design considerations behind these innovations. It also evaluates their impact on current maintenance workflows and explores potential future enhancements. With full deployment of these innovations, HKIA anticipates significant enhancement in maintenance efficiency, manpower and cost savings, quality of maintenance works, and occupational health and safety compared to traditional methods.

1. INTRODUCTION

The HKIA once again broke its post-pandemic records by handling 54.9 million passengers and 5.00 million tons of cargo and airmail in fiscal year 2024/25 [1], making it the busiest cargo airport in the world, with a flight departing or arriving every minute. The commissioning of the 3RS in November 2024 marks a significant milestone in HKIA's expansion, as it continually evolves to meet the demands of increasing air traffic. The 3RS is supported by the airfield operation systems, including the aerodrome safety - critical Airfield Ground Lighting (AGL) system. This critical AGL system ensures aerodrome safety by providing visual guidance to pilots during take-offs, landings, and ground movements, particularly in low visibility conditions.

To ensure safe operation of the airport, continuous inspection and preventive maintenance of the AGL system is required to ensure compliance with the requirements of the International Civil Aviation Organization (ICAO) and Civil Aviation Department (CAD). The development into 3RS poses the following significant challenges for maintenance activities:

(a) Increasing asset quantity: The commissioning of the new North Runway and the reconfigured Centre Runway during the 3RS operation, has resulted in a substantial increase in AGL light fittings from around 16,000 to around 31,000 units. This doubling of the amount of assets has intensified the scale of maintenance activities.

(b) Reducing maintenance window: AGL maintenance is constrained to runway closure periods, in which one of the runways would be closed for inspection from midnight each day until dawn. As the number of runways increased from two to three, the available runway closure period per week has been further squeezed among the runways. Moreover, the duration of runway closure is reduced as well that makes the maintenance task more challenging to complete.

(c) Expertise shortfall: Training inspectors for AGL maintenance is time-intensive, exacerbating workforce allocation pressures towards increasing maintenance demand.

This paper addresses the challenges with two innovative maintenance tools developed by HKIA and local technology company and organization, the patented Airfield Ground Lighting Scanning and Inspection System and Autonomous Airfield Ground Lighting Cleaning and Inspection Robot, and introduces the technology behind the tools.

2. DEVELOPMENT ROADMAP OF INNOVATIVE SOLUTIONS

To address the challenges in maintenance resulted from the development of Two Runway System (2RS) to 3RS, HKIA unveiled its “Technovation Programme” in 2015 to boost operational prowess by forging strategic partnerships with technology companies to pioneer ground breaking solutions.

Among these innovations are the Airfield Ground Lighting Scanning and Inspection System and the Autonomous Airfield Ground Lighting Cleaning and Inspection Robot.

These solutions leverage AI image analysis, automation, robotic technologies, data analytics, cutting-edge digital infrastructure, and more to revolutionize maintenance practices. The development roadmap of these tools embodies a forward-looking approach focused on enhancing maintenance efficiency, reducing workforce requirements, optimizing costs, and elevating the overall quality of maintenance services at HKIA.

2.1 Smart Autonomous Inspection Leveraging Computer Vision and AI Analytics

Among the programme’s crown jewels is the Airfield Ground Lighting Scanning and Inspection System, born from a partnership between Airport Authority Hong Kong (AAHK) and a local start-up company D2V. The system promises to revolutionise the inspection of AGLs.

Airfield Ground Lighting Scanning and Inspection System has evolved considerably since its origins as a proof-of-concept in 2015. The first production model emerged in 2019, followed by a substantially enhanced iteration in 2025. Each upgrade reflects AAHK’s commitment to technological excellence.

The proof-of-concept stage in 2015 focused on exploring the feasibility of automating AGL inspections, in which human expertise’s factor adds complexity to the equation. Training inspectors to master AGL assessment typically requires years of development, during which personnel learn to identify structural issues, assess component integrity, and distinguish between acceptable wear and potential safety concerns. Airfield Ground Lighting Scanning and Inspection System offers an elegant solution. The system can seamlessly adapt to new installations, maintaining rigorous standards whilst allowing skilled personnel to focus on higher-value tasks such as complex diagnostics and strategic maintenance planning.

Inspired by manual inspection, the Airfield Ground Lighting Scanning and Inspection System is equipped with advanced computing to learn and adapt to different surface conditions of AGL. High-speed cameras capture images of AGL fittings, which are then analysed by computer vision and compared with a database using AI. This process allows high-speed inspection of the AGL, from the missing bolt (see Figure 1), bolt tightness (see Figure 2), cracks on the epoxy surrounding the AGL (see Figure 3), to the inset light and adapter ring (see Figure 4 and 5), which is scheduled via the automated system, which has increased accuracy and efficiency.

Fig. 1 - The Missing Bolt was highlighted in the Operator Mobile Device

Fig. 2 - The Bolt Tightness was examined by Comparing the Inspection Photo with Historical Benchmark

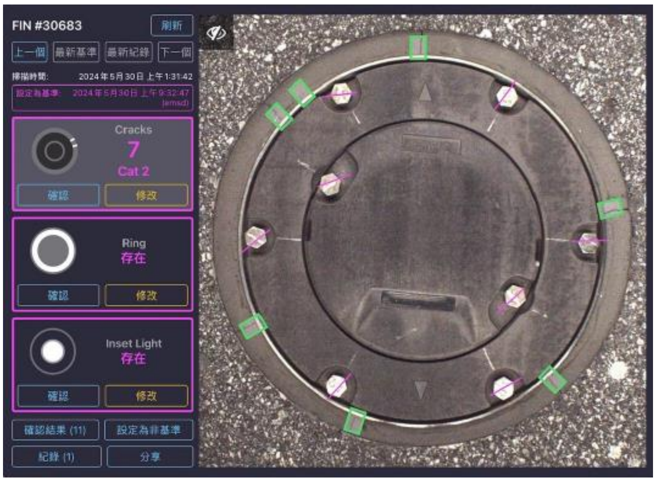
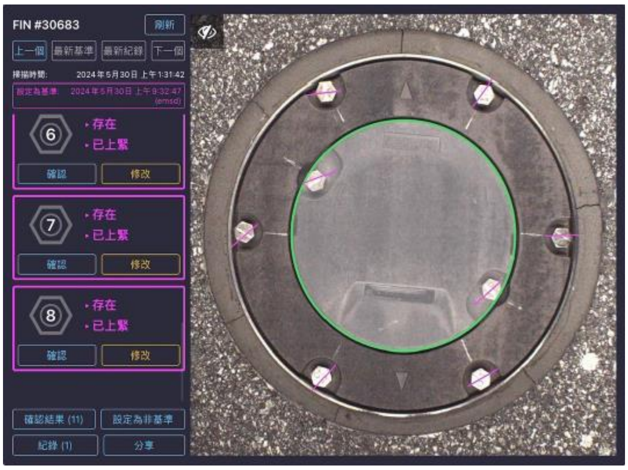


Fig. 3 - The Epoxy Cracks were highlighted in the Operator Mobile Device. The Severity of the Epoxy Cracks will be categorized into Cat 1, 2, or 3



FIN #30683

掃描時間: 2024年5月30日 上午1:31:42

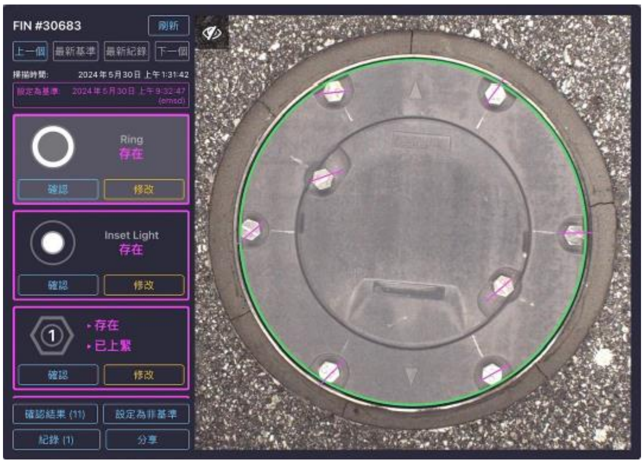
設定為基準: 2024年5月30日 上午9:32:47 (emsd)

6 • 存在 • 已上緊

7 • 存在 • 已上緊

8 • 存在 • 已上緊

Fig. 4 - The Existence of Inset Light was highlighted in the Operator Mobile Device



FIN #30683

掃描時間: 2024年5月30日 上午1:31:42

設定為基準: 2024年5月30日 上午9:32:47 (emsd)

Ring 存在

Inset Light 存在

1 • 存在 • 已上緊

Fig. 5 - The Existence of Adapter Ring was highlighted in the Operator Mobile Device

As the concept matured, the first production model of the Airfield Ground Lighting Scanning and Inspection System emerged (see Figure 6).

Fig. 6 - Proof-of-Concept Model: Inspection System developed as a Detachable Tool, required to install on a specific Inspection Vehicle

This milestone marked the transition from theoretical ideas to practical implementation. The system was being integrated with a high-throughput scanning machine as a detachable tool, which shall be installed on a specific inspection vehicle, offering high mobility for AGL inspections. Thus, inspectors could swiftly navigate the airfield at high speed with the inspection vehicle. At the same time, the scanning machine would take photos and transmit them to the inspection system to conduct thorough assessments of the AGL system with ease and precision.

The transition from proof-of-concept to production model involved a strategic design evolution from the original rear-attachment configuration to a more practical trailer-type system. This enhancement was driven by operational requirements for daily deployment, where frontline personnel needed to efficiently install the system on vehicles before use.

The original proof-of-concept design, while innovative in demonstrating the technology’s feasibility, presented practical challenges for routine airport operations. The rear-attachment configuration required manual handling of sophisticated scanning equipment, involving lifting, positioning, and securing components that could weigh several dozen kilograms. Such procedures not only consumed valuable time during shift changes but also exposed our maintenance teams to potential ergonomic risks, particularly when working under time-sensitive operational windows between aircraft movements.

The production version addressed these practical considerations through comprehensive redesign. By transitioning to a trailer-type configuration, the system eliminates manual loading and unloading procedures entirely. Frontline personnel can now simply couple the trailer to any compatible vehicle, dramatically reducing setup time from approximately 30 minutes to less than 5 minutes. This efficiency gain proves particularly valuable during peak operational periods when runway access windows are limited.

Fig. 7 - Inspection System converted to Trailer-based Universe Equipment, adaptable to various Towing Vehicles

The trailer design (see Figure 7) delivers multiple operational advantages beyond convenience. Enhanced occupational safety and health standards protect our operational teams by removing heavy lifting requirements and reducing repetitive strain risks associated with equipment handling. The larger form factor accommodates significantly expanded capacity for processing power, enabling real-time analysis of more complex inspection parameters. Advanced battery systems provide extended operational endurance, supporting comprehensive runway sweeps without interruption for recharging, while redundant power systems ensure mission continuity even during equipment maintenance cycles.

The expanding operational requirements prompted AAHK to commission a comprehensive system enhancement from 2023 to 2025, designed to improve detection capabilities and broaden the scope of automated inspections. The objective was ambitious: create a system capable of matching, then exceeding, human expertise across an ever-expanding array of maintenance requirements.

One particularly sophisticated challenge demonstrates the system’s advanced capabilities: verifying correct bolt specifications on AGLs. This critical task carries important safety implications. Non-compliant fasteners, perhaps fractionally different in size or composed of inappropriate materials, may fail under the demanding forces of landing, take-off, and high-speed aircraft operations. A single compromised bolt can affect the lighting system’s reliability, potentially impacting runway safety during critical operations.

Conventional approaches to this challenge would require extensive manual documentation: photographing numerous bolts under varying conditions, carefully cataloguing each image, and building comprehensive databases to train detection algorithms. Such detailed work could require substantial resources whilst extending development timelines.

The enhanced Airfield Ground Lighting Scanning and Inspection System addresses this through synthetic rendering (see Figure 8), an advanced technique from computer graphics and AI research. The system generates bolt images across numerous configurations, simulating different imaging angles, lighting conditions, weather effects, lens characteristics, and camera sensor variations in operational environments. This sophisticated approach produces an extensive synthetic database that enables neural networks to learn bolt identification without manual annotation, significantly accelerating development whilst enhancing detection accuracy.

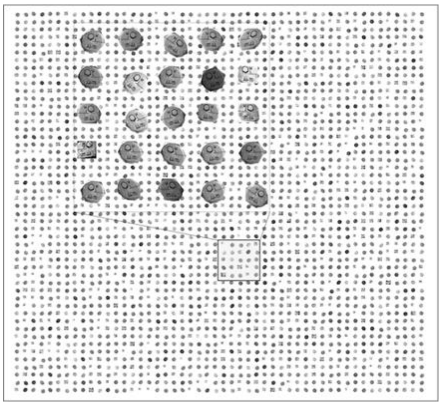
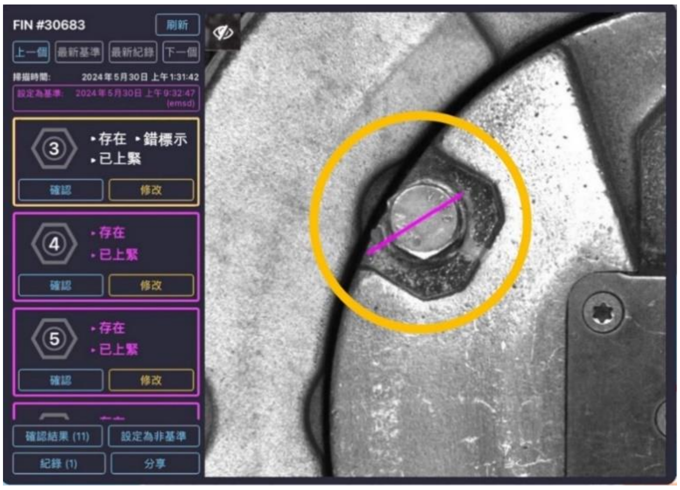


Fig. 8 - Synthetic Rendering of Bolt as Training Set for the Bootstrapping of the Neural Network for the Bolt Mark Detection

The latest version represents a significant advancement: It now exceeds human detection accuracy whilst examining fastener specifications (see Figure 9) and AGL prism quality (see Figure 10). What once required the experienced judgment of skilled professionals can now be accomplished by automated systems with superior reliability and remarkable efficiency.

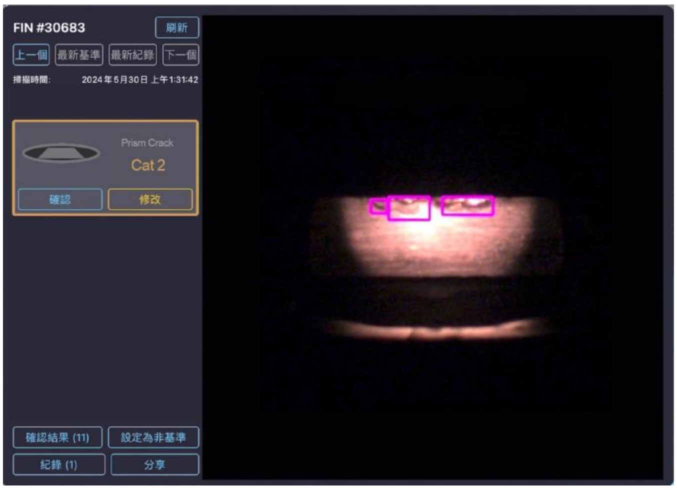


FIN #30683

掃描時間: 2024年5月30日 上午1:31:42

設定為基準: 2024年5月30日 上午9:32:47 (emsd)

Fig. 9 - Wrong Bolt with Wrong Bolt Marking was highlighted in the Operator Mobile Device



FIN #30683

掃描時間: 2024年5月30日 上午1:31:42

Prism Crack: Cat 2

Fig. 10 - The Detected Prism Cracks were highlighted in the Operator Mobile Device. The Severity of the Prism Cracks will be categorized into Cat 1, 2, or 3

2.2 Smart Autonomous Maintenance Leveraging Autonomous Vehicle and Robotic Control

Another innovative solution is being developed to revolutionize the maintenance of Autonomous Airfield Ground Lighting Cleaning and Inspection Robot. This development involves close collaboration between the AAHK, the Electrical and Mechanical Services Department (EMSD), and the Guangdong Academy of Sciences (GDAS), integrating various technologies for this unique maintenance solution.

The Autonomous Airfield Ground Lighting Cleaning and Inspection Robot has been under development since 2023. It addresses the critical challenges of prism cleansing for AGLs with shortening runway closure period, allowing for increased flight frequencies and launching new routes to maximize the utilization of HKIA. Through a series of design developments, trials, configurations, and scenario testing, it is expected that the first production model will conduct on-site trials at HKIA starting in late 2025 (see Figures 11 and 12).

Fig. 11 - Conceptual Design of the Autonomous Airfield Ground Lighting Cleaning and Inspection Robot

Fig. 12 - Production Implementation of Autonomous Airfield Ground Lighting Cleaning and Inspection Robot

This solution targets the AGLs located on the runways, where the emitted lights are often blocked by unwanted rubber deposits on the prisms, including the runway centreline and touchdown zone lights. These rubber deposits resulted from the melting of rubber tires on landing aircraft, where the high friction generated by the runway surfaces creates a large amount of heat energy that melts the tires. With the busy landing movements at HKIA, rubber deposits accumulate on the prisms, obstructing the emitted light and hindering clear guidance for pilots during landing.

This unique development focuses on exploring the possibility of automating AGL maintenance to optimize human resources for repetitive and time-consuming tasks. The solution consists of two major parts: the autonomous vehicle and the prism cleaning system.

The Autonomous Airfield Ground Lighting Cleaning and Inspection Robot takes advantage of the fixed locations of each AGL, allowing the system to plan the routine maintenance route before the cleaning work begins. However, unlike other similar autonomous vehicle technologies operating on open roads, where the use of Global Positioning System (GPS) and the detection of nearby road markings and obstacles are sufficient for achieving autonomous control, the target cleaning area on the runway is situated in empty spaces, where no reference obstacles or road markings can be used to verify the vehicle's exact location during operation. Therefore, the vehicle is equipped with a real-time kinematic (RTK) precise positioning system, which incorporates error correction data from fixed base stations in Hong Kong, improving accuracy from 5m with GPS to 5cm with RTK. With this enhanced positioning system and the fixed geographical coordinates of each AGL pre-input into the system, the vehicle can identify every AGL on the runway and control the autonomous vehicle to stop at each AGL for cleaning after the operator sets the maintenance route.

The prism cleaning system activates once the Autonomous Airfield Ground Lighting Cleaning and Inspection Robot arrives at the designated AGL (see Figure 13). This innovative solution leverages AI to pinpoint the exact location of the prism based on the AGL contour through image recognition.

Fig. 13 - Prism Cleaning System of Autonomous Airfield Ground Lighting Cleaning and Inspection Robot

The system adjusts the robotic arm to the optimal cleaning angle, regardless of the AGL's alignment beneath the vehicle, and subsequently ejects dry-ice particulates directly onto the prism (see Figure 14).

Fig. 14 - Robotic Arm Control during Development Testing

An AGL prism fully covered by rubber deposits can be satisfactorily cleaned within 30 seconds (see Figure 15).

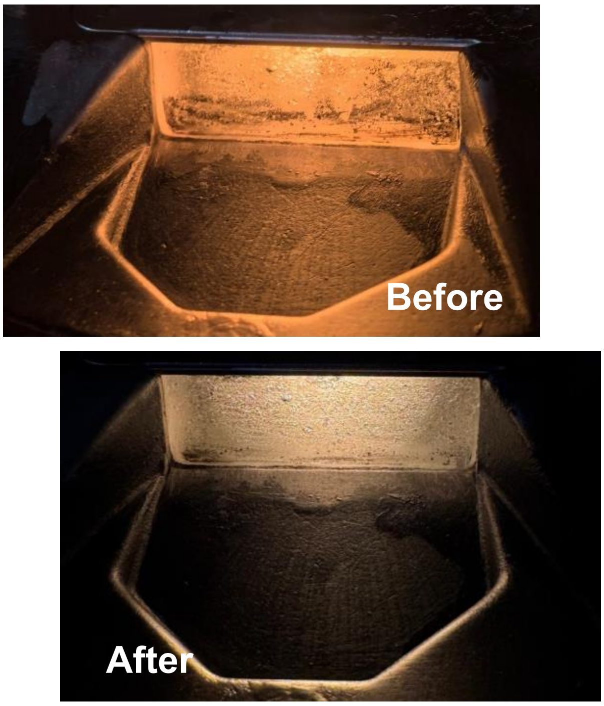


Fig. 15 - Comparison of the Cleaning Effect on AGL Prism

The use of dry-ice particulates utilizes both the chemical and physical properties of the substance for the effective removal of rubber deposits. The dry-ice particulates are ground to less than 0.3 mm in size, allowing them to slide through the tiny gaps between the rubber deposits and the prism surface. Under room temperature conditions, the dry ice sublimates from a solid to a gaseous state, creating a “mini-explosion” that facilitates the easy removal of the rubber deposits. Another beneficial property of dry-ice particulates is their extremely low temperature. The sudden drop in temperature upon contact with the ejected dry-ice particulates makes the rubber deposits brittle, causing them to fall off easily with the high-pressure ejection. These factors make dry ice an effective cleaning agent for the AGL prisms in removing rubber deposits.

As far as operation is concerned, the system allows remote monitoring and control of cleaning process, when necessary, by operators via a remote console. The system also facilitates systematic maintenance record documentation. Every cleaning action and record for each AGL will be stored in the system for improved record management, including image comparisons before and after the cleaning process.

The extensive database on the condition of the AGLs enables the system to assess the cleanliness of the prisms, allowing for efficient use of dry-ice ejection. It is expected that maintenance records generated by the system would enable optimisation of maintenance priority and frequency of individual AGL in the future.

3. IMPROVEMENT IN MAINTENANCE WORKS

3.1 Airfield Ground Lighting Scanning and Inspection System

3.1.1 Impact on maintenance workflow

In application, the Airfield Ground Lighting Scanning and Inspection System comprises an advanced high-throughput scanning machine, which is towed by a vehicle (see Figure 16), and a remote computer server. The vehicle is enabled to carry out an integrity inspection of the AGL at a speed of 50 km/h.

Fig. 16 - Rover of the Latest Airfield Ground Lighting Scanning and Inspection System

Everything from the missing bolt, bolt tightness, the number of cracks on the epoxy surrounding the AGL, the inset light and adapter ring, prism quality, and bolt type is scheduled via the automated system, which has increased accuracy. The solution allows maintenance teams to efficiently detect any damage to the light fittings.

Once the frontline personnel have scanned the AGLs, the airport management keeps track of the scan results through the mobile app. The maintenance team follows in a second vehicle equipped with the necessary tools and parts to repair damaged lights. The maintenance can be finished right after the inspection immediately.

The mobile device application (see Figure 17) can review the current and previous inspection results (see Figures 1 to 5).

This workflow allows technical personnel to carry out concurrent, in-depth follow-ups on AGLs, which optimizes inspection and repair of AGLs while keeping the whole team on the same page at the same time. Furthermore, corporate with the big data analysis data system behind, the Airfield Ground Lighting Scanning and Inspection System could achieve predictive maintenance.

Fig. 17 - The Operator's Mobile Device enables the user to understand the Network and the Equipment Healthiness, pinpoint AGL locations for Inspection, Review Scanned AGLs, and assess Current and Past Inspection Outcomes, as shown in Fig. 1 to 5

3.1.2 Effectiveness on maintenance

In contrast to the time-consuming manual inspections that could exceed 90 minutes for runway centreline AGLs, the Airfield Ground Lighting Scanning and Inspection System completes the task in just 15 minutes, showcasing an impressive 83% enhancement in efficiency. Demonstrating resilience across diverse surface conditions and weather scenarios, the system excels in maintaining accuracy. These precise inspection outcomes enhance runway inspection efficiency and cater to the escalating needs to facilitate increased flight operations, thus accommodating higher passenger volumes and cargo traffic.

The system integrates big data processing and advanced AI methodologies, specifically neural networks, to deliver fully automated AGL integrity verification with high-throughput capabilities. Before the system's invention, there was no easy way to inspect more than around 31,000 units of airfield ground lights in such detail and in such a short period. It demonstrates how technical expertise can fundamentally revolutionize an important sector of airport maintenance and development. Notably, even amidst a 100% increase in AGL light fittings due to a new runway, the Airfield Ground Lighting Scanning and Inspection System requires only a modest 10% rise in manpower to uphold maintenance standards, showcasing its exceptional efficiency in managing expanded workloads with minimal staffing adjustments and cost implications.

3.1.3 Improvement in occupational health and safety

Additionally, by minimizing manual on-site inspections that involve physically demanding actions such as bending and crouching, the system significantly prioritizes inspectors' occupational health and safety. This approach not only reduces the risk of workplace injuries but also promotes a more efficient and ergonomic workflow. These safety enhancements contributed to the system's recognition as the Gold Winner in 2019 for the Hong Kong SAR Occupational Safety & Health Council (OSHC) awards, affirming its excellence in fostering a safer working environment.

3.2 Autonomous Airfield Ground Lighting Cleaning and Inspection Robot

3.2.1 Effectiveness on maintenance

In application, the Autonomous Airfield Ground Lighting Cleaning and Inspection Robot is designed to clean all AGLs in the runway areas, including the runway centreline and touchdown zone lights at both ends of each runway. Each runway contains at least 600 AGLs, requiring extensive cleaning to accommodate busy aircraft movements.

Conventionally, AGL cleaning requires significant manpower for visual inspections and selective cleaning of specific AGLs by melting rubber deposits and scraping them away manually. This process is not only time-consuming but also repetitive, making it nearly impossible to clean all runway AGLs within a short period. Under the limited maintenance window during night time, only 6 AGLs can be cleaned per hour through manual methods.

However, with the implementation of the Autonomous Airfield Ground Lighting Cleaning and Inspection Robot, each AGL cleaning task requires only 30 seconds. Taking into account the travelling and system preparation time between AGLs, the cleaning process last around 3 minutes for each targeted AGL, increasing the average number of AGLs that can be cleaned in an hour to 20 AGLs dramatically. This brings out an improvement of more than 200% compared to the original manual cleaning method. A complete cycle of cleaning all AGLs across the three runways can be achieved within 3 weeks, ensuring that the prisms remain clean for optimal light emission.

3.2.2 Simplified maintenance workforce

The autonomous system simplifies the maintenance workflow, beginning with the planning of cleaning tasks. In addition to a pre-set cleaning route, the system can generate routes based on the last cleaned AGLs. Once the cleaning task is confirmed, only one click is needed to initiate the entire process. All vehicle movements, operating parameters, cleaning comparisons, and photo records can be displayed and stored in the integrated control system.

In the event of an unsuccessful cleaning of an AGL after repeated attempts, the system will prompt an alert following the maintenance work, notifying maintenance personnel to follow up on-site. Furthermore, the system is expected to provide a uniform cleaning effect through efficient dry-ice cleaning for each AGL during maintenance, ensuring that the maintenance standard remains at the highest quality.

3.2.3 Improvement in occupational health and safety

The system utilizes robotic technology to replace the repetitive manual cleaning procedures performed by maintenance personnel, ultimately reducing the manpower required for on-site work and alleviating the discomfort associated with working in awkward postures due to the installation of AGLs on the runway surface, especially in hot weather. Furthermore, the adoption of this faster system also lowers the risk of maintenance personnel being exposed to nearby aircraft manoeuvring areas during cleaning operations.

4. FUTURE DEVELOPMENT

In the future, the Airfield Ground Lighting Scanning and Inspection System will undergo a transformative upgrade by integrating autonomous vehicles, revolutionizing airfield maintenance at HKIA. These vehicles will enhance operational efficiency by enabling autonomous inspection according to scheduled maintenance tasks, while leveraging AI-driven algorithms for predictive maintenance practices based on operational big data analysis. This future advancement promises would further improve inspection efficiency, maintenance cost effectiveness, and optimized manpower allocation in managing the AGL system, ensuring top-notch operational excellence and sustainability. Moreover, it is planned to use autonomous vehicle to attach to the Airfield Ground Lighting Scanning and Inspection System to make it fully automated for further efficiency improvement.

Meanwhile, the Autonomous Airfield Ground Lighting Cleaning and Inspection Robot is expected to conduct on-site trials at HKIA, with fine-tuning of the geographical configuration to adapt to the local conditions in Hong Kong. It is foreseeable that this solution will be fully implemented across all three runways to improve cleaning efficiency, optimize manpower allocation, and enhance the safety of maintenance personnel while maintaining a better uniform standard for AGL maintenance.

5. GLOBAL RECOGNITION FLYING HIGH WITH INNOVATION

The Airfield Ground Lighting Scanning and Inspection System's trophy cabinet tells its own story: champion of Hong Kong's Electronics Project Competition (2017), gold winner at the SAR Occupational Safety & Health Council awards (2019), and recipient of International Airport Review's inaugural Airside Operations Award (2017) (See Table 1). An expanding international patent portfolio aims to spread this innovation worldwide.

Airfield Ground Lighting Scanning and Inspection System represents more than mere technological prowess; it embodies a paradigm shift towards automated inspection capabilities that render runway maintenance safer, swifter, and more reliable. In doing so, it burnishes HKIA's credentials as aviation's smartest operator.

With the latest development of the Autonomous Airfield Ground Lighting Cleaning and Inspection Robot, it has been recognized by achieving the Silver Medal at the 49th International Exhibition of Inventions in Geneva (2024). This accolade showcases its unique design and future expandability within the global aviation maintenance industry.

Champion of the Hong Kong Electronics Project Competition (2017) organized by the Electronics Division of the Hong Kong Institution of Engineers, highlighting the system's technical excellence.
Gold Winner in 2019 for the Hong Kong SAR Occupational Safety & Health Council (OSHC) awards.
The Winner of the Year, International Airport Review Inaugural Airside Operations Award (2017), recognizing its innovative automated inspection system that reduces inspection time and improves efficiency.

Table 1 - International Accolades of Airfield Ground Lighting Scanning and Inspection System over the years

6. CONCLUSION

The evolution of smart autonomous maintenance technologies for Airfield Ground Lighting system at HKIA is a testament to technological innovation's transformative power in the aviation maintenance landscape. From the proof-of-concept to the latest implementation of every project, these systems not only adapted to the dynamic growth of AGL at HKIA, but it has also served as a beacon for the aviation industry at large. By streamlining maintenance operations, enhancing efficiency, and ensuring meticulous attention to detail in the upkeep of lighting arrays, the smart autonomous maintenance technologies, including the Airfield Ground Lighting Scanning and Inspection System and the Autonomous Airfield Ground Lighting Cleaning and Inspection Robot, have created a benchmark for excellence and innovation that other airports worldwide can aspire to emulate.

REFERENCE

1. Airport Authority Hong Kong. (16 July 2025). "Solid Air Traffic Growth Recorded in 2024/25 as AAHK Delivers Sound Financial Performance". Hong Kong International Airport. https://www.hongkongairport.com/en/media-centre/press-release/2025/pr_1797

Paper No. 10

HARNESSING BIG DATA-DRIVEN PEDESTRIAN TRAFFIC AND WEATHER INSIGHTS FOR SMART BUILDING MANAGEMENT

Author/Speaker: Dr. Andrew HC Wu
Lecturer
Department of Electrical and Electronic Engineering
The University of Hong Kong

HARNESSING BIG DATA-DRIVEN PEDESTRIAN TRAFFIC AND WEATHER INSIGHTS FOR SMART BUILDING MANAGEMENT

Dr. Andrew HC Wu
Lecturer
Department of Electrical and Electronic Engineering
The University of Hong Kong

ABSTRACT

In large metropolises, understanding pedestrian or occupant traffic and weather insights is vital for optimizing smart building management. Urban developments with multimodal transportation and mixed-use spaces often experience fluctuating energy demands for escalators, lifts, and air conditioning based on pedestrian patterns influenced by weather. In this paper, we will present an overview followed by a case study in Osaka, Japan, demonstrating how to leverage deep learning to predict pedestrian traffic using real-time three-dimensional (3D) range sensor measurements and current weather data from the internet. These predictions can drive artificial intelligence-assisted decisions to enhance operational efficiency in smart buildings.

1. INTRODUCTION

The emergence of big data has significantly enriched Building Energy Management Systems (BEMS) by enabling real-time monitoring, predictive analytics, and optimized energy usage [1]. By integrating vast number of measurements from multi-modal sources, such as internet of things (IoT) sensors, smart meters, public databases and etc. - BEMS is becoming increasingly important in Smart Grids (SGs) as it enables the consumers to interact with the SGs through demand response (DR). As countries are adopting more and more renewable energy resources, various DR strategies such as time-of-use (TOU), peak or real-time pricing (RTP) can be used to generate price signals that initiate the BEMS to reduce or shift the load during peak demand. This alleviates the stress of the overall grid and reduces costs. Various methodologies are summarised in recent surveys and reviews [2][3].

While our previous works [4][5][6] focused on price/load forecasting and demand response optimisation for home energy management systems (HEMS), which could also be generalised to BEMS, recent studies suggest the occupant behaviour pattern may affect the energy usage [7]. Hosamo & Mazzetto (2024) [8] evaluated various machine learning (ML) algorithms in predicting energy consumption and occupant dissatisfaction. Yun (2018) [9] suggested patterns of occupancy affect thermal comfort of the occupants. Wang & Shao (2017) [10] suggested patterns of occupancy would influence the space heating design, lighting and other building services. They employed wifi based indoor positioning techniques to reduce wastage. Pang et al. (2023) [11] suggested occupancy sensing for heating, ventilation and air-conditioning (HVAC) systems is crucial for improving energy efficiency and carbon savings.

Recently, transit-oriented developments are increasing popular in metropolitan cities in hope of reducing the reliance on private cars and reducing carbon emission. In HKSAR, stations like Shatin and Kowloon Tong are integrated with commercial and residential developments. In Central and Tsuen Wan, the railway station and bus terminuses are connected to nearby shopping malls and commercial buildings via climate-controlled pedestrian walkways. Examples in other countries includes Osaka station (Osaka, Japan), Sapporo station (Sapporo, Japan) and Shinjuku station (Tokyo, Japan), where vast underground street networks are created to facilitate seamless connection to nearby communities. Predicting the pedestrian traffic patterns is hence essential to improve the energy efficiency of these urban complexes, especially the HVAC and lighting systems covering all these climate-controlled pathways.

With the rise of next generation artificial intelligence (AI) such as the Large Language Models (LLMs), this paper provides a gentle review from traditional mathematical optimisation to more recent deep learning (DL) and their applications to BEMS and occupancy prediction, which can be used to predict the electricity demand and hence improve efficiency.

2. OPTIMISATION IN BEMS

BEMS optimises energy use by scheduling the load based on price signals and consumer comfort. Various works for smart home [2][3] or smart building scheduling [12] have been reported. They mainly focus on day-ahead energy management and their objectives are to reduce energy consumption and cost to enhance efficiency meeting the expected consumer comfort and other demand side management goals, such as peak demand reduction. More specifically, consider a finite time horizon t=1, 2, …, T and continuous (discrete) decision variables $\boldsymbol{a} \epsilon \mathbb{R}^{MT}$ ($\tilde{\boldsymbol{a}} \epsilon \mathbb{R}^{NT}$), where M (N) is the number of continuous decision variables for electricity allocation, such as the temperature of HVAC. N is the number of discrete decision variables, e.g. turning on/off interruptible or non-interruptible loads. In a traditional Home Energy Management System (HEMS) or Building Energy Management System (BEMS), mathematical optimisation is used to find the best set of decision variables that minimize the following:

$$\begin{aligned} &\min_{\boldsymbol{a},\tilde{\boldsymbol{a}},\boldsymbol{u}} \phi(\boldsymbol{u}) \\ \text{s.t. } & u_t \geq \max\left\{0,\ \widehat{E}_t(\boldsymbol{a},\tilde{\boldsymbol{a}}) - \widehat{v}_t\right\}, \\ & \varphi_{eq,i}(\boldsymbol{a},\tilde{\boldsymbol{a}}) \leq 0\ ,\ i = 1,2,\dots,I, \\ & \varphi_{ieq,i}(\boldsymbol{a},\tilde{\boldsymbol{a}}) = 0\ ,\ j = 1,2,\dots,J, \end{aligned} \qquad (1)$$

where $\phi(\boldsymbol{u})$ is the objective function and the simplest one can be chosen as $\phi(\boldsymbol{u}) = \sum_{t=1}^{T} \widehat{C}_t u_t$. $\widehat{C}_t$ is the real-time pricing for an unit of electricity and hence $\phi(\boldsymbol{u})$ represents the total cost for the electricity purchased from utility and $\boldsymbol{u} = [u_1, u_2, \dots, u_T]^T$ is the energy purchased from the utility. Suppose there is self-owned renewable generation $\widehat{v}_t$, the amount of purchased energy can be subtracted by the predicted renewables and hence $u_t \geq \max\left\{0,\ \widehat{E}_t(\boldsymbol{a},\tilde{\boldsymbol{a}}) - \widehat{v}_t\right\}$. $\widehat{\boldsymbol{E}}_{\boldsymbol{t}}(\boldsymbol{a},\tilde{\boldsymbol{a}})$ is the total day-ahead load demand. $\varphi_{eq,i}(\boldsymbol{x},\boldsymbol{y})$ and $\varphi_{ieq,i}(\boldsymbol{x},\boldsymbol{y})$ are the equality and inequality constraints, respectively. Beaudin et al. [2] and Han et al. [3] provide extensive surveys on the types of objective functions and constraints used for HEMS/BEMS. Other than just the electricity cost, $\phi(\boldsymbol{u})$ can be related to user comfort, load profiling and carbon emissions. Meanwhile, the constraints can be related to load and user comfort. For example, interruptible loads such as washing machines can be interrupted, paused and resumed to satisfy a target running time. Hence, the constraint is to ensure the target running time is satisfied.

In our previous work [4][5], we proposed a $\boldsymbol{L_1}$ regularisation based convex relaxation-based home energy management algorithm to convert the binary decision variables to continuous variable. More specifically, we relax the discrete decision variables $\tilde{a}_{n,t}$ to continuous and impose bound constraints $0 \leq \tilde{a}_{n,t} \leq 1$ to mimic the lower and upper bounds of binary decision variables. Afterwards, $\boldsymbol{L_1}$ regularisation is added to the objective function, which becomes $\phi(\boldsymbol{u}) + \sum_t w_{n,t}|\tilde{a}_{n,t}|$, where $w_{n,t}$is a positive weight indicating the importance of time instant t. Interested readers are referred to [4] and [5] for details.

In (1), the electricity price $\widehat{C}_t$, total day-ahead load demand $\widehat{E}_t(\boldsymbol{a},\tilde{\boldsymbol{a}})$ and renewable $\widehat{v}_t$ are often estimated by forecasting algorithms. Hence, this can be referred to as a predict-then-optimize (PTO) approach.

2. MACHINE & DEEP LEARNING FOR FORECASTING

As mentioned earlier, the day-ahead electricity demand $\widehat{E}_t(\boldsymbol{a},\tilde{\boldsymbol{a}})$ and renewables $\widehat{v}_t$ must be provided in (1) for the load scheduling in BEMS. If a set of historical observations are provided, the time series can be learnt by a forecasting algorithm to predict the day-ahead demand or renewable. Similar concept can be applied to occupancy and pedestrian trajectory prediction. In traditional statistical learning [13], a large class of time series models [14] such as auto-regressive model (AR), moving average (MA), ARMA and autoregressive integrated moving average (ARIMA), are designed to model the lagged observations and/or past error terms:

$$y = f\left(\, x_{t-1}, \dots x_{t-p}, \varepsilon_t, \varepsilon_{t-1}, \dots \varepsilon_{t-q}\right) \qquad (2)$$

where $y = x_t$ is the current observation (univariate) at time instant *t*, p is the time-lag of the observations. ε_t is the error and q is the time-lag of the error terms. The concept can be generalized to multiple variables, such as vector auto-regression (VAR). One of the challenges in employing statistical time series models for forecasting multiple quantities is that the physical model between the quantities (such as pricing signals and renewables) have to be explicitly defined. When the physical relationship across different quantities are not exactly known, separate time series models are used to capture the temporal relationship of the quantities.

3.1 Machine and Deep Learning for Forecasting

Machine Learning (ML) and Deep Learning (DL) are important subsets of artificial intelligence (AI). Forecasting can be framed as a kind of supervised learning [13], where past observations are adopted as input features to predict future observations. Unlike traditional statistical models, supervised learning of a ML model does not require explicitly defining the physical model. The mapping function can be learnt from a set of training data containing input features and corresponding labels. This enables the relationship between different input features, such as weather, Socioeconomic & Operational data and Grid & Energy System Data to be learnt from data and enriching the forecasting model [15]. Support vector regression, Radial Basis Functions, K-Nearest Neighbour regression, CART regression trees, Gaussian Processes, Multi-Layer Perceptron (MLP), Bayesian Neural Network (BNN) and Kernel Regression have been used for forecasting and a comprehensive review is available in [13]. Deep learning, on the other hand, is a more recent technique that leverages neural networks (NNs) to automatically learn the feature representation. Examples are convolutional neural network (CNN), recurrent neural network (RNN), Long Short-Term Memory (LSTM), CNN-LSTM, Graph Neural Network (GNN), Generative Adversarial Network (GAN), Stacked Autoencoder (SAE) and etc. [16] and [17] provide comprehensive reviews of various deep learning algorithms for forecasting. In our previous work [4][6], a recursive dynamic factor analysis (RDFA) approach was proposed for electricity price and load forecasting. It is an unsupervised learning approach that can uncover latent patterns from the electricity price and load data and perform forecasting with a low complexity.

3.2 Large Language Models for Load Scheduling and Forecasting

Large language models (LLMs) has recently emerged as next generation AI for natural language processing (NLP) [18]. LLM is renowned for its superb performance in text generation, reasoning, translation, summarization and question answering. However, when it comes to numbers, one has to bridge the gap between LLM's text training to numerical nature of time series [18]. Zhang et al. (2024) [18] outlines various approaches such as time series quantization, alignment techniques and visual modality for converting the numerical time series into a format where LLM will perform better in distilling the knowledge. On the other hand, Mongaillard et al. (2024) [19] recently employed LLM to convert voice requests to power scheduling vector. However, there are very few works that directly use LLM for optimisation.

4. OCCUPANT TRAJECTORY PREDICTION IN URBAN COMPLEX

As the pattern of occupancy will affect thermal comfort [9] and energy usage [11], accurate prediction of occupant trajectory is essential for estimation of electricity load demand in smart buildings. This calls for advanced algorithms to predict the occupant trajectories and intended destinations within the building. However, pedestrian trajectory prediction is mainly studied for outdoor applications: i) Knowledge-based methods: They model the trajectories using physical, social or psychological rules. Examples are collision avoidance and social force models [20]; ii) Context-based approaches: incorporates context information to predict pedestrian intent and use it to guide subsequent trajectory prediction [21]; iii) Deep Learning approaches: Examples are CNNs, RNNs, GAN, Convolutional LSTM, Transformer. LSTM performs well in sequence-to-sequence prediction. CNN predicts the trajectories by capturing the patterns through images or videos. AgentFormer integrates attention and a conditional variational autoencoders based framework to transformer. The Social LSTM incorporates interactions of other pedestrians to the trajectory prediction. Xue et al. (2020) [22] proposed the predicting pedestrian paths using Long Short Term Memory (PoPPL), which used k-mean to cluster the pedestrian trajectories followed with subsequent LSTM trajectory prediction. Shi et al. (2023) [23] employed the Trajectory unified transformer (TUTR) to classify the pedestrian intent and trajectory prediction.

In large metropolis, urban complexes such as transit-oriented developments are very popular and accurate forecast of the pedestrian /occupant traffic is the key to improve energy efficiency. In single-used complexes such as residential apartments, office, factories, the occupants often share a common pattern, i.e. they go to work/leave work together and the trend is more predictable. However, in mixed-use urban complexes, the pedestrian/occupant traffic is less predictable as individuals could have different purposes of travel, e.g. go to work, shopping or eating. Moreover, Rose et al. (2022) [24] suggested bad weather may lead to fewer customers in shopping malls. Chung (2005) [25] suggested bad weathers may lead to delay or cancellations. This may affect the occupant traffic in train stations too. This calls for advanced algorithms that can predict the occupants' intent and trajectories considering the effect of weathers and time-of-day.

4.1 The Weather - Time - Trajectory Fusion Network for Pedestrian Trajectory Prediction in Urban Complex

In our recent work [26], we proposed the WTTFNet, which considers the factor of varying weather and time-of-day using a novel probability refinement network with multiplexer structure for fusing the trajectory representation, weather and time-of-day information. Figure 1 shows the proposed WTTFNet, in which input trajectories are first divided into clusters according to their destinations.

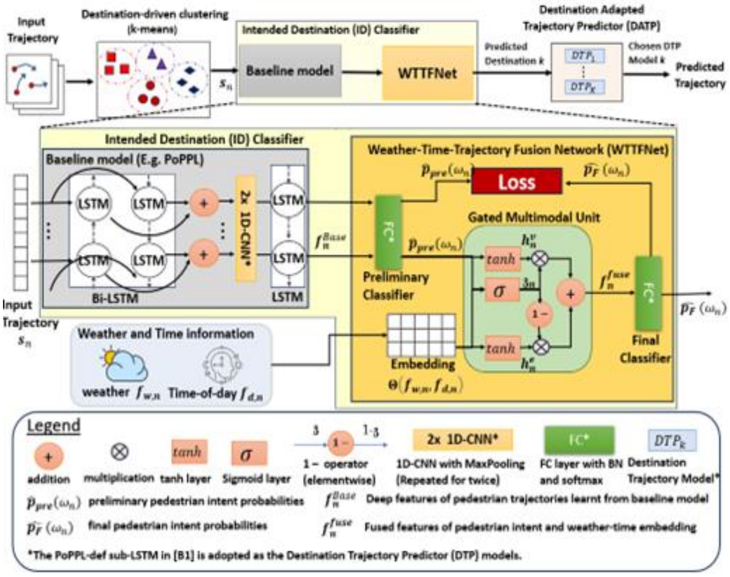


Fig. 1 - The Weather-Time-Trajectory Fusion Network (WTTFNet)

Afterwards, a pedestrian intent classifier based on a deep learning model is used to extract the trajectory features. Weather and time-of-day information is then encoded via embedding and augmented to the network via a Gated Multimodal Unit and the final classifier is optimised via a joint focal loss function to cater possible class imbalance. A subsequent destination adapted trajectory predictor (DATP) trained by the clustered trajectories can be used to predict the trajectory. More specifically, the CIPRNet uses the observed trajectory $\mathbf{s_n} = \{(\boldsymbol{x_{n,1}}, \boldsymbol{y_{n,1}}), \dots, (\boldsymbol{x_{n,L}}, \boldsymbol{y_{n,L}})\}$ to predict both the destination $\boldsymbol{\omega_n} = \mathbf{1}, \dots, \boldsymbol{K}$, and future trajectory $\boldsymbol{\hat{z}_n} = \{(\boldsymbol{\widehat{x}_{n,L+1}}, \boldsymbol{\widehat{y}_{n,L+1}}), \dots, (\boldsymbol{\widehat{x}_{n,L+L'}}, \boldsymbol{\widehat{y}_{n,L+L'}})\}$. $(\boldsymbol{x_{n,t}}, \boldsymbol{y_{n,t}})$ is the location of the occupant at time instant t. The WTTFNet employs the PoPPL as baseline for extracting the trajectory features. The input trajectory $\boldsymbol{s_n}$ will pass through a bi-directional LSTM, followed by two layers of one-dimensional CNN and a final LSTM for extracting the trajectory representation. A preliminary classifier in the WTTFNet is then used to learn the labelled intent obtained from the destination-driven clustering algorithm in Figure 1. Interested readers are referred to [26] for detailed formulation.

5. CASE STUDY OF THE OSAKA ASIA & PACIFIC TRADE CENTRE (ATC)

We consider the occupant trajectory dataset captured from the first floor of Osaka Asia and Pacific Trade Centre (ATC) published in [27] for illustration. The Osaka ATC is a multi-purpose transit-oriented development linking the Osaka Metro and the inter-city ferry. It contains a conference centre and a multi-purpose entertainment complex. We considered the trajectories from a sunny day (22 May, 2013) and cloudy day (29 September, 2013) as an illustration. The weather information was obtained from the website via the following link: https://www.timeanddate.com. 28536 occupant trajectories are resampled to duration of 40 time-instants, where trajectories from the first 20 time-instants are used to predict the subsequent 20 time-instants. Google Colab Tesla T4 notebook with 16 Gigabytes (GBs) of Graphics Processing Unit (GPU) memory and 17 GB system memory is employed. For performance evaluation, the classification accuracy (ACC), Cohen's Kappa (κ), average displacement error (ADE) and final displacement error (FDE) are used. The accuracy is given as:

$$ACC = \frac{1}{N_T}\sum_{k=1}^{K} CM[i,i], \tag{4}$$

where N_T is the total number of testing samples.

$$CM[i,j] = \sum_{n=1}^{N_T} I(\omega_n = i \,\&\, \widehat{\omega_n} = j) \tag{5}$$

is the total number of predicted class j matching the actual class i among the N_T testing samples. $I(.)$ is the indicator function. The Average Displacement Error (ADE) is given as:

$$ADE = \frac{1}{N_T L'}\sum_{n=1}^{N_T}\sum_{t=1}^{L'}\left\|\begin{pmatrix}x_{n,L+t}\\ y_{n,L+t}\end{pmatrix} - \begin{pmatrix}\hat{x}_{n,L+t}\\ \hat{y}_{n,L+t}\end{pmatrix}\right\|_2^2. \tag{6}$$

The Final Displacement Error (FDE) is given as:

$$FDE = \frac{1}{N_T}\sum_{n=1}^{N_T}\left\|\begin{pmatrix}x_{n,L+L'}\\ y_{n,L+L'}\end{pmatrix} - \begin{pmatrix}\hat{x}_{n,L+L'}\\ \hat{y}_{n,L+L'}\end{pmatrix}\right\|_2^2, \tag{7}$$

where $(\hat{x}_{n,t}, \hat{y}_{n,t})$ is the predicted coordinate.

5.1 Experimental Results

Figure 2 shows an illustration of the predicted trajectories at Osaka ATC. Four different weather and time-of-day conditions are considered: 1) cloudy and off-peak, 2) cloudy and peak period, 3) sunny and off-peak, and 4) sunny and peak period. The k-means algorithm originally split the trajectories into 10 clusters. However, after examining the validity of the clusters with $\boldsymbol{\chi^2}$ test, two of the clusters cannot meet the minimum sample requirement and they have to be merged, resulting in $\boldsymbol{K = 9}$ clusters. The trajectory of the first 20 time-instants (denoted in black) is used to predicted the later 20 time-instants. For better readability, we print the markers at an time interval of 4. Figure 3 shows the validation protocol and learning curves. We employed stratified 5-fold cross validation (CV) for parameter tuning and validation. Roughly 60% (three-folds), 20% and 20% are used for training, validation and testing, respectively. From Figure 2, we may see that the proposed WTTFNet with weather-and-time (WT) information give the most accurate trajectory prediction, where the prediction (blue line) coincides with the actual trajectory (black line).

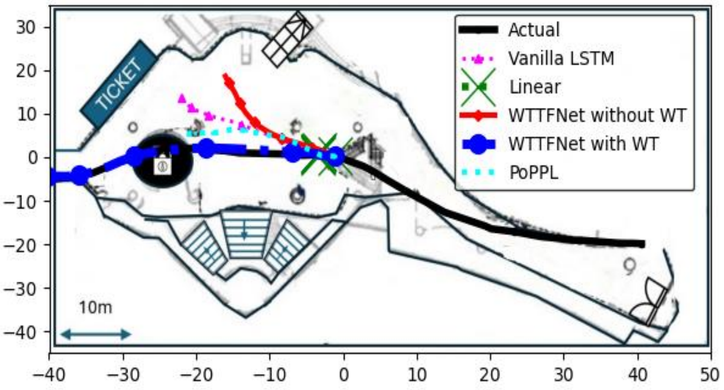


Fig. 2 - Illustration of Predicted Trajectories at Osaka ATC 1/F.
WT: Weather-and-Time information

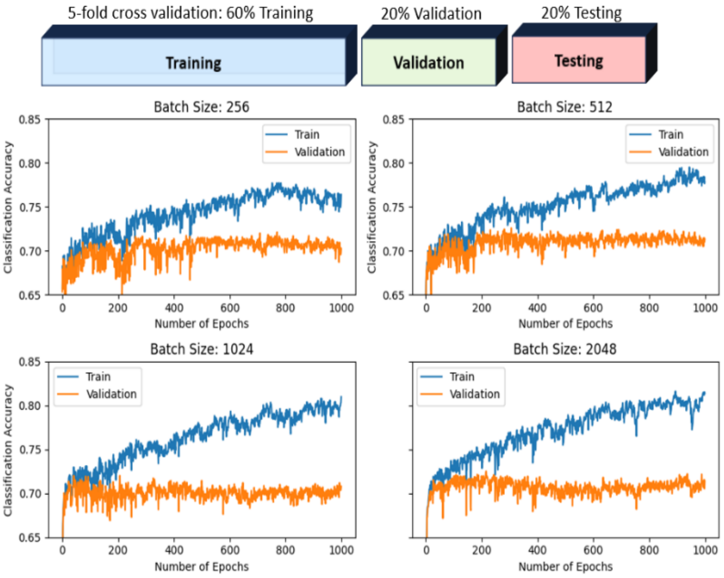


Fig. 3 - Validation Protocol and Learning Curves for Various Batch Sizes.
Stratified 5-fold Cross Validation (CV) is Used

Model Metric	Linear Model	Vanilla LSTM	PoPPL (Original)	Proposed WTTFNet	
				(A)	(B)
ACC (%)	N/A[a]	N/A[a]	58.18%	71.50%	**71.95%**
ADE(m)	13.28	6.263	6.488	5.93	**5.894**
FDE(m)	22.84	10.687	11.266	10.42	**10.315**

A: Proposed WTTFNet without weather-time (WT) information
B: Proposed WTTFNet with WT information
[a]The Linear model and Vanilla LSTM do not contain any classifier. Hence, classification performance is not applicable.

Table 1 - Trajectory Prediction Performance of Various Algorithms

This contrasts with Vanilla LSTM, PoPPL and the Linear model. Table 1 shows a quantitative comparison of intent classification (ACC), Average Displacement Error (ADE) and Final Displacement (FDE). It can be seen that the proposed WTTFNet with WT information performed the best in intent classification accuracy, ADE and FDE. To test whether the statistical significance of the improvement from 71.50% to 71.95%, we find that a *p*-value of 0.0196 (<0.05) is obtained from the McNemar’s test. This suggests under the large samples of 28536, even a slight improvement of 0.45% is significant.

6. CONCLUSION

We reviewed various optimisation, machine learning and deep learning techniques for BEMS load scheduling optimisation and occupant trajectory prediction. Meanwhile, it has been demonstrated from various studies that the electricity demand can be predicted from occupancy. Sandels et al. (2015) [28] predicts the day-ahead demand of an office building using weather, occupany and temporal data. Chen et al. (2021) [29] predicted the electricity demand of an office building using artifical neural network (ANN) and occupancy rates. Ding et al. (2019) [30] predicted the electricity demand using an occupancy-based model for three campus buildings in Tianjian, China. In future, we shall extend our work in occupancy prediction to electricity demand prediction and load scheduling.

REFERENCES

1. Marinakis, V., 2020. Big data for energy management and energy-efficient buildings. Energies, 13(7), article no. 1555.
2. Beaudin, M., Zareipour, H.: ‘Home energy management systems: A review of modelling and complexity’, Renew. Sustain. Energy Rev., 2015, 45, pp. 318–335. doi: 10.1016/j.rser.2015.01.046
3. Han, B., Zahraoui, Y., Mubin, M., Mekhilef, S., Seyedmahmoudian, M., Stojcevski, A.: ‘Home Energy Management Systems: A Review of the Concept, Architecture, and Scheduling Strategies’, IEEE Access, 2023, 11, pp. 19999–20025. doi: 10.1109/ACCESS.2023.3248502
4. Chan, S.C., Tsui, K.M., Wu, H.C., Hou, Y., Wu, Y.C. and Wu, F.F., 2012. Load/price forecasting and managing demand response for smart grids: Methodologies and challenges. IEEE signal processing magazine, 29(5), pp.68-85.
5. Tsui, K.M. and Chan, S.C., 2012. Demand response optimization for smart home scheduling under real-time pricing. IEEE Transactions on Smart Grid, 3(4), pp.1812-1821.
6. Wu, H.C., Chan, S.C., Tsui, K.M. and Hou, Y., 2013. A new recursive dynamic factor analysis for point and interval forecast of electricity price. IEEE Transactions on Power Systems, 28(3), pp.2352-2365.
7. Schweiker, M., Hawighorst, M. and Wagner, A., 2016. The influence of personality traits on occupant behavioural patterns. Energy and Buildings, 131, pp.63-75.
8. Hosamo, H. and Mazzetto, S., 2024. Performance Evaluation of Machine Learning Models for Predicting Energy Consumption and Occupant Dissatisfaction in Buildings. Buildings, 15(1), article no. 39.
9. Yun, G.Y., 2018. Influences of perceived control on thermal comfort and energy use in buildings. Energy and Buildings, 158, pp.822-830.
10. Wang, Y. and Shao, L., 2017. Understanding occupancy pattern and improving building energy efficiency through Wi-Fi based indoor positioning. Building and Environment, 114, pp.106-117.
11. Pang, Z., O'Neill, Z., Chen, Y., Zhang, J., Cheng, H. and Dong, B., 2023. Adopting occupancy-based HVAC controls in commercial building energy codes: Analysis of cost-effectiveness and decarbonization potential. Applied Energy, 349, article no. 121594.
12. Zhao, B., Cao, X., Zhang, S., Ren, J. and Li, J., 2025, February. Day-ahead energy management of a smart building energy system aggregated with electrical vehicles based on distributionally robust optimization. In Building Simulation (Vol. 18, No. 2, pp. 339-352). Beijing: Tsinghua University Press
13. Makridakis, S., Spiliotis, E. and Assimakopoulos, V., 2018. Statistical and Machine Learning forecasting methods: Concerns and ways forward. PloS one, 13(3), article no. e0194889.

14. Hamilton, J.D., 2020. Time series analysis. Princeton university press.

15. Ugbehe, P.O., Diemuodeke, O.E. and Aikhuele, D.O., 2025. Electricity demand forecasting methodologies and applications: a review. Sustainable Energy Research, 12(1), article no. 19.

16. Torres, J.F., Hadjout, D., Sebaa, A., Martínez-Álvarez, F. and Troncoso, A., 2021. Deep learning for time series forecasting: a survey. Big data, 9(1), pp.3-21.

17. He, Z., Zhang, T., Wang, W. and Li, J., 2024. A deep pedestrian trajectory generator for complex indoor environments. Transactions in GIS, 28(2), pp.411-432.

18. Zhang, X., Chowdhury, R.R., Gupta, R.K. and Shang, J., 2024. Large language models for time series: A survey. arXiv preprint arXiv:2402.01801.

19. Mongaillard, T., Lasaulce, S., Hicheur, O., Zhang, C., Bariah, L., Varma, V.S., Zou, H., Zhao, Q. and Debbah, M., 2024, October. Large language models for power scheduling: A user-centric approach. In 2024 22nd International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt) (pp. 321-328). IEEE.

20. Helbing, D. and Molnar, P., 1995. Social force model for pedestrian dynamics. Physical review E, 51(5), article no. 4282.

21. Tsiamitros, N., Mahapatra, T., Passalidis, I., K, K. and Pipelidis, G., 2023. Pedestrian flow identification and occupancy prediction for indoor areas. Sensors, 23(9), article no. 4301.

22. Xue, H., Huynh, D.Q. and Reynolds, M., 2020. PoPPL: Pedestrian trajectory prediction by LSTM with automatic route class clustering. IEEE transactions on neural networks and learning systems, 32(1), pp.77-90.

23. Shi, L., Wang, L., Zhou, S. and Hua, G., 2023. Trajectory unified transformer for pedestrian trajectory prediction. In Proceedings of the IEEE/CVF International Conference on Computer Vision (pp. 9675-9684).

24. Rose, N. and Dolega, L., 2022. It’s the weather: Quantifying the impact of weather on retail sales. Applied Spatial Analysis and Policy, 15(1), pp.189-214.

25. Chung, E., Ohtani, O., Warita, H., Kuwahara, M. and Morita, H., 2005, September. Effect of rain on travel demand and traffic accidents. In Proceedings. 2005 IEEE Intelligent Transportation Systems, 2005. (pp. 1080-1083). IEEE.

26. Wu, H.C., Lau, E.H.S., Yuen, P.C.H., Hung, K., Chui, J.K.T. and Lui, A.K.F., 2024. WTTFNet: A Weather-Time-Trajectory Fusion Network for Pedestrian Trajectory Prediction in Urban Complex. IEEE Access.

27. Brščić, D., Kanda, T., Ikeda, T. and Miyashita, T., 2013. Person tracking in large public spaces using 3-D range sensors. IEEE Transactions on Human-Machine Systems, 43(6), pp.522-534.

28. Sandels, C., Widén, J., Nordström, L. and Andersson, E., 2015. Day-ahead predictions of electricity consumption in a Swedish office building from weather, occupancy, and temporal data. Energy and Buildings, 108, pp.279-290.

29. Chen, S., Ren, Y., Friedrich, D., Yu, Z. and Yu, J., 2021. Prediction of office building electricity demand using artificial neural network by splitting the time horizon for different occupancy rates. Energy and AI, 5, article no. 100093.

30. Ding, Y., Wang, Q., Wang, Z., Han, S. and Zhu, N., 2019. An occupancy-based model for building electricity consumption prediction: A case study of three campus buildings in Tianjin. Energy and Buildings, 202, article no. 109412.