THE HONG KONG
INSTITUTION OF ENGINEERS
ELECTRICAL DIVISION

The 41st Annual Symposium
Thursday
19 October 2023

EMERGING TECHNOLOGIES FOR SUSTAINABLE DEVELOPMENT

Ballroom
Sheraton Hotel
Nathan Road
Kowloon
Hong Kong

SYMPOSIUM PROGRAMME

08.30 Registration and Coffee

09.00 Welcome Address
- Ir Andrew KW Yan
  Chairman, Electrical Division, The HKIE

09.05 Opening Address
- Mr. Kevin O'Brien
  Chairman
  Business Environment Council, Hong Kong

09.20 Keynote Speech
- Ir Professor CY Chung
  Chair Professor of Power Systems Engineering and Head
  Founding Director of Research Centre for Grid Modernisation
  Department of Electrical and Electronic Engineering
  The Hong Kong Polytechnic University

1. Sustainable Development

09.50 Sustainable Development Goals and Electrical Engineering Perspective
- Ir Dr. FC Chan
  Past President
  The Hong Kong Institution of Engineers

10.10 Nuclear Fusion for Sustainable Development?
- Ir Professor Herman YW Tsui
  Chairman, Nuclear Division
  The Hong Kong Institution of Engineers

10.30 New Technical Initiatives of Sustainable Development in New Line Railway
- Ir Louis WK Lau, Chief Construction Manager - Building Services
- Mr. Alex TK Wong, Design Management Engineer
- Ms. Judy YL Tsoi, Design Management Engineer
- Ms. Rosa WH Lo, Design Management Engineer
  Capital Works Business Unit
  MTR Corporation Limited

10.50 Discussion

11.05 Coffee Break

2. AI Applications

11.35 Utilizing AI-enabled Digital Twin for ESG Compliance and Smart Facility Management
- Ir Dave CH Chan, Chief Executive
- Dr. P Lee, Technical Manager
- Ms. Karen MC Ho, Marketing Manager
  Information, Communications & Building Technologies
  ATAL Technologies Ltd.

11.55 Artificial Intelligence Based Forecast Models Developed for Photovoltaic Power System
- Dr. Zhang Langwen, Associate Professor
  School of Automation Science and Engineering
  South China University of Technology, Guangzhou
- Ir Stanley KW Leung, General Manager
  GDEPRI Power Control Systems & Equipment (HK) Limited

12.15 Discussion

12.30 Lunch

3. New Technologies in Power Systems

14.00 LV Smart Grid Technologies for the Utility of the Future
- Ir Bruce KM Chan, Director - Smartgrid & Innovation
- Dr. Tianxiang Jiang, Principal Manager - Smartgrid Strategy
- Ir Dr. Vincent KW To, Senior Lead Engineer - Smartgrid Strategy
- Dr. Jiaxin Wen - Engineer
- Mr. Timothy LF Lam - Assistant Engineer
  The Department of Smartgrid and Innovation, Power Systems
  CLP Power Hong Kong Limited

14.20 Road to Carbon Neutrality with Microgrid Implementation
- Ir Keith TM Wong, Head of Digital Business and Electrical Products
- Mr. Terrence YT Choi, Project Manager
- Mr. Hydren HC Lam, Senior Product Engineer
  Smart Infrastructure Division, Siemens Limited Hong Kong

14.40 A State-of-the-Art Environmentally Friendly Transformer Oil for Extended Transformer Life Cycle
- Mr. James Reid
Technical Manager - Ester Applications
- Mr. Budi Wicaksono
Applications Engineer - MIDEL Asia Pacific
M&I Materials Limited

15.00 Discussion

15.20 Coffee Break

4. ***<u>Digital Applications in Construction & Built Environment</u>***

15.50 City Data Repository and Applications Development for Built Environment
- Ir Dr. Bruce WH Chong
City Advisory, Climate & Urban Sustainability Leader
East Asia Region, Arup

16.10 Unlocking Digital Power in Construction and Built Environment
- Ir Raymond WM Kwok
Former MEP & Innovation Lead
- Ir Eric NK Tsung, Manager, Projects
Swire Properties Limited

16.30 Discussion

16.45 Summing Up
- Ir Mandy MY Leung
Symposium Chairman
Electrical Division, The HKIE

Closing Address
- Ir Eric SC Ma, JP
Senior Vice President
The Hong Kong Institution of Engineers

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

Mr. Kevin O'Brien
Ir Professor CY Chung
Ir Dr. FC Chan
Ir Professor Herman YW Tsui
Ir Louis WK Lau
Mr. Alex TK Wong
Ms. Judy YL Tsoi
Ms. Rosa WH Lo
Ir Dave CH Chan
Dr. P Lee
Ms. Karen MC Ho
Dr. Zhang Langwen
Ir Stanley KW Leung
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Mr. Terence YT Choi
Mr. Hydren HC Lam
Mr. James Reid
Mr. Budi Wicaksono
Ir Dr. Bruce WH Chong
Ir Raymond WM Kwok
Ir Eric NK Tsung

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Paper No. 1

SUSTAINABLE DEVELOPMENT GOALS AND ELECTRICAL ENGINEERING PERSPECTIVE

Author/Speaker: Ir Dr. FC Chan
Past President
The Hong Kong Institution of Engineers

SUSTAINABLE DEVELOPMENT GOALS AND ELECTRICAL ENGINEERING PERSPECTIVE

Ir Dr. FC Chan
Past President
The Hong Kong Institution of Engineers

ABSTRACT

Sustainable Development Goals (SDGs) are a set of 17 goals established in 2015 by the United Nations to promote sustainable development. These SDGs have become a widely adopted standard to achieve the aim of sustainable community development. Energy is the heart of these 17 SDGs, particularly the SDG 7 which aims to ensure access to affordable, reliable, sustainable and modern energy for all by 2030. Internet-of-Things, 5G communications network, Artificial Intelligence are various emerging technologies that work towards digital transformation. This paper explores, from an electrical engineering perspective, how we can help to assist in achieving those related SDGs.

1. INTRODUCTION

Nowadays, people ask ChatGPT to write article for a specific topic. When this paper title "Sustainable Development Goals and Electrical Engineering Perspective" was input to ChatGPT, the following short paragraph was generated:

> *"From an electrical engineering perspective, the Sustainable Development Goals (SDGs) present a framework for designing and implementing sustainable energy systems that can help achieve the SDGs. Electrical engineers play a key role in developing and implementing clean energy technologies, such as renewable energy sources, energy storage systems, and smart grid systems, that can help increase access to affordable and clean energy, improve energy efficiency, and reduce greenhouse gas emissions. By designing and implementing sustainable energy systems, electrical engineers can help contribute to several of the SDGs, including SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action)".*

Interestingly, this paragraph has rightly highlighted the role of electrical engineering profession and the related sustainable development goals!

2. SUSTAINABLE DEVELOPMENT GOALS

In September 2015, the United Nations General Assembly adopted a set of Sustainable Development Goals (SDGs) for the post-2015 development envisioning a world that is comprehensively sustainable: socially fair, environmentally secure, and economically prosperous for a concerted effort to build a future based on sustainability targets intended to be achieved by 2030. The 17 SDGs are briefly explained in Table 1 in this paper. Each goal comes with several targets, making a total of 169.

Figure 1 shows these 17 SDGs logos. The 17 SDGs are not legally compulsory. Governments are expected to take ownership and form policies and roadmaps to reach these goals. Each government should collect relevant data to review annual progress and take the required follow-up actions. These goals can be more effectively implemented by embedding all their required initiatives in the action plans of government's functional departments.

Fig. 1 - 17 SDGs Logos

3. SDG7: AFFORDABLE and CLEAN ENERGY

Energy is the heart of these 17 SDGs, particularly the SDG 7 which aims to ensure access to affordable, reliable, sustainable and modern energy for all by 2030. For the least developed countries, expanding the access to electricity is an example; for developing countries, improving choice of energy and its usage is an example; for developed countries, reducing energy wastes is an example. The five targets under SDG 7 by 2023 are:

Goal No.	Goal	A brief description of the Goal	Number of targets to be achieved
SDG 1	No Poverty	End poverty in all its forms everywhere	7
SDG 2	Zero Hunger	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	8
SDG 3	Good Health and Well-being	Ensure healthy lives and promote well-being for all at all ages	13
SDG 4	Quality Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	10
SDG 5	Gender Equality	Achieve gender equality and empower all women and girls	9
SDG 6	Clean Water and Sanitation	Ensure availability and sustainable management of water and sanitation for all	8
SDG 7	Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable and modern energy for all	5
SDG 8	Decent Work and Economic Growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	12
SDG 9	Industry, Innovation and Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	8
SDG 10	Reduced Inequalities	Reduce inequality within and among countries	10
SDG 11	Sustainable Cities and Communities	Make cities and human settlements inclusive, safe, resilient and sustainable	10
SDG 12	Responsible Consumption and Production	Ensure sustainable consumption and production patterns	11
SDG 13	Climate Action	Take urgent action to combat climate change and its impacts	5
SDG 14	Life below Water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	10
SDG 15	Life on Land	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	12
SDG 16	Peace, Justice and Strong Institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	12
SDG 17	Partnerships for the Goals	Strengthen the means of implementation and revitalize the global partnership for sustainable development	19

Table 1 - 17 Sustainable Development Goals

- 7.1: Ensure universal access to affordable, reliable and modern energy services.
- 7.2: Increase substantially the share of renewable energy in the global energy mix.
- 7.3: Double the global rate of improvement in energy efficiency.
- 7.4: Enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.
- 7.5: Expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support.

4. ENERGY UTILIZATION

Considering energy is an essential component in the implementation of the SDGs, the utilization of energy is closed related to more SDGs, not only SDG7 but also including other SDGs. Figure 2 shows 12 areas closely related to energy utilization.

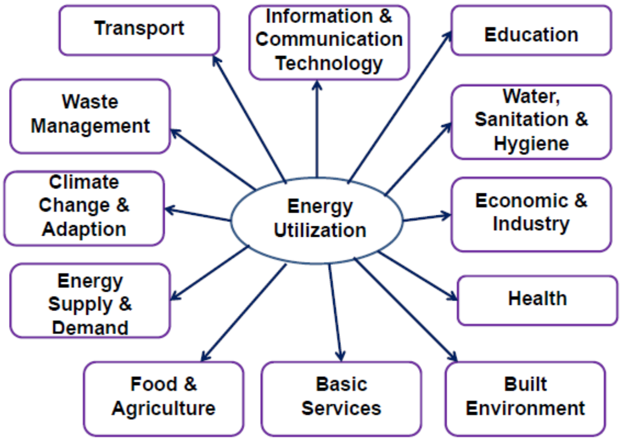

Fig. 2 - Energy Related SDGs

These 12 areas related to respective SDGs are outlined as below:

- Energy Supply & Demand: 7.1 on universal access to modern energy, 7.2 on increase share of renewable energy, 7.3 on double energy efficiency.
- Climate Change & Adaption: 13.1 on reduce national vulnerability to climate-related hazards & disaster.
- Waste Management: 11.6 on improve urban waste management, 12.5 on reduce waste and improve recycling, 12.3 on reduce food loss by half.
- Transport: 9.1.1 on all season road for rural population, 9.1.2 on passenger and freight transport, 11.2 on access to public transport.
- Information and Communication Technology: 5.b on use of ICT technology to empower women, 9.c on access to ICT technology, 17.6 and 17.8 on access to Internet.
- Education: 4.1, 4.2 & 4.3 on access to all levels of education.
- Water, Sanitation and Hygiene: 6.1 on access to drinking water, 6.3 on improve water quality.
- Economic and Industry: 8.1 on sustain economic growth.
- Health: 3.8 on universal access to health care.
- Built Environment: 11.1 on access to housing.
- Basic Service: 1.4 on access to basic service.
- Food and Agriculture: 2.1 & 2.3 on food production and access, 2.4 on sustainable agricultural practice.

5. INTERNET-OF-THINGS

The Internet-of-Things (IoT) is a key component in various systems that enable sustainability to be formulated for operation. For example, a smart street lighting IoT supports energy efficiency enhancement while an IoT for condition-based maintenance of smart grid supports infrastructure. The IoT is a network of physical devices, capable of communicating to one another including sensors, actuators, computers and machines. Each device is assigned with a unique identifier (UID), establishing the context of a device within a larger wired or wireless network. Through a host of network protocols, the device is able to transfer data and self-reporting in real time. Hence an IoT platform manages these devices by digitally monitored and controlled both hardware and software.

A typical structure of IoT consists of 5 layers. The bottom layer is Perception Layer where sensors and connected devices gather data information, for example, taking measurements of temperature, air quality, pressure, speed, electricity etc. Most of these devices are connected to the network gateway like Local Area Network, Wi-Fi etc. Next layer above the perception layer is Network Layer which is responsible for data transmission from sensor devices to the information processing system using technology like Bluetooth. The next layer is Middleware Layer which carries out information processing through analytics, security controls, process modelling and management of devices. This layer is also responsible for the service management and received data stored into the database. The next layer is Application Layer which is responsible for delivering application specific services to the user. The top layer is Business Layer which manages the overall IoT system. The technologies for the first 4 layers are shown in Figure 3.

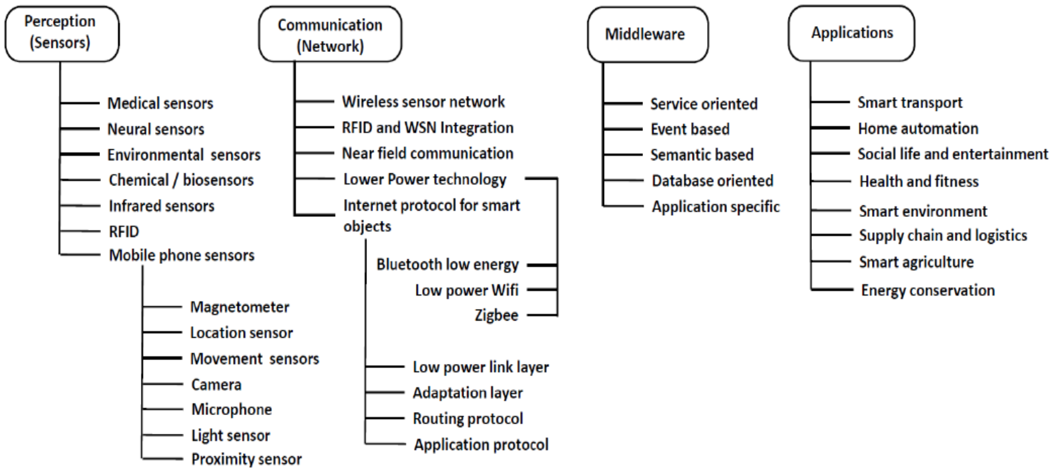

Fig. 3 - The First 4 Layers of IoT Technologies

6. SMART GRID

A smart grid is essentially an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. Smart grids coordinate the needs and capabilities of all generating sources, grid operators, end users and electricity market stakeholders to operate all assets as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience, flexibility and stability. Smart grid utilizes phasor measurement unit (PMU) together with Wide Area Monitoring System (WAMS) technologies, the grid status is real time with a delay of just 10 to 20ms instead of the SCADA response in the range of 4 to 6 sec. Traditional grid is equipped with limited amount of sensors but for smart grid, sensors application is throughout. In handling renewable energy of an intermittent generation nature, smart grid can be firmly and securely integrated.

7. ENERGY INTERNET

Recently, there is a new concept called Energy Internet (EI) being proposed, researched and developed. These include: EI as a Smart Grid, EI as Global EI, EI as a Quantum Grid, and EI as a large scale Cyber-Physical System. In an internet, information flows are from server to Cloud then to end users via routers. In Energy Internet, energy flows are from bulk generation via transmission system to substation for power distribution with the use of energy router like transformer. Figure 4 is a comparison of information flows in internet and energy flows in power system network The Energy Router, apart from the basic function of energy transformation, it also serves as communication link for supply and demand information to be assessed with formulated decision and strategy. For the Quantum Grid, power transmission is attributed as Energy Packets similar to data packets thus energy distributed would use allocated addresses with the use of Quantum Grid Router.

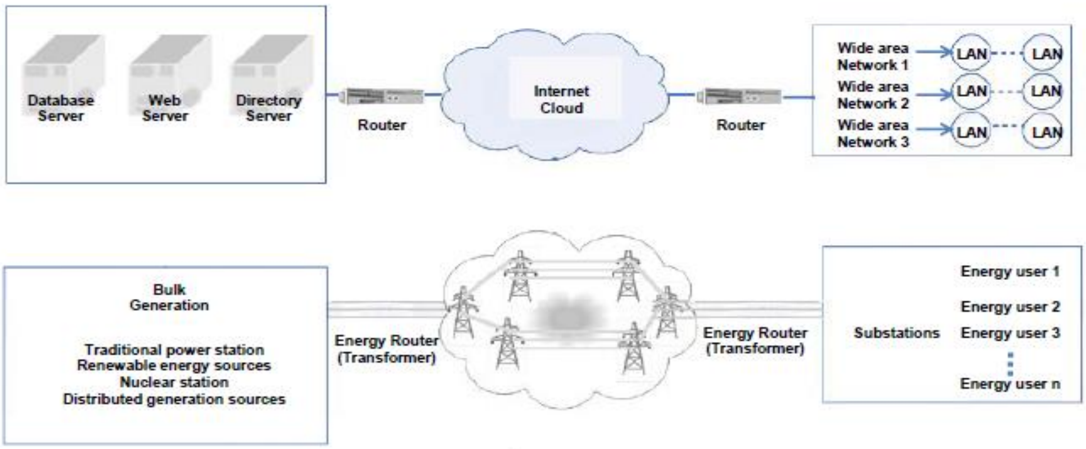

Fig. 4 - A Comparison of Energy Flows and Information Flows

8. CYBER-PHYSICAL SYSTEM

Communication technology is the key element in developing the Cyber-Physical System which helps the development of Energy Internet. Tactile Internet is referred as the interaction between humans and cyber-physical systems by dropping off the distance and ensuring a fast communication (a few milliseconds). Hence, Tactile Internet (TI) is of low latency with high availability, reliability and security thus providing a better quality of lifestyle of people, society and business. TI is one of the next generation wireless network services with end-to-end delay as low as 1 ms. A typical Tactile Internet system components can be shown in Figure 5.

In the physical world, there are various applications related to industry like automation, healthcare, gaming etc and for smart cities, like road traffic management with autonomous vehicles. Smart computing linked with artificial intelligence would result in better quality of services. Communication is the key element in handling high data rate and 5G is the minimum requirement. The IoT includes embedded sensors for data collection as well as actuators for domain action. The storage and computation aspects require integration with means of computing from fog, edge to cloud. The feedback in TI is the path completing the control loop which can be closed or open.

9. 6G FOR TACTILE INTERNET

The development of information communication technology is roughly a 10-year cycle since the 1980s. 5G is achieved with many breakthrough resulting in better transmission speed, ultra-low latency, reduced power consumption and suitable for IoT applications. In terms of services, 5G is an enhanced mobile broadband (eMBB). It is essentially for massive machine-type communications (mMTC) with ultra-reliable and low latency communications (URLLC). In terms of applications, Tactile Internet can provide services as remote surgery, remote monitoring, distance education and remote driving, etc.

6G is the next generation communication as shown in Figure 6. The 6G network will enable everything to be linked deeply, intelligently and seamlessly. High frequency like Terahertz THz (0.1-10 THz) will be central to 6G, thus having ample spectrum, above 100 Gbps data rates. Hence, 6G will present new system paradigms: human-in-the-loop communication and human-centric services. A comparison of 5G and 6G is shown in Table 2. By looking at these technology

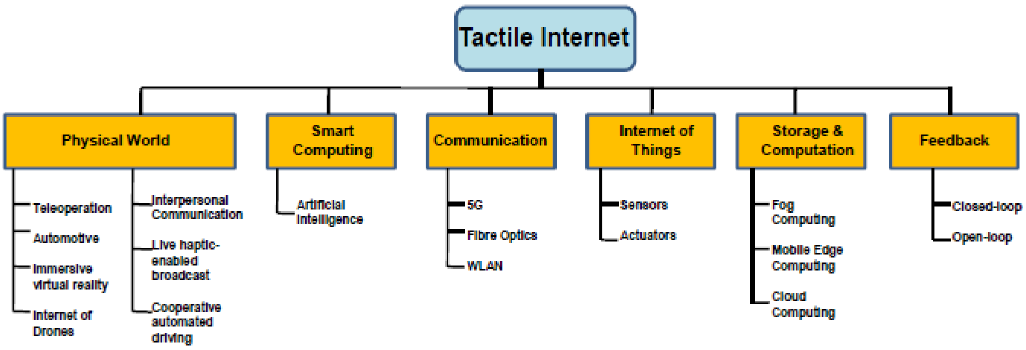

Fig. 5 - Tactile Internet Components

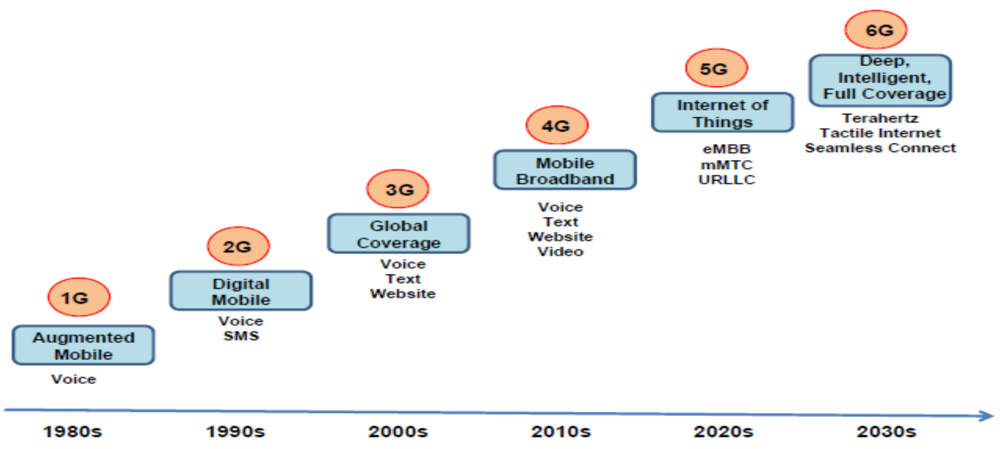

Fig. 6 - 6G Development Trends

features, 6G will have a much better performance over 5G.

Technology Feature	5G	6G
High peak data rate	20 Gbps	1 Tbps
Experience rate	Up to 1 Gbps	Counted as Gbps
Latency	1 ms	As low as 0.1 ms
Traffic density	10 tbps/sq meter	100-10,000 tbps/sq meter
Mobility	500 km/h	>1000 km/h
Spectrum efficiency	100 bps/Hz	200-300 bps/Hz
Error coding rate	Less than 1/100 thousand	Less than 1/1 million
Positioning capability	Outdoor/10 m, Indoor/1 m	Outdoor/1 m, Indoor/10 cm
Network energy efficiency	100 bits/J	200 bits/J

Table 2 - Comparison of 5G and 6G

When 6G is further integrated with Artificial Intelligence, many functions can be implemented for the betterment of the society. The AI-enabled 6G Network functions can be highlighted as shown in Figure 7 with various defined layers of applications.

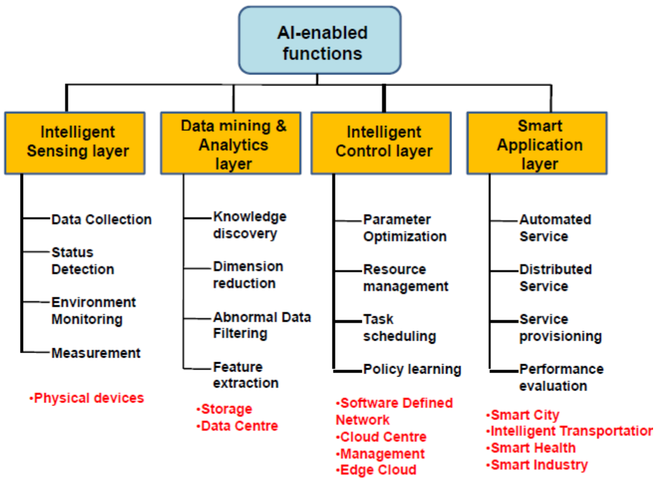

Fig. 7 - AI Enabled Functions

With this enhanced communication technology, the IoT can be further expanded to nearly everything and renamed as IoE, Internet of Everything. With low power for 6G communication, the device aims for energy self-sustainability (ESS) and a technology named as Simultaneous wireless information and power transfer (SWIPT) will support the IoE development.

10. INDUSTRY 5.0

Industry 5.0 is a stage of development of manufacturing where machines become smart enough to perform complex actions all by themselves, leverage advanced technologies and computing capabilities to collaborate with humans and work faster and more efficiently. Industry 5.0 uses collaborate robots and AI to bring a human touch to the concept of digital transformation. Industry 5.0 has three pillars: namely, human-centric, resilient and sustainable. A review of the evolution form Industry 1.0 to Industry 5.0 is shown in Figure 8. With the increasing complexity of work, the Industry can be categorized by its main characteristics, that include mechanization, electrification, automation, digitalization and personalization. Sustainability is a key element in developing various technologies in enhancing human living in the world.

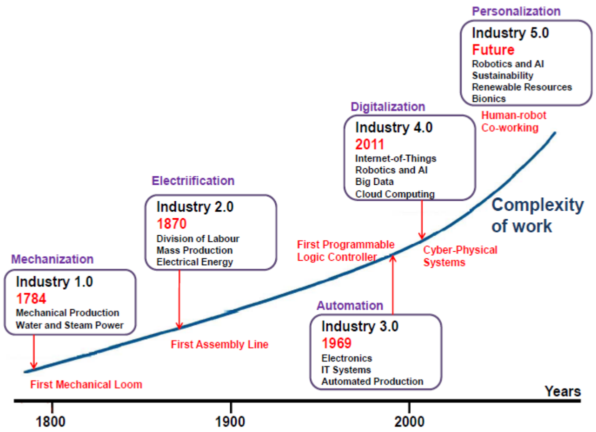

Fig. 8 - Evolution from Industry 1.0 to Industry 5.0

11. CONCLUSION

The era of Industry 5.0 has started and various emerging technologies will play an important role towards sustainability. This paper examines what is required to be achieved for sustainability with reference to the United Nations' 17 Sustainable Development Goals (SDGs). With the development of new technologies, the key issue is on its understanding and innovative applications for a better world. Electrical engineering profession has a key role to play for sustainable development!

Paper No. 2

NUCLEAR FUSION FOR SUSTAINABLE DEVELOPMENT?

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NUCLEAR FUSION FOR SUSTAINABLE DEVELOPMENT?

Ir Professor Herman YW Tsui
Chairman, Nuclear Division
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ABSTRACT

The attainment of an energy gain factor (Q ≥ 1) in fusion energy development on 5 December 2022 represents a momentous milestone, signifying the feasibility of sustainable power generation through fusion. Nonetheless, the journey towards achieving commercial fusion power and its implications for sustainable development present additional challenges and necessitate ongoing research.

Mainstream fusion devices such as ITER (magnetic confinement fusion) and NIF (inertial confinement fusion) are progressing steadily towards the goal of fusion power generation. However, the scale of these facilities is becoming enormous, presenting challenges for achieving commercial viability. Fortunately, recent developments, particularly in high-temperature super-conductors, offer promising solutions for more compact magnetic confinement devices, potentially enhancing commercial feasibility.

In addition to mainstream development, the fusion community is exploring alternative concepts that require smaller facilities, thereby enhancing their economic viability. These concepts include reducing (tightening) the aspect ratio in conventional Tokamak geometry, utilizing different drivers and compressional mechanisms for inertial confinement, and combining magnetic and inertial approaches in hybrid devices. Initial numerical modeling and experimental results suggest that these alternate concepts have significant potential for achieving commercially more viable power generation.

1. INTRODUCTION

1.1 Sustainable Development and Nuclear Power

Sustainable development is essential for the well-being of our planet, but it is not without its challenges. Two of the most pressing challenges are global warming and energy shortage. The current reliance on fossil fuels for energy not only contributes to climate change but also depletes finite resources and causes environmental harm.

While renewable energy is a crucial component of sustainable development, certain renewable sources such as wind and solar, have their limitations. They are weather-dependent and require effective and viable storage solutions to address fluctuations in power generation. Nuclear power plays a significant role in reducing carbon emissions. The International Energy Agency (IEA) envisages that to help achieve the carbon neutrality of Net Zero, the nuclear power capacity in the world will be doubled by 2050 [1].

- China is the leader in nuclear power expansion, with several new plants under construction. The China Nuclear Energy Association estimates that nuclear power capacity will reach 100-120 GW by 2030. As at January 2023, 55 nuclear power plants are in operation in the Mainland China with a total installed capacity of 53 GW.

- The United Kingdom has plans to build a new fleet of nuclear power stations, starting with Hinkley Point C and followed by Sizewell C, with the hope to reach 24 GW nuclear capacity by 2050. The UK government sees nuclear as a critical part of its strategy to decarbonize the electricity sector and achieve net-zero emissions by 2050.

- India has a significant expansion plan for nuclear power as part of its commitment to the Paris Agreement. The country aims to increase its nuclear capacity to 22.5 GW by 2030.

- Russia: Russia has been actively building new nuclear power plants both domestically and abroad. To reduce its carbon footprint, Russian has envisaged a plan to develop 12 new nuclear reactors by 2035 and a programme for 17 additional reactors by 2045. Power generation from Russian nuclear plants is expected to reach 373 TWh in 2045 (225.5 TWh in 2021).

However, it is important to recognize that the current generation of nuclear fission power is not without its drawbacks and limitations. These concerns, such as production and management of irradiated nuclear fuel, the potential for accidents, and the high cost of building and maintaining nuclear power plants are being addressed to various degrees in the new generations (Generation 3 and Generation 4) of nuclear power plants [2].

1.2 Nuclear Fusion for Sustainable Development

At present, nuclear power generation is based on nuclear fission, a process that involves splitting atoms to generate energy. However, there is growing interest in nuclear fusion, which is often referred to as the holy grail of nuclear power due to its many advantages.

One advantage of nuclear fusion is that it uses hydrogen isotopes, deuterium (D) and tritium (T), as fuel. Abundant supply of D can be extracted from seawater and T converted from lithium, ensuring a nearly limitless supply of fuel.

Fusion reactors also produce no long-lived radioactive waste, unlike fission reactors. The only byproduct of fusion is helium, which is non-toxic and does not pose any environmental risks.

Fusion reactions are inherently safe, as they require precise conditions of temperature and pressure to sustain the fusion process. If any disruptions occur, the fusion reaction stops immediately, without the risk of a runaway chain reaction or a severe accident.

The risk of nuclear proliferation is low due to the fact that fusion reactors do not produce fissile materials (such as plutonium) that can be used in nuclear weapons. The fuel used in fusion reactions does not lend itself to weapons proliferation.

Despite these advantages, achieving controlled fusion reactions at high temperatures and maintaining them for a sustained period is a significant technical challenge. The extreme conditions required for fusion, such as plasma temperatures of over 100 million °C, pose numerous engineering and technological difficulties.

Nevertheless, scientists and engineers are working towards overcoming these challenges and making nuclear fusion a viable and sustainable source of energy. If successful, nuclear fusion has the potential to transform the energy landscape by providing a near-limitless and clean source of energy for generations to come.

2. NUCLEAR FUSION

Nuclear fusion is the process of combining two atomic nuclei into a single, more massive nucleus, releasing a large amount of energy in the process. This process is the source of energy for stars, including our sun. Since nuclei are positively charged, high velocities (or temperatures) are required to overcome the repulsive Coulomb force to bring them close enough to undergo fusion. The primary challenges in harnessing fusion power involve maintaining the fuel plasma at extremely high temperatures, around 10^8 °C, while ensuring sufficient density and confinement time.

Magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) are the two primary approaches for achieving controlled nuclear fusion. There are many different devices developed to study fusion power [3]. In MCF, a plasma of the fuel (D-T) is confined by magnetic fields. The plasma is heated Ohmically and via auxiliary heating to extremely high temperatures, causing the nuclei to collide and fuse, releasing energy in the process. In ICF, a small target containing the D-T fuel is rapidly compressed and heated, for example by intense laser pulses, causing the fuel to fuse and release energy.

Both MCF and ICF have their own unique challenges and advantages. Tokamak is the mainstream development of magnetic confinement, represented by the International Thermonuclear Experimental Reactor (ITER) and laser fusion is the mainstream development of inertia confinement, represented by the US National Ignition Facility (NIF).

2.1 Advancements in Magnetic Confinement Fusion

Significant progress has been made in the field of MCF, which is approaching the demonstration of fusion power generation. The progress is supported by technology innovation in superconductor for stronger and more efficient magnetic fields; plasma auxiliary heating for efficient heating and longer plasma sustainment; diagnostic to better characterize energy deposition profile, plasma heating and current drive; advanced simulation, and modelling to predict and optimize fusion device performance.

In an operational cycle or discharge, the fuel plasma is initially heated through Ohmic heating and the plasma current is maintained inductively using magnetic coils. Advanced plasma auxiliary heating methods, including neutral beam injection, electron cyclotron heating, ion cyclotron resonance heating, and lower hybrid current drive, are utilized to supplement heating and current drive. The recent advancements in these methods have successfully raised the plasma temperature to fusion conditions and facilitate a near steady-state operation for over 1,000 seconds.

Another notable innovation is the superconductor, particularly the discovery of the high-temperature superconductor (HTS) which allows for construction of more compact magnets to generate stronger and more efficient magnetic fields, see for example, [4].

The performance of fusion reactor increases with the major radius (R) and more so with the magnetic field (B) as can be seen from the scaling relationships [5] at fixed Tokamak aspect ratio and shape for the thermal fusion power gain via the triple-product,

$$nT\tau_E \sim \frac{\beta_N H_{89}}{q_*^2} R^{1.3} B^3 \quad (1)$$

and for the fusion power P_{fusion} loading over the wall/blanket surface area S_{wall},

$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^2}{q_*^2} RB^4 \quad (2)$$

It can be seen from (1) and (2) that a small high magnetic field device can achieve the same level of performance as a much bigger low field device. This can lead to cost savings and make fusion reactors more economically viable. A summary figure (extracted from [7]) shows high Q can be achieved with a smaller device (smaller major radius, R_0) and hence a smaller plasma volume (V_p) with a higher magnetic field (toroidal field on axis, B_0).

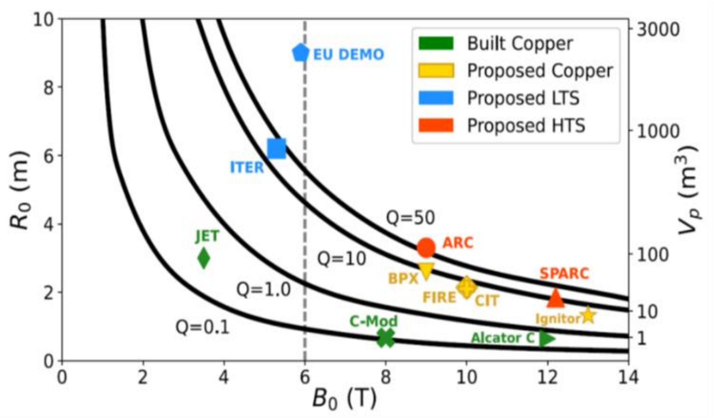

Fig. 1 - The Relationship of Fusion Gain Q to Toroidal Field on Axis B_0 and Major Radius R_0 (Source: From [7])

Furthermore, HTS can reduce the energy consumption of fusion reactors by reducing the Ohmic loss of the magnets. This, in turn, can lead to lower operating costs and make fusion more competitive. HTS can also enable longer sustained plasma pulses, which is important for practical fusion power generation. For example, the Experimental Advanced Superconducting Tokamak (EAST) achieved a plasma pulse lasting 1056 seconds in December 2021 [6].

In addition to the mainstream Tokamak approach, there have been several advances in alternate concepts, aimed at improving the efficiency, stability, and economic feasibility. One alternate concept is the Spherical Tokamak (ST) which in essence is a conventional Tokamak with a small aspect ratio (a ratio of major to minor radius), but has a more compact and spherical shape. The compactness allows for stronger magnetic fields and higher plasma pressure, leading to improved plasma performance and a smaller device. ST typically have a hollow plasma current profile, with current more concentrated towards the outer edge of the plasma. This current profile helps to stabilize the plasma and reduce instabilities.

Advances in ST designs, such as the MAST Upgrade of UK and the NSTX-U of US, have demonstrated improved plasma performance in heat exhaust and impurities control, and reduced energy losses. ST together with the use of HTS leads to a compact, spherical-shaped fusion devices that have shown promise in achieving high plasma pressure and stability, making MCF more commercially viable.

2.2 Advancements in Inertia Confinement Fusion

ICF aims to achieve fusion reaction by compressing and heating a target containing fusion fuel. Laser fusion is the mainstream development wherein powerful lasers are used as the drive to compress and heat the fuel. The process begins with the laser pulses interacting with the outer surface of the fuel pellet, creating a plasma and ablating the pellet surface materials. The ablation and the expanding plasma exert a reaction force that compresses the remaining fuel material inwards and the plasma also drives a strong shock wave inward through the fuel pellet, further compressing the fuel. The compression increases the temperature and pressure within the fuel pellet, creating conditions necessary for fusion reactions to occur.

Laser fusion has made steady progress through advances in high power laser system, better design of the hohlraums (the cylindrical housing for the D-T, fuel), and a better understanding of the compression process. Computer simulation plays an important role to provide insights into the design of the hohlraum, the behaviour of the induced X-rays, the implosion dynamics and the physics of a burning plasma.

On 5 December 2022, for the first time, the energy gain factor $Q_{sci} \geq 1$ had been achieved in NIF, signifying that fusion energy released is more than the heating power injected and a sustainable power generation is feasible. To achieve the breakthrough, NIF used 192 lasers to deliver 2.05 MJ of energy onto a pea-sized gold hohlraum containing a frozen pellet of D-T fuel, which caused the pellet to collapse, reaching temperatures of 10^8 °C, and initiated D-T fusion reactions which released 3.15 MJ to yield a Q_{sci} of 1.54 [8]. Beyond the significant scientific achievement are enormous engineering challenges:

- Energy conversion efficiency: the lasers consumed 322 MJ to generate the X-rays that actually spark fusion, resulting only about 1% of the input energy for heating the fuel.
- High energy drivers: much higher output than the 3.15 MJ is needed.
- Repetition rate: the facility can fire laser only once a day at a single target but 3-10 Hz is needed.

Advanced ignition schemes have been explored in order to lessen the requirements on high power laser to improve the overall efficiency. One of the schemes, shock ignition, involves the rapid compression of a fuel capsule using one set of lasers, followed by another powerful laser pulse (ignitor) that generates a strong shockwave. The shockwave heats and ignites the fuel, initiating fusion reactions. Another scheme is the fast ignition whereby after the fuel is compressed using one set of lasers, a short high power fast ignitor beam at proper time generates fast electron beam that increases the temperature of the central part of the target leads to an effective hot spot that completes the ignition process of fuel.

An alternate approach to ICF is to use other type of drivers, such as gas gun or railgun, instead of a powerful laser system. In the Projectile Fusion (PF) or impact fusion scheme as depicted in Figure 2 below, a driver accelerates a projectile to high velocity. The projectile collides with the target, causes cavity collapse to create a shockwave that facilitates compression and heat of the fuel.

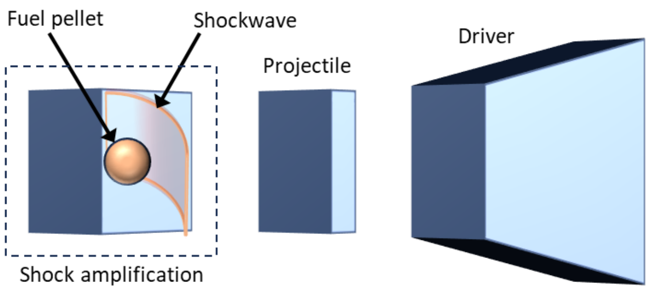

Fig. 2 - Schematic of the Projectile or Impact Fusion Approach

Interest in this PF approach started in the early 1960s and some of the early investigations can be found in the Proceedings of the Impact Fusion Workshop, 1979. The Impact Fusion Workshop determined some basic requirements for impact fusion.

- The minimum velocity of the projectile is 200 km/s and with a kinetic energy of about 10 MJ.
- A characteristic thickness of the macroparticle and plasma cavity might be a few mm, and the time scale (burn) might be 5 - 10 ns.
- One challenge is to convert the linear kinetic energy into a 3-dimensional compression without energy losses.

It was considered that a major block to PF is the development of drivers capable of accelerating the projectile to the necessary high velocity with sufficient impact precision.

Recently in 2022, the First Light Fusion (FLF) team made a significant step forward to demonstrate achieving fusion using a 2-stage light gas gun [9].

The breakthrough was resulted from a better understanding of the shock amplification effect arising from cavity collapse. Computer simulations as well as the development of high-speed X-ray imaging system (with an effective frame rate reaching Mfps for images separated by 10^{-7} s) played a crucial role in gaining understanding of the collapse dynamics and providing insight into the behavior of the target [10]. The fusion results were confirmed by a UKAEA diagnostic team [11] with their report stated that "… neutrons have been produced which would be consistent with the energy of those produced in D–D fusion processes".

Fig. 3 - The Two-stage Light Gas Gun used to Accelerate Projectiles Up to 6.5 km to Achieve Projectile Fusion (©First Light Fusion Limited, 2021)

The Projectile Fusion approach, recently revitalized by the FLF team, offers a compelling alternative to traditional Tokamak and laser fusion concepts. By utilizing an external driver, such as a pulsed power machine, to propel projectiles and create the extreme temperatures and pressures required for fusion, this approach introduces a simpler and more cost-effective design. It eliminates the need for massive magnetic coils or complex laser systems, potentially reducing both construction and operational costs associated with fusion research and development. Through numerical simulations, FLF was able to optimize the target design to better harness the shock amplification effect to enhance compression to achieve higher fusion gain.

The advancement of railgun technology for the driver offers a more reliable and controllable means to propel the projectiles, providing a greater precision generation of the shockwave for a stronger amplification effect.

3. WHEN WILL FUSION POWER BE AVAILABLE?

Initially, in the late 1950s, there was great optimism, with many scientists and researchers believing that it was only 15 years away. In the following years, the sentiment became more cautious, with suggestions that it would be at least 50 years away. However, recent developments and innovations have sparked a renewed sense of optimism. Table 1 shown some of the targeted achievements of the updated and newly announcements [3, 12, 13]:

Table 1 are just a few examples of the ongoing fusion research efforts with mainstream developments typically expect to demonstrate electricity generation by 2050s. The alternate lines are more optimistic and some expect to see electricity delivery by 2030s. While there is renewed optimism, there are engineering challenges to be overcome before commercial viability can be achieved in as early as 2030s.

Device	Target Date	Organization
ITER (Tokamak)	2030s, technical feasibility of fusion power, Q ~ 10	International Collaboration
CFETR EU-DEMO JA-DEMO K-DEMO DEMO-RF (Tokamak)	2040s, $Q_{eng} > 1$, 200MW$_e$ 2050s, $Q_{eng} > 1$, 500 MW$_e$ 2050s, $Q_{eng} > 1$ 2050s, $Q_{eng} > 1$ 2050s, $Q_{eng} > 1$	China EU Japan Korea Russia
SPARC (Tokamak)	2025+, $Q_{sci} \approx 11$	Commonwealth Fusion Systems & Plasma Science and Fusion Center, MIT
STEP/SPR (Spherical Tokamak) ST80-HTS/ST-E1 (Spherical Tokamak)	2030s, deliver electricity 2030s, deliver electricity	UKAEA Tokamak Energy
LM26 (Magnetized Target Fusion)	2020s, Q > 1 Early 2030s, net energy gain	General Fusion
C-2W C-2E (FRC)	2020s, net energy gain 2030s, prototype power plant	TAE Technologies
NIF (Laser Fusion)	Dec 2022, achieved Q of 1.54	Lawrence Livermore National Laboratory
M3 (Projectile Fusion)	2030s, net energy gain	First Light Fusion

Table 1 - Target Performance of Some Different Types of Devices

In order to advance MCF to large-scale power generation, further R&D efforts are required to enhance understanding of burning plasma physics, impurity control, disruption avoidance, and instability control. Furthermore, engineering development is needed to establish essential technologies for all subsystems, particularly in plasma-facing materials to address irradiation protection and efficient heat removal, high-temperature superconducting materials, and large auxiliary heating power systems.

In the case of ICF, enhancing the energy conversion efficiency and increasing the repetition rate of the laser system are crucial for scaling up to energy production. While the alternate Projectile Fusion concept has shown considerable promise, further advancements are needed in the precision control of high-power railgun technology and the construction of targets to achieve optimal shockwave amplification. The engineering challenges associated with ash removal and refuelling are yet to be demonstrated.

4. CONCLUSION

Accurately predicting the timeline for achieving commercially viable nuclear fusion power is a challenging task. Nonetheless, the diligent R&D on harnessing fusion energy for many years has resulted in significant progress. Demonstrations of scientific feasibility in both MCF and ICF have been achieved, exemplified by recent accomplishments such as reaching a Q of 1.5 in NIF.

While mainstream fusion devices are steadily progressing towards realizing fusion power generation, it is still estimated that achieving commercially viable fusion power will be in the 2050s. The development of the HTS for generating stronger magnetic fields offers promising solutions for more compact magnetic confinement devices, making commercial fusion power more viable. In addition to HTS, alternative magnetic confinement approaches, such as the ST, show great potential for reducing the size of fusion reactors even further and offer an attractive and expedited solution, with some experts anticipating commercialization as early as the 2030s.

In laser fusion, alternate ignition schemes hold promise for reducing the requirements on high-power laser systems. This, in turn, can lead to smaller and more cost-effective facilities, accelerating the path to viable commercial fusion power. Additionally, the Projectile Fusion scheme, utilizing alternate drivers like railguns, presents an attractive opportunity to achieve net energy gain as early as the 2030s.

In summary, although challenges and uncertainties persist, progress in fusion research, coupled with technological innovations and exploration of alternate concepts, brings us closer to realize commercially viable fusion power. Continued dedication and collaboration within the scientific community hold the promise of harnessing fusion as a sustainable energy source in the near future.

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Paper No. 3

NEW TECHNICAL INITIATIVES FOR SUSTAINABLE DEVELOPMENT IN NEW LINE RAILWAY

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ABSTRACT

According to Railway Development Strategy 2014 and ongoing Strategic Studies on Railways and Major Roads Beyond 2030, existing Hong Kong railway network will be expanded to increase the mobility of people and to support future development of Hong Kong. As one of the leading railway operators in the globe, MTR is devoted to providing environmentally friendly mass transit services by embedding environmental, social and governance ("ESG") considerations in the design of new railway projects. In MTR Sustainability Report, it outlines targets that MTR strives to accomplish as to maintain sustainable business model. For instance, achieving BEAM Plus Gold rating in stations of MTR new projects is one of the targets. Thus, aspiration of sustainable design is being upheld from first day of new projects as guided by the report.

Reduction in energy consumption is a major aspect in sustainability since it is directly correlated to carbon emission rate. In a station, it consists of many systems, such as lighting and air conditioning, and these systems are studied during design stage to explore if there is any opportunity to be improved in terms of energy efficiency. Subsequently, it appears that various kinds of technology can be implemented, and they can collectively contribute to a significant improvement in energy consumption.

In this paper, it illustrates what kind of system is introduced in the design of stations in MTR new projects and it reveals promising prospect of these efforts.

1. INTRODUCTION

Mass Transit Railway Corporation (MTR) is recognized as one of the world's leading railway operators and MTR has a pivotal role in Hong Kong's public transportation system. Thus, MTR places a significant emphasis on sustainability as a core part of its business strategy. Among all aspects in sustainability, Environmental Responsibility is a key element that MTR is deeply committed to fulfil, and MTR endeavours to reach carbon neutrality by 2050 [1]. In addition, MTR sets interim targets for reducing greenhouse gas (GHG) emissions by 2030. This effort is acknowledged and approved by Science Based Targets initiative (SBTi), which is a global collaboration between agencies such as United Nation Global Compact and Worldwide Fund for Nature (WWF). SBTi encourages businesses to set ambitious and scientifically grounded carbon reduction targets in order to meet the goals of the Paris Agreement [2]. Under SBTi, MTR commits to reduce carbon emission and to limit global warming to well below 2°C above pre-industrial levels. MTR pledges that carbon emissions from rail transport of MTR will be reduced by 46.2% per passenger kilometre, and emissions from investment properties will be reduced by 58.6% per square metre of floor area by 2030, from a 2019 base year.

In Railway Development Strategy 2014 and Major Roads Beyond 2030, current railway network will be further developed, and multiple railway projects will commence shortly. In order to pursue sustainability and SBTi targets for carbon emission, MTR is developing many strategies. For instance, in new railway line projects, MTR aims to attain BEAM Plus Gold certification or above for all new station projects. Carbon emission is reduced through improvement in building energy profile of E&M systems and waste reduction. With regards to the improvement in building energy profile, MTR proactively invests in new technology of clean energy and implements energy-saving initiatives. Meanwhile, MTR encourages recycling, reusing materials, and reducing waste produced from its operation and construction. In Section 2 of this paper, it describes the initiatives and approaches that MTR takes to reduce carbon emission. With collective outcome from all of these efforts, MTR is confident to achieve carbon neutrality by 2050.

2. INITIATIVES & APPROACHES

2.1 Energy

2.1.1 PV panel

To accommodate 6-car to up to 10-car train normally in Hong Kong, a railway station usually comes with few-storey but with a relatively large footprint. By making effective use of the large area at the station roof with ample sunlight irradiation, collecting solar energy by using PV panel is an effective and sustainable measure for carbon neutrality. The implementation of PV panels in railway stations brings several merits. Power generated from solar energy helps reducing the dependence on non-renewable sources of energy like coal and natural gas. As a result, the carbon footprint of railway stations is reduced and contributes to climate change alleviation. From the Corporate's point of view, PV system also helps in cutting down the electricity tariff and the operating expense in the long term.

Subject to the power that the PV system generated, on-grid connection PV system are usually adopted together with Feed-in Tariff (FiT) scheme, while the power output of the PV system is connected to the electrical distribution centre which refers to the main LV (Low Voltage) switchboard of the station. The status of PV system is monitored in the Station Control Room under the Station Based Control System (SBCS) for use by operators and maintenance personnel.

Apart from the basic system design architecture, MTR has taken into account the lessons learned from the market and industry to enhance operational safety, system reliability and operability. Fire-retardant cables, cable connectors with standard pins and socket connectors with ingress protection are employed to assure fire safety and system reliability. Installation details are developed to secure the natural cooling performance of panel and avoid water accumulation by introducing the minimum for natural water draining. To avoid creating glare and reflection to the nearby neighbourhood, PV panels with anti-reflective coating are favoured to reduce the reflection of light from the surface of the PV panels.

Larger PV panels (approximately 2.2m ~ 2.3m (L) x 1.1m (W)) with higher power rating are preferred to be adopted. Major components such as inverters and distribution boards of PV system are installed in PV equipment room level below station roof for ease of maintenance. The active equipment like DC combiner box, inverter, AC distribution board, isolation transformer, etc. for each PV zone are installed at PV equipment room.

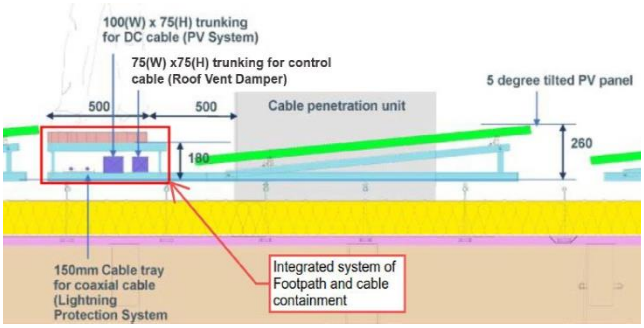

Fig. 1 - Arrangement of PV Panel and Integrate System of Foot Path and Cable Containment on Station Roof (Section View)

2.1.2 Station light

In station lighting design, it is necessary to consider the use of daylight to reduce the energy consumption on lighting as well as to provide a comfortable environment for different passenger's needs. For aboveground stations, the daylight permeable façade design with the equipped daylight sensors effectively reduced the station lighting load. Intelligent lighting control system including automatic control, photo sensing, occupancy sensing and adjustable time schedule is provided in station lighting and connected to Station Based Control System (SBCS) which integrates with loops and controllers to control and monitor various building services equipment including lighting fixtures and Environmental Control System (ECS) equipment to optimize the energy use. Station entrance bridging the station internal areas and the outdoor environment are usually installed with photosensor and lighting control to provide a progressive lux adjustment at the station entrance to ensure passengers' vision comfort and more importantly to assist elderlies and persons with vision impaired to easily adapt to the transition from an environment of outdoor sunlight to indoor lighting.

2.1.3 IoT application

The trend of using AI (Artificial Intelligence) and Machine Learning have grown substantially. To effectively manage and maintain the vast variety of asset equipment including rolling stock, overhead line equipment, signalling control relay, etc., MTR employs Big Data and Machine Learning technology for operation and maintenance. MTR establishes an internal data studio collecting all the operational engineering data for analysis to facilitate asset management, boost maintenance regime and ameliorate operational conditions. To achieve the condition monitoring purpose for predictive maintenance and asset life analysis, energy efficiency analysis and to receive real-time operational response, the infrastructure and backbone of the data studio is required to be built. New stations and other railway footprints are to plant with several IoT sensors to collect diverse types of data. With the sensors we built in the greenfield, data collected can be used in the future for different use cases and studies. It is not impossible to plant these sensors when needed. Nevertheless, much more resources, effort, time, and cost are required when planting sensors in brownfield environment. It is therefore considered to be beneficial to any future IoT application, a data readily available environment in the new railway station is to be built.

2.1.4 Smart power supply system

MTR's power distribution network is relatively comprehensive including different voltage levels (e.g. 33kV, 25kV, 11kV) serving the traction power and other station power, meanwhile guaranteeing the system reliability. As a further improvement, Smart Power Supply System adhering IEC 61850 is also adopted.

Smart power supply system provides an on-line condition monitoring platform for power supply system using IEC 61850 system configuration and can collect breakers and equipment status, alarms, protection relay setting and metering data for monitoring, real time data storage, instant alarm pop-up, trend, and pattern analyses with respect to the service condition and power demand management [3].

IEC61850 is an international standard that defines the communication protocols specifically for electrical substations. It is well known for the interoperability among several equipment from different vendors and the facilitation of integration of new technologies like IoT application in substation automation. One of the paramount features of IEC 61850 is the use of common data model. The common data model can map with various communication protocols via TCP/IP or LANS promptly and delineate the data of substation devices in a standardized way.

In light of the aforementioned merits of the protocol, it is commonly accepted in the power utility industry. MTR adopts IEC 61850 protocol in the Smart Power Supply System to enhance the system reliability, provide prompt response and prevent downtimes. Operators can easily control and monitor the power supply system through the workstation installed in the station computer room.

To act in concert with the Smart Power Supply System, several sensors and measures enable the health monitoring of LV switchboard. Temperature sensors are installed at strategic locations along the busbar for early fault detection. In addition, infrared window is embedded at the back of LV switchboard to allow the portable infrared scanner checking the inner switchboard for thermal abnormality. After the identification of atypical hot spots in busbar junction or cable terminals, maintainers can proactively rectify the potential faults, minimize the risk of electrical fire, and reduce the chance of downtime through improving the power supply reliability. This initiative aids on the asset management by early identifications of equipment fault and hence reduces the risk of power outage.

2.1.5 Water ionizer in cooling system

To maintain the reliability of cooling systems serving safety critical equipment, redundant cooling equipment using different systems is designed in stations. For instance, centralized chiller system is used as the duty plant for cooling. Water-cooled package units are used as the standby units of cooling. The scale formed around the heat exchanger coils deteriorates the rate of heat exchange, or even worse resulting in clogging the cooling coils of water-cooled packaged unit leading to service breakdown.

With the effect of reducing calcium carbonate in the condensing water, scale formed around the heat exchanger coils is significantly reduced. Hence, the heat exchange rates can be much enhanced, and the system is more energy efficient. For this reason, water ionizer is adopted in the station cooling tower system.

The water ionizer utilizes a combination of water ionizing and Electrodeionization (EDI) technologies, which is a unique approach to water treatment. It consists of electrodes that ionize water molecules and separate dissolved ions, which help to purify the water [4]. Moreover, the ion exchange columns contain ceramic resin molded into porous plates that aid in capturing and removing mineral salts, thereby purifying the condensing water of the cooling tower system.

In addition, the water ionizer causes positive ions like calcium, magnesium, and sodium to form chemical compounds, particularly scale ($CaCO_3$), which adheres to the stainless-steel basket. This process of scale adherence is similar to an electroplating process. The accumulation of scale leads to a lower concentration of total dissolved solid and thus a lower bleed-off rate, resulting in water savings. The collection baskets adhered with scale can be brushed off on regular basis [5].

The energy savings that can be expected with the water ionizer will depend on numerous factors such as the size of the cooling system, the amount of scale build-up, operating conditions, and maintenance regime. However, in general, the use of this technology can result in energy savings by improving the efficiency of the cooling system. By dissolving the scale build-up on the inner walls of pipes, heat exchangers, and cooling towers, the cooling system can operate more efficiently, reducing the energy needed to maintain the same cooling capacity.

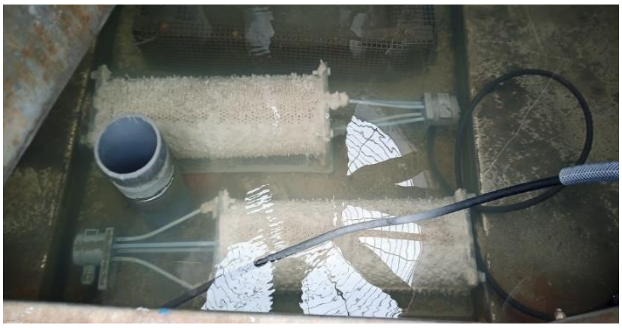

Fig. 2 - Water Ionizer

2.1.6 Automatic speed change system of escalator

Acting as the rapid and bustle hubs in Hong Kong, most escalators in MTR stations are running at the maximum regulated speed of 0.75m/s, which is about 50% faster than that of escalators adopted by commercial buildings, shopping malls, etc.

Energy consumption and equipment deterioration rates exert a direct correlation relationship with the escalator operating speed. Apart from allowing some degree of enhancements in passenger safety (especially for children and elderly), slowing down the escalator speed can be an environmentally friendly option. Operating the escalators at a lower speed when appropriate will achieve energy savings and slow down the wear-and-tear rates of escalator components, which in turn shall improve the reliability and availability of escalators.

In existing MTR, some escalators are provisioned with speed selection function to adjust the operating speed manually to suit operational needs. However, this is impractical to manually change the escalator speed due to the hustle pace in stations. A safe and smooth automatic speed change system can therefore be employed to allow speed alteration automatically while maintaining passenger safety and comfort.

Functional tests under different dead load conditions are conducted to verify the acceleration rate, deceleration rate, speed change duration and jerk rate when the escalator changes speed automatically. With the satisfactory test result using non-human load, further tests are carried out with live loads under different loading conditions of live load including no-load, 25%, 50% and 80% to confirm that speed changes without compromising the passenger safety and riding comfort. Escalators are operating at their full rated capacity at peak hour to address demand, and the users are regular commuters, more familiar with escalator use and more self-caring on safety. On the other hand, demand for escalators is lower and the users are not necessarily regular commuters (e.g. elderly, householders) during non-peak hours. When escalators are running from peak hours to non-peak hours or vice versa, reasonable reduction or increment in speed (~20%/~25%) at a safe deceleration/acceleration rate (transition time of approximately 20 seconds) is proposed, pre-programmed and automatic, in order to save power, extend asset life, and ensure safety. The speed change is imperceptible and scarcely noticed by the passengers. Meanwhile, when there are no passengers present after a predefined time and by controlling from the station control room remotely, the escalator will further slowdown to idling speed (~0.25m/s) until required again for services. See Table 1 below.

	Concourse / Platform	**External Entrances**
Peak hour	0.75 m/s	0.6 m/s
Non-peak hour	0.6 m/s	0.5 m/s
Emergency / Default	0.75 m/s	0.6 m/s
Idling	~0.25 m/s	~0.25 m/s

Table 1 - Different Escalator Speeds of the Automatic Speed Change System

In the event of a common fire alarm, emergency incident (e.g. arriving train on fire), emergency evacuation, non-emergency evacuation or to address an abnormal increase in patronage, the escalators will immediately resume the full rated speed at a safe acceleration rate automatically with triggering of evacuation by the main control system, and will be initiated remotely by the station operators in any other circumstances.

2.1.7 Natural ventilation and high volume low speed (HVLS) fan

The energy consumption of environmental control is approximately 50% of energy consumption of station. Sustainable design of station environmental control is one of the focuses in MTR. Station cooling by mechanical ventilation is one of the effective measures in reducing power consumption. However, there are a few constraints in environmental control design in station. The summer in Hong Kong is hot and humid. Afternoon temperatures often exceed 31 ºC [6]. It is expected that the ambient temperature of Hong Kong would rise in the next few years. Design of environmental control system shall be based on summertime maximum dry bulb of 35˚C with wet bulb temperature lower than 29 ˚C or maximum wet bulb temperature of 29 ˚C with dry bulb temperature lower than 35 ˚C [7]. Thus, the cooling effect of mechanical ventilation is less effective. Moreover, natural ventilation is blocked by Wall Effect of the city. “Wall effect” refers to the negative connotation that urban city contains extremely high built densities due to lack of flat land and which in turn generate an urban heat island of up to 12 ˚C in urban core [8, 9]. As per the novel method using Geographic Information Systems, the wind speeds on the lee side of “wall effect” buildings as well as further inland could be ¼ of the windward side of “wall effect” buildings [10]. Nevertheless, even applying natural ventilation is challenging, MTR is promoting it in public area in new projects to achieve green station design with due consideration to passengers’ comfort experience.

(a) Design criteria of station’s natural ventilation

To ensure a comfortable condition for our passengers, design criteria is set for new station’s natural ventilation design. The natural ventilation shall be designed based on ambient temperature and relative humidity at 32.5 ˚C and 85%. Thermal sensation index (TSI) and predicted mean vote (PMV) are two of the parameters of accessing thermal comfort. TSI demonstrates the thermal comfort in outdoor spaces based on the ambient temperature, air movement, relative humidity, and solar irradiation.

Fig. 3 - Thermal Sensation [11]

There are seven levels of thermal sensation scale. Level 4 is considered to be comfortable and most favourable to human while levels from 3 to 5 can be reasonably categorized as comfort level where no obvious discomfort is expected. For all the new natural ventilation design, TSI shall be less than or equal to 5.

TSI Level	Thermal Sensation	
1	Cold	
2	Slight Cold	
3	**Acceptably Cool**	**Range of Thermal Comfort**
4	**Comfortable**	
5	**Acceptably Warm**	
6	Slightly Hot	
7	Hot	

Table 2 - Thermal Sensation Level

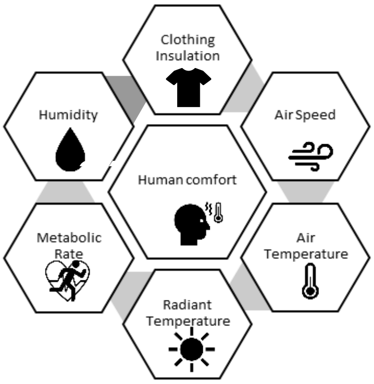

Fig. 4 - Human Comfort Factors

The standard of PMV is to specify the combinations of indoor thermal environmental factors [12] and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space. As PMV is mainly used for indoor environment, the calculated PMV value in the current study serves as a reference in addition to the outdoor thermal comfort indicator, i.e. TSI. PMV is a thermal sensation scale that represents the average response of people on four factors related to environment: (1) air temperature, (2) mean radiant temperature, (3) air speed, (4) relative humidity and two factors related to personal parameters (5) metabolic rate and (6) clothing insulation.

(b) Factors affecting thermal comfort - PMV

Within the PMV index, +2 translates as Warm, while -2 translates as Cool, as depicted in Table 3.

PMV index larger than +1 or smaller than -1 is considered as uncomfortable. The target PMV shall be less than 1 which refer to a slightly warm environment in natural ventilated station.

General thermal comfort from outdoor to concourse and to platform with a thermal gradient from hot to warm to cool is desirable. The air velocity at 1.6m above finished floor level shall be less than 2m/s. CFD simulation shall be conducted to analyse the thermal comfort of the design.

PMV Value	Comfort Condition
-3	Cold
-2	Cool
-1	**Slightly Cool**
0	**Neutral**
+1	**Slightly Warm**
+2	Warm
+3	Hot

Table 3 - PMV Index Level

There are three common ventilation strategies for natural ventilation: single-sided ventilation, cross ventilation, and stack ventilation. Stack ventilation is considered as the most efficient natural ventilation design. To optimize the thermal comfort of new generation of natural ventilation station, there are three features adopted to achieve stack ventilation. Stack effect or chimney effect refers to the movement of air into and out of building through unsealed openings, resulting from air buoyancy. During the hot season, the warmer indoor air rises through the building and escapes at the top either through building openings or louvres. The rising warm air reduces the pressure in the base of the building, drawing cool air in through entrance or building openings. Featured roof design enhances stack effect and allows hot air exhaust from high level weatherproof louvres. High headroom of front-of-house area with automatic platform gate (APG) maximizes the fresh air intake as well as air movement across the station. High volume low speed fan is used for enhancing air movement and improves the thermal comfort. CFD simulation is conducted to evaluate the existence of stagnant zone and optimizes the fan arrangement. New natural ventilation design will be adopted in selected stations in new projects.

2.1.8 Electronically commutated fan

Electronically commutated (EC) fan is used in air handling unit (AHU) instead of conventional centrifugal fan AHU. EC fan is 10% more energy efficient than conventional air-conditioning system with alternative current (AC) motor [13]. Unlike the conventional centrifugal fan which required regular maintenance attention such as replacement of fan belt and maintaining the lubricant level, EC fan requires less maintenance and repairing work. The acoustic and vibration performance is better than conventional centrifugal fan and hence less acoustic and vibration treatment is required. The equipment size of EC fan AHU is generally smaller than centrifugal fan AHU. With the reduced equipment size, the plantroom area could be optimized and reduction in construction material and cost. The arrangement of fan grid configuration subjects to the airflow required, space available and required level of redundancy. The use of multiple EC plug fans in fan grid can enhance the system resilience and avoid total failure of AHU. MTR is reviewing the opportunity of fan grid arrangement of EC plug fan AHU as a substitution of duty and standby arrangement of AHU.

MTR is also reviewing the potential use of stacked AHU in plantroom. By stacking duty and standby AHUs as one combined unit, it can fully utilize the plantroom high headroom as well as simplify air ducts and chilled water pipes arrangement and installation. With stacked duty and standby AHU arrangement, AHU plantroom area could be reduced by around 30% and hence a reduction of construction material and cost. The stacked AHU arrangement could also simplify delivery and logistic arrangement in some situation.

2.2 Reduction in Operation and Construction Waste

2.2.1 Lithium ion battery

In a railway system, there are some crucial systems, such as signalling and communication, which need continuous and uninterruptible power supply. In past MTR projects, Lead Acid Battery was employed to store power and serve as a backup power source during power failure situation. However, MTR is now replacing it by Lithium Ion Battery in new line projects, and one of the reasons is that it performs better than Lead Acid Battery by studying the environmental impact and life cycle analysis. Generally, this can be attributed to the fact that Lead Acid Battery has a lower power density and shorter lifetime than that of Lithium Ion Battery. This means more battery cells are necessary to respectively obtain equal power demand and service time as Lithium Ion Battery.

By comparing Lithium Ion Battery and Lead Acid Battery, the former has a better performance in environmental impact than latter [14]. It offers approximately 40% lower acidification potential to nature. Besides, referring to lifecycle analysis, Lead Acid Battery leaves 30% more carbon footprint and consumes ten times more materials in extraction and manufacturing stage. Therefore, by replacing Lead Acid Battery with Lithium Acid Battery, MTR is able to minimize the environmental impact with respect to consumption of natural resources, acidification, and carbon emission.

2.2.2 DfMA (Design for Manufacturing and Assembly)

In MTR new projects, there is a momentum to implement DfMA in construction and contractors are bounded by contract to achieve a high percentage rate of implementation. For instance, Building Services contractors are required to establish a plan to identify all the potential area or system which can embrace the concept of DfMA and target to adopt DfMA modules for at least 80% of the entire premises. Undoubtedly, DfMA has remarkable advantages in terms of time and cost. Besides, DfMA has a positive impact on sustainable environment through reduction of construction waste. The introduction of DfMA can lead to a reduction of 65% of construction waste [15]. Automation in off-site construction offers a controllable environment and precision in manufacturing of construction components. DfMA allows engineers to calculate quantity of material with high accuracy, especially with the assistance of BIM and simulation software.

MTR aims to reduce construction waste induced by application of DfMA module. To ensure the robustness of a DfMA module for safe delivery from the factory to the designated location at the work site, it is necessary to provide extra supports for the module. These extra supports in most cases become redundant to the installation and undesirable obstruction to access for maintenance. For MTR projects, it is intended to avoid such undesirable situations by removing unnecessary supports after installation and recycling of temporary support members for DfMA module. This has to be well considered in DfMA design at early stage. By this way, DfMA becomes one of the solutions to allow MTR to eliminate waste in construction and to promote sustainable environment.

2.2.3 Rainwater harvesting system

To reduce the water consumption of station, MTR has explored the use of water recycling system. There are 3 common sources of rainwater harvesting system including roof catchment, gutters and downpipes. Rainwater is collected from station roof catchment and used to irrigate the green roofs. Concrete tank is provided for rainwater collection from the aboveground structure which is capable to collect the amount of rainfall for 10 days in the month with the annual peak rainfall. Before the use of recycled rainwater, the collected water shall be treated by three processes, pre-treatment, filtration, and disinfection to ensure the water quality and hygiene. Pre-treatment shall include a first flush removal device. Coarse filtration followed by sand filtration and granular activated carbon filtration (GAC) shall be used. The coarse filter shall be used to remove large particulate matter. The sand filter or cartridge filter to further remove smaller particulate matter and GAC filtration shall be used to remove smallest particulate matter and hydrocarbons. Disinfection is required as the final treatment step which includes chlorine disinfection and/or UV disinfection. The treated storm water would be transferred to the irrigation system after the filtration and water treatment. Rainwater is proposed for use as irrigation system only. A reduction of 100% annual potable water use is expected to be achieved for irrigation purpose.

3. CONCLUSION

MTR endeavours to embrace sustainability into core of its business strategy. MTR implements green initiatives and new technologies, as described in Section 2, to enhance building energy profile and efficiency. Also, MTR adopts approaches to reduce construction and operation waste. Although MTR is implementing these initiatives to become more sustainable, it is only the beginning of the journey to our goal. MTR will continue its role as one of the leading contributors by exploring potential opportunities to fulfil its commitment as pledged in SBTi.

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Paper No. 4

UTILIZING AI - ENABLED DIGITAL TWIN FOR ESG COMPLIANCE AND SMART FACILITY MANAGEMENT

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UTILIZING AI - ENABLED DIGITAL TWIN FOR ESG COMPLIANCE AND SMART FACILITY MANAGEMENT

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ABSTRACT

Mandatory Environmental, Social & Governance (ESG) disclosures for the purpose of complying with a growing wave of ESG regulations is an increasing challenge for organizations, prompting them to transform ESG strategies from manual-based work practices to AI-driven automation. This paper presents a holistic view of how to adopt AI-enabled Digital Twin and create ESG-centric buildings for optimised performance by leveraging IoT technologies and big data analytics. The deployment of AI-enabled Digital Twin will be discussed in detail from the perspectives of big data collection, data processing, data analytics, ESG-centric visualization and smart facility management.

1. INTRODUCTION

The pandemic has accelerated the shift of ESG away from the sidelines to the centre. ESG is no longer a choice but a duty resulting in permanent changes to company work practices and corporate accountability. Integrating ESG aspects into the day-to-day decision-making process has become essential for a business's long-term success. Organizations must rise to the challenge by adopting advanced technologies to navigate the ever-evolving ESG landscape. Driven by data, Digital Twin realises smart facility management by bridging the gap between the physical and virtual worlds. Integrating AI and machine learning into Digital Twin enables the system to perform data analytics for ESG insights and business intelligence. AI-based optimization builds a strong foundation in facilitating ESG reporting to demonstrate corporate responsibility. AI-driven Digital Twin adapts and evolves while performing a range of tasks through experiences, it also serves as a dynamic real-time database that minimises manual processes, increases maintenance efficiency, and enables remote management across the property portfolio for optimum asset management.

1.1 AI-enabled Digital Twin

The AI-enabled Digital Twin designed for the built environment is a virtual representation of a building that uses artificial intelligence to simulate and analyse real-world behaviour and performance. The Digital Twin is connected to physical systems for data collection to train machine learning algorithms. The AI-enabled digital twin can then make predictions about the operation, identify potential problems, and suggest solutions for optimization. This allows organizations to monitor, optimise, and improve their building systems in real-time, leading to increased efficiency and reduced downtime.

Fig. 1 - User interface of AI-enabled Digital Twin

2. DATA COLLECTION & MANAGEMENT

2.1 IoT Connectivity for Real-time Data Collection

IoT is the backbone for AI-driven Digital Twin in bringing multi-source data together. To establish a fundamental basis for a truly robust digital twin, a wide range of data reflecting the building performance is required for analytics and machine learning. Examples of big data within a built environment include data from HVAC systems, lighting, and security systems, as well as many other building services. Such data is normally not available in existing buildings where the BMS provision is primitive. However, collection of big data has become easier as technology advances. With wireless IoT sensors, real-time operation, environmental and energy data can be easily obtained through IoT-enabled sensors and connected devices via an IoT network, feeding Digital Twin with billions of data points every day to generate enterprise-wide transparency.

2.2 Integration with Different Facility Management Systems

Integrating different facility management systems in a Digital Twin for a data lake can provide a comprehensive view of a facility's performance by combining data from various sources. Facility management systems such as Building Management Systems (BMS), Power Quality Management Systems (PQMS), IoT Systems, Carpark Systems, Turnstiles and Lift Systems as well as Maintenance Management Systems (MMS) can be integrated to create a unified view of the facility's operations.

To integrate different facility management systems in a Digital Twin for a data lake, it is important to identify the relevant data from each system. This can include sensor data, operational data, maintenance data, and energy consumption data. Once the data has been identified, it can be extracted from each system using APIs or other data integration tools.

Once the data has been integrated and transformed, it can be ingested into the data lake.

2.3 Data Lake for Enhanced Data Processing Capability

The large volumes and variety of data collected from each individual system need to be stored in a database with enhanced capacity and processing abilities for data analytics. Hence, data lake emerged.

Data lake is a centralised repository that stores all kinds of structured and unstructured data at any scale. Unlike traditional data warehouses, which are designed for structured data, data lake is designed to handle a wide variety of data types, including structured, semi-structured, and unstructured data for easy access, management, and analysis. Data lake allows the flexibility to store data in a variety of formats, including text, image, audio, and video, making it an ideal solution for facility management. Data lake can be integrated with other data management solutions for multiple data accesses, such as data warehouses or cloud-based analytics tools. As the amount of data generated by buildings continues to grow, so as the data lake, which enables large-scale data processing to derive insights and make data-driven decisions.

Fig. 2 - System Architecture of Data Lake

3. ANALYTICS AND OPTIMIZATION

3.1 Automated Fault Detection and Diagnostics (AFDD)

Advanced analytics accompanied by efficient data cleansing eliminates inaccurate, incomplete, inconsistent, and repetitive data in avoidance of misleading conclusions. Inconsistency in the collected data presents a performance risk in Digital Twin as it will act on corrupted or missing data. A constant, noise-free stream with high quality data is required to perform AI-driven FDD for the implementation of efficient Digital Twin. Due to sensor issues, equipment deterioration, improper system control and settings, the building services systems often fail to operate at efficient performance, leading to unnecessary energy use. As such, there is a need for AI-driven FDD that adopts AI and machine learning algorithms to monitor and diagnose building systems in real-time for discovering faults, investigating root problems, and recommending best-suited solutions, ultimately, achieving optimal system performance. AFDD is a data-driven and model-based algorithm comprising five layers of monitoring, including data quality, fault detection and diagnostics, energy performance, control stability and tenant comfort. Big data analytics aims at deriving conclusions and correlations from a huge amount of data. Data quality can be detected for any missing data in avoidance of incomplete model training. Unnoticed faults are commonly found in building systems. These unnoticed faults, such as insufficient charge of refrigerant in chillers, VAV box damper stuck, sensor biases etc., are not easy to identify as the existence of these faults will not lead to the breakdown of the overall system operation. It only affects thermal comfort, system control as well as energy performance. However, if there is not any action to rectify these unnoticed faults, energy performance will not be optimised. For energy performance, equipment performance models are developed using advanced modelling techniques to describe actual operating performance. The developed model is considered as the baseline model to compare the future model for performance deterioration detection. In order to analyse system stability, it is essential to obtain high frequency data in buildings. In Digital Twin, high frequency data is used to represent real-time physical characteristics, behaviours, and interactions of a physical system. The purpose of high frequency data is to provide a detailed and accurate representation of the physical system, allowing for more accurate predictions, simulations, and data-driven decision making.

3.2 Dynamic Optimization

Dynamic optimization in Digital Twin involves using real-time data and advanced algorithms to make continuous improvements to building systems. This works particularly well with energy management in the built environment where large sets of operating data are accessible. The AI algorithms applied in optimising energy use of building systems are built upon the basis of physics-guided machine learning (PGML). Physics laws are adopted in machine learning algorithms to make it into a hybrid approach for ensuring modelling accuracy so that Digital Twin can help identify inefficiencies and areas for continuous improvement by analysing data on energy usage and other environmental factors. The AI-enabled Digital Twin comes with the ability to test and analyse different scenarios before physically implementing them in the building. With the AI-enabled Digital Twin, facility managers can visualise and evaluate the impact of changing the control settings of building systems which facilitates informed decision-making and enhances overall building performance by saving resources and reducing the risk of costly mistakes.

4. APPLICATIONS

4.1 ESG-centric Digital Twin with AI Machine Learning

An ESG-centric Digital Twin for buildings is designed to optimise ESG performance on a holistic level using AI algorithms. Implementing an ESG-centric Digital Twin involves identifying ESG factors, integrating data sources, developing AI models, optimising ESG performance, generating customised ESG reports, and continuously improving ESG performance over time.

4.1.1 Define ESG metrics and integrate data sources

The ESG metrics can be updated in Digital Twin anytime so it can operate effectively according to the latest regulatory requirements. An AI-enabled Digital Twin can integrate data from various sources, including **BMS** (Building Management Systems) for the insights into a building's energy usage, water consumption etc., **environmental sensors / IoT devices** for the data on a wide range of environmental factors (e.g., temperature, humidity, air quality, noise levels etc.), **financial systems** for the insights into the financial impact of sustainability initiatives (e.g., renewable energy investment, waste reduction programmes etc.) and **supply chain data** for the information on the sustainability performance of suppliers and vendors. By collecting data from multiple sources, organizations can gain a comprehensive view of their ESG performance.

4.1.2 Analyse ESG data with AI models

Training AI models with the collected data via machine learning algorithms helps identify trends and patterns in data for insights. This may involve using regression analysis to identify data points, clustering analytics to group data points with similar characteristics, and deep learning to solve complex problems with large amounts unstructured data in different formats. By leveraging the insights generated by the AI models, areas for improvement can be identified for further evaluation and actions.

4.1.3 Identify and prioritise ESG opportunities for improvement

AI models can generate forecasts for the selected ESG metrics. The insights derived from AI analysis help organizations to identify areas that may not be immediately apparent. For example, AI can identify energy-saving opportunities to reduce electricity consumption by optimising lighting or HVAC systems. AI-enabled Digital Twin can also prioritise the identified opportunities based on their potential impact and feasibility of implementation. Opportunities with a high potential impact and high feasibility of implementation would be prioritised.

4.1.4 Develop sustainability plans and implement ESG initiatives

Once the opportunities have been prioritised, the insights and suggestions provided by the AI-enabled Digital Twin can be used to develop a sustainability plan that outlines the initiatives to be implemented with clear timelines and required resources. This plan should be aligned with the sustainability goals of organizations for ESG compliance. A set of actions and criteria from the plan can be input to the AI-enabled Digital Twin for continuous progress monitoring and analysis.

4.1.5 Generate ESG reports & continuous improvement

ESG reporting and digital twin are closely related. An AI-enabled Digital Twin can generate ESG reports that provide regulatory bodies and stakeholders with a detailed and up-to-date view of an organization's ESG performance. These reports can be customised to meet the needs of different stakeholders, such as investors, customers and employees, facilitating effective communication with them on their ESG performance for enhanced stakeholder engagement. An ESG-centric Digital Twin should be an ongoing process of continuous monitoring and improvement that requires timely and regular reviews of sustainable strategies and initiatives for ensuring high ESG performance.

Fig. 3 - ESG-centric Digital Twin

Using AI-enabled Digital Twin for ESG reporting helps organizations drive sustainable innovation and demonstrate their commitment to social and environmental responsibility by providing transparency with accurate ESG data, implementing sustainability initiatives, facilitating decision-making, and engaging with stakeholders.

4.2 AI-enabled Digital Twin for Smart Facility Management

4.2.1 Smart facility management

Smart facility management aims to provide a more efficient, sustainable and safe environment by automating processes, optimising energy utilization, and enhancing occupant experience. An AI-driven Digital Twin delivers smart facility management and automated operations by enabling energy management, predictive maintenance, indoor environmental quality (IEQ) management, safety and security, space utilization, and building portfolio management.

4.2.2 Energy management

An AI-enabled Digital Twin helps monitor and analyse energy usage patterns in real-time. This data can be used to adjust the control settings of building systems, such as lighting, HVAC, and ventilation, to minimise energy usage while maintaining occupant comfort. For example, if a room is unoccupied, the AI-enabled Digital Twin can detect this and adjust the lighting and HVAC settings to save energy. Similarly, if the outside temperature changes, the system can adjust the HVAC settings of buildings to maintain a comfortable indoor temperature while minimizing energy usage.

4.2.3 Predictive maintenance

Predictive maintenance is possible with AI-enabled Digital Twin to identify potential issues before causing a breakdown in building systems. Predictive analytics is able to forecast when maintenance is required for building systems. The AI-enabled Digital Twin can be integrated with maintenance systems to automate maintenance scheduling for streamlining the entire work order management processes.

Predictive maintenance is a process that involves several key steps designed to detect potential equipment issues before they cause significant downtime or costly repairs. The process typically starts with data collection, where data is collected from the equipment being monitored. Such data can include sensor data, machine logs, and other relevant data sets, which are then analysed using advanced analytics tools such as machine learning algorithms and artificial intelligence.

Once the data is collected and analysed, the equipment's condition can be monitored in real-time or near real-time to detect any changes that may indicate an impending failure. This is known as condition monitoring, and it can involve a range of techniques, including vibration analysis, thermal imaging, and ultrasonic testing.

Based on the results of the data analysis and condition monitoring, the maintenance team can plan and schedule maintenance activities to address the potential issues before they cause a failure.

One of the key benefits of predictive maintenance is that it is an ongoing process, and the data collected can be used to continuously improve the process and refine the predictive models used to identify potential issues. This allows organizations to continually optimise their maintenance schedules and improve equipment reliability over time.

By using advanced analytics tools and real-time data analysis, organizations can detect potential issues early and address them before they become major problems, ultimately leading to improved equipment reliability, reduced maintenance costs, and prolonged equipment life.

4.2.4 IEQ management

IEQ is closely linked to occupant comfort with a significant impact on occupant health, well-being, and productivity. Real-time monitoring and analytics of IEQ factors, such as air quality, temperature, and humidity help identify areas where improvement is needed for optimization. The insights collected from IEQ analytics can be fed into the AI models of building systems for further analysis to optimise energy efficiency and occupancy management.

Data-driven IEQ management typically involves several key steps. Firstly, data is collected from various sources, such as indoor air quality sensors, temperature and humidity sensors, and lighting and noise monitoring systems. This data is then analysed using advanced analytics tools to identify patterns, anomalies, and potential issues.

Based on the results of the data analysis, facility managers can make data-driven decisions to address any issues and improve the indoor environment. This can involve adjusting temperature and humidity levels, increasing ventilation, upgrading HVAC systems or air filters, and managing lighting and noise levels.

The indoor environment is monitored continuously using real-time data, and the data collected is used to refine the data-driven IEQ management plan and improve the indoor environment over time. This approach allows facility managers to take a proactive approach to IEQ management and address potential issues before they become major problems, ultimately leading to improved occupant health, productivity, and well-being.

Fig. 4 - Data Collection of IEQ Parameters

4.2.5 Safety and security

Incorporating video analytics with a digital twin, large volumes of unstructured video data collected from multiple targeted locations can be transformed into intelligence and actionable insights. It covers a wide range of applications beyond crime prevention and accident management. By leveraging video analytics technologies, customer demographics and their shopping behaviours can be captured for further analysis in real-time. The function of crowd detection monitors occupancy levels within a given space, triggering alarms when exceeding allowed number of people. The advanced people tracking function, which utilises facial recognition technology, will not only detect movement of people in both indoor and outdoor environment, but also instantly identify and verify authorised personnel by facial attributes. The object detection feature identifies the presence of unattended static objects. Real-time notifications and alarms are generated for security staff to provide responsive actions. AI-enabled Digital Twin can ensure crowd security, engage shoppers, and enhance operation efficiency.

Fig. 5 - Video Analytics to Automate Detection and Analysis

4.2.6 Space utilization

AI-enabled Digital Twin provides insight into space utilization by analysing the data collected from the IoT sensors and room booking system in real-time to optimise space utilization while identifying underutilized areas that can be repurposed for different uses.

By using AI-enabled Digital Twin, facility managers can gain insights into how spaces are being used in real-time. This data can include information on room occupancy, traffic flow, and utilization patterns. By analysing such data, facility managers can identify areas of the building that are underutilized or overutilized.

For example, if a conference room is consistently underutilized, facility managers can repurpose it for a differ end use, such as a collaborative workspace. Similarly, if a particular area of the building is consistently overcrowded, facility managers can identify this and take steps to optimise the space utilization to improve occupant comfort.

In addition to optimising space utilization, AI-enabled Digital Twin can also help facility managers identify potential safety hazards. By monitoring traffic flow and occupancy patterns, the system can detect potential safety hazards, such as congested areas or blocked fire exits, and alert facility managers to take corrective action.

4.2.7 Building portfolio management

Creating an AI-enabled Digital Twin for multiple buildings allows building owners and facility managers to gain a comprehensive view of their entire property portfolio as a whole, enhancing overall operation and improving resource allocation.

Furthermore, AI-enabled Digital Twin can enhance communication and collaboration among building owners and facility managers across multiple buildings. This technology allows stakeholders to share data and insights, collaborate on maintenance and repair activities, and coordinate resources more effectively.

5. CONCLUSION

ESG disclosure is widely considered to be inevitable with increasing accountability imposed on corporates and investors to assess ESG risk effectively in complying with the constantly evolving regulations. Organization must stay up-to-date with the latest ESG regulations and reporting requirements to ensure compliance. These changes have caused organizations to rethink their reliance on manual-based work practices. To catch up and stay ahead of ESG trends, it is essential to make every process as tech-driven as possible. AI-enabled Digital Twin with a strong ESG focus helps automate multiple aspects of operation and maintenance from data collection, data analysis, to visualization and ESG reporting. By leveraging the power of AI-enabled Digital Twin, smart applications catered for different purposes can be built upon the system to address to specific challenges from energy saving and maintenance optimization to space utilization and emergency response. Building functionalities are holistically optimised with AI-enabled Digital Twin to address the pressing needs of property owners, facility managers and building occupants in response to arising challenges. Property owners gain enhanced visibility for closer tracking of buildings' health in facilitating valuation and risk management of their property portfolio. Empowering facility managers with a holistic view of building performance, AI-enabled Digital Twin enables automated fault detection and monitoring of data quality, energy performance and control stability. Incorporating big data analytics into measuring IEQ helps achieve healthier workplaces to optimise occupants' comfort and well-being. Keeping pace with ESG requirements is essential to the success of a business. It is time to embrace change and take steps towards better business practices.

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Paper No. 5

ARTIFICIAL INTELLIGENCE BASED FORECAST MODELS DEVELOPED FOR PHOTOVOLTAIC POWER SYSTEM

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ABSTRACT

Accurate solar photovoltaic (PV) generation forecast is critical to the reliable and economic operation of a modern power system. In this paper, Artificial intelligence based on Long Short-Term Memory Network (LSTM) employed for PV generation forecast will be described. See Figures 1 and 2.

Firstly, to obtain reliable data for model training and daily maintenance, a web-based and easy-to-use online data cleansing method was developed for PV generation data cleaning. Secondly, AI algorithm models trained by historical data were used with different time scales by both BP neural network and LSTM. Thirdly, equipment maintenance notification and pre-matured fault alarm strategies based on the established prediction method and real measured data were implemented. Finally, the complete set of AI forecast tool can be customized to web-based HMI according to the end-user requirements or specifications.

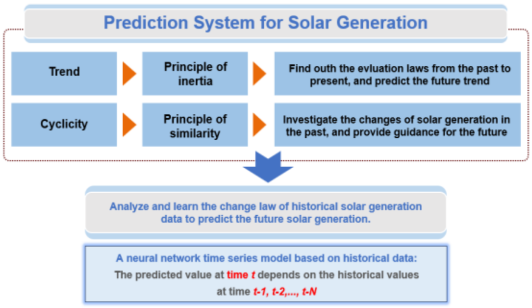

Fig. 1 - Procedures of Establishing Prediction Model

1. INTRODUCTION

Compared to the existing prediction models, the proposed prediction model has the following characteristics:

(1) Based on LSTM, a comparison between multiple regression and single regression was conducted. In the multiple regression, we firstly introduced Spearman's rank correlation coefficient to complete the feature selection on solar power generation. The positively correlated factors (e.g. solar irradiance and temperature) were utilized to predict the power generation. Additionally, the single regression took the advantage of the time information in historical sequences and achieves time-based future power prediction.

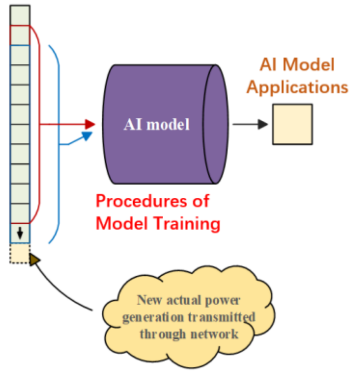

Fig. 2 - Applications of AI Models

(2) A photovoltaic power prediction model was constructed based on CNN-BiLSTM-Attention technique. It is worth giving stacked LSTM to deepen the training network and improve the efficiency. Especially, the use of quantile regression contributed to the robustness of prediction and decision making. For the better management of system operation and convenience of facilities maintenance, we built the confidence intervals of power generation.

(3) A smart AI engine platform, integrated with data preprocessing, power generation prediction, state evaluation, etc., was developed. The diagram can be found in Figure 3. As the results shown in practical applications, good performance was achieved.

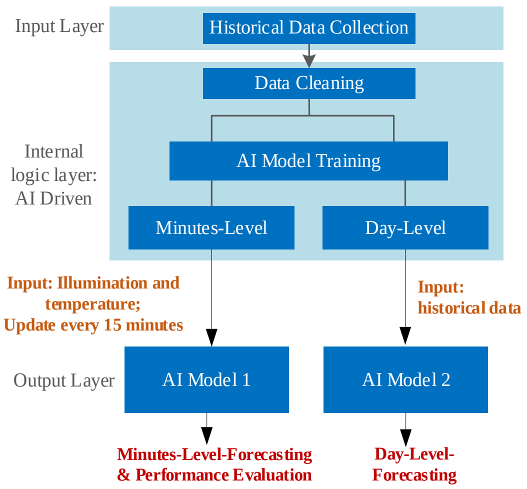

Fig. 3 - Functions of AI Platform

2. RESEARCH AND FINDINGS

The key technical challenges are:

(1) Intelligent analysis of multi-source data in photovoltaic power generation system

The techniques such as Internet of Things (IoT) and sensors were utilized to collect and transmit the crucial data online (e.g., generated electricity, power, temperature, and solar irradiance) in PV power generation systems. Based on data mining and machine learning, we proceeded the collected data and analyzed the internal correlation by means of data cleaning, feature extraction, anomaly detection and so on.

As a result, the accuracy and reliability can be greatly enhanced. The performance can be found in Figure 4. Besides, such processing functions were integrated into a smart toolbox aiming that:

a) Connecting multi-format data

b) Capturing formatted data

c) Summarizing, merging, deduplicating, filtering, converting, outliers detecting

Accordingly, they provide intelligent data support for subsequent AI modeling and smart optimization.

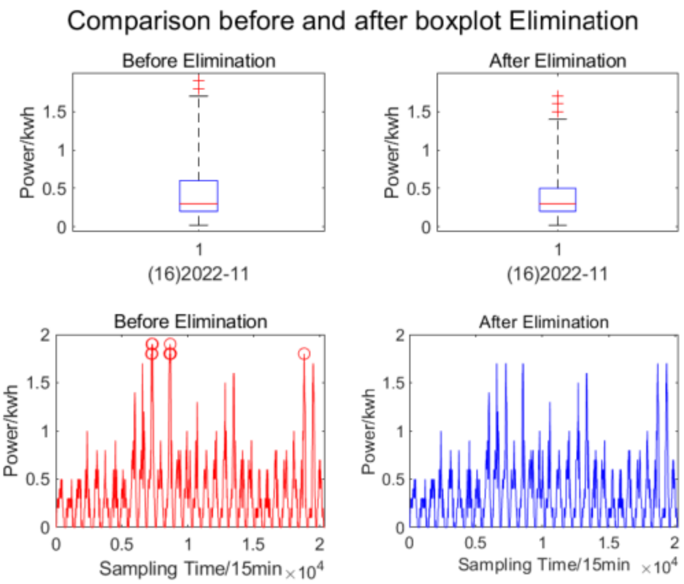

Fig. 4 - Results of Data Filtering

(2) Real-time intelligent interval prediction of photovoltaic generating capacity

Noting that the photovoltaic power generation has strong randomness and intermittency, it was necessary to develop a real-time prediction algorithm for the intervals of generating capacity, and to solve the problems about gradient vanishing and exploding during the medium- and long-sequence training process. It can learn about the laws, relations, and evolution from historical data, which facilitated the model training and parameter optimization. Based on predicted data and measured data, the proposed algorithm conducted real-time evaluation of system states and performs the intelligent analysis to construct a series of fault diagnosis strategies. The prediction performances for different time scales can be found in Figure 5.

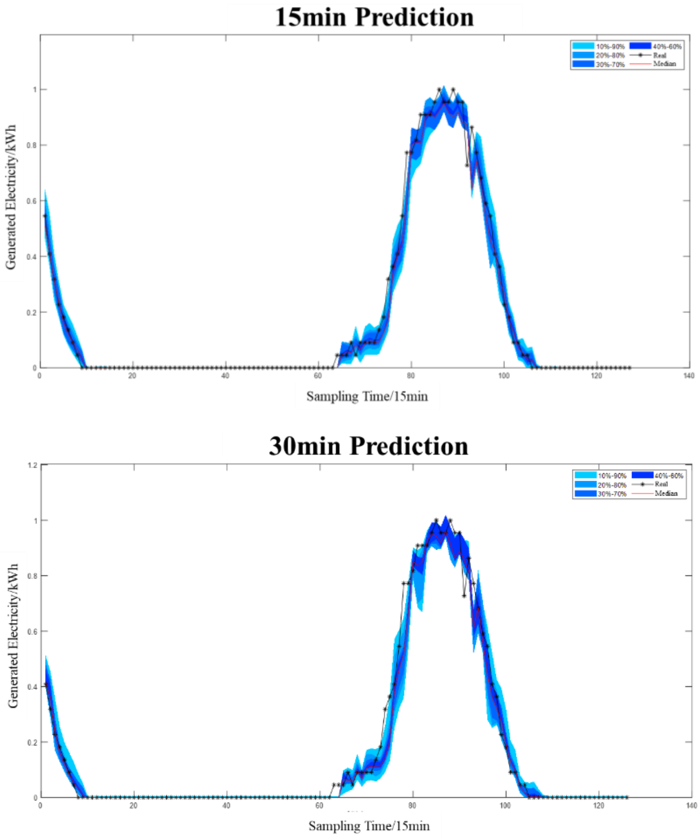

Fig. 5 - Intelligent Interval Prediction of PV Generating Capacity

(3) Smart AI engine platform of PV power generation

By using big data analysis, knowledge graph and expert decision-making system were constructed to locate the fault sources and guide the real-time control and scheduling. A “3-pre” centre, inspired by the concept “prediction-prewarning-prevention”, was established for the intelligent optimization of power generation system. To this end, big data technique was imported to carry out the comprehensive management and the safety-risk assessment on equipment, operation, and maintenance.

Finally, we concluded the AI-based work for PV power generation system in Guangzhou. Noting with the randomness, intermittency, and volatility in PV system (for example, brought about by the changing weather and climate), the terminal power grid will be greatly impacted with undesirable deterioration. To tackle the issues, a photovoltaic big data platform was constructed incorporating with a series of smart functions (e.g., data processing, efficiency evaluation, fault diagnosis, analysis and judgment, dynamic warning, intelligent optimization, etc.). Through assessing the collected data from various schools, it succeeded to display the processed results and synthesizes the control proposals, which made a good reference for the resource management and scheduling. Compared with the existing methods, like single-layer LSTM, the proposed forecasting models achieved good forecasting accuracy. See Figure 6 and Table 1.

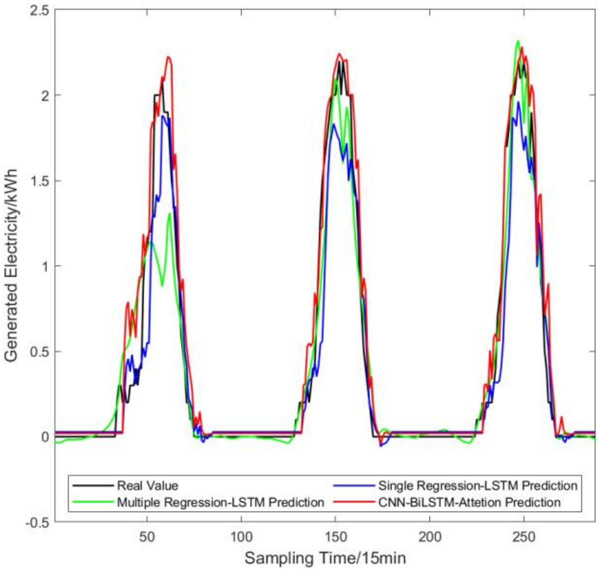

Fig. 6 - Results of Different AI Models

Model	Mean R2	Mean RMSE
Multiple Regression-LSTM	0.905	0.218
Single Regression-LSTM	0.911	0.211
CNN-BiLSTM-Attention	0.937	0.178

Table 1 - Indices of Different Results

3. CONCLUSION

In conclusion, based on the proposed AI model, a Generative Pre-trained Transformer (GPT) model on photovoltaic power generation may be a future goal. It is required to gather huge data to study and pre-train different possible models. Based on reward technique, these pre-trained models will be screened to output the best one. In other words, when the users input the data about the equipment, location, climate and so on, the intelligent GPT programme can output a corresponding AI model for the actual use (e.g., power prediction, operation warning, etc.).

Paper No. 6

LV SMART GRID TECHNOLOGIES FOR THE UTILITY OF THE FUTURE

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ABSTRACT

The deployment of distributed clean energy resources (e.g., PV) and electrified transportation helps the reduction of greenhouse gas emission but also brings challenges to the electrical utilities. Issues such as voltage rise and equipment overloading threaten the reliability and quality of power supply.

CLP Power Hong Kong Limited (CLP Power) has recently developed a demonstration smart grid project with the purpose of facilitating distributed clean energy and EV adoption by leveraging smart grid technologies rather than conventional network reinforcement. Within the designated low voltage community network, the Battery Energy Storage System (BESS), and Line Voltage Regulator (LVR) are coordinated by a smart controller, which is empowered by optimization theory and artificial intelligence-based prediction, to maintain the voltage within the statuary limits and transformer not overloaded even when relative high penetration PV and electrical vehicles are connected to the network.

1. BACKGROUND

In Hong Kong, the city is actively striving to achieve carbon neutrality before 2050, supported by various policies and a clear roadmap, such as "2050 Hong Kong (HK) carbon neutrality", "Hong Kong Smart City Blueprint 2.0", HKSAR's 2022 Policy Address have been implemented to accelerate the decarbonisation efforts to pave the way towards the city's ambitious goal. CLP Power actively responds to the policies issued by the Government and specifies corresponding strategic policies. 1) Reduce the emission of greenhouse gas in traditional plants. CLP Power decided to cease the use of coal for daily electricity generation in Hong Kong by 2035. 2) Zero-carbon energy is employed for generation. CLP Power will also increase the share of zero-carbon energy in the fuel mix for electricity generation to around 60% to 70% by 2035 through trailing new energy and closer cooperation with neighbouring areas.

2. INTRODUCTION

Renewable energy (RE) resources are gradually replacing traditional plants for power generation, for the target of the decarbonisation around the world [1]. However, the high penetration of PV has raised concerns to the operation of the power system, especially on the low voltage (LV) network [2]. A conventional power system network is designed in a way that the power will flow from grid side to customer end. With high penetration of RE at LV network, the voltage at load end may be higher than that at supply end, such that the power will flow from low voltage network to high voltage supply, which makes the power system bi-directional. This symptom may cause some potential risks to the power system such as power quality, voltage fluctuation which mitigation measures shall be made.

For voltage control, according to a literature survey, there are various approaches adopted by different power companies all over the world. In America, power companies use the MV/LV on-load tap changer and LVR, reactive compensation, and distributed energy storage to control the voltage. While companies in Europe employs not only traditional methods like MV/LV on-load tap changer, reactive compensation, low voltage meshed network and distributed energy storage, but also customer engaged programmes, such as smart inverter control, vehicle-to-grid (V2G), and demand side management to maintain the voltage within the limits. In Australia, power companies rely on smart inverter control and LVR.

In Hong Kong, PV and EV can be two main means to support low-carbon community transition. According to the characteristics of Hong Kong's natural resources, i.e., sufficient sunlight resources, PV generation is feasible. However, one of the challenges in adopting large PV project would be the land resources. Roof-top PV panel might be an effective method to harvest the sunlight resources. To support a greener Hong Kong, CLP Power facilitates clean energy from the residential customers at attractive Feed-in Tariff (FiT) rates. The FiT Scheme was launched in May 2018 [3] that customers who install solar or wind energy generation systems at their premises can sell the RE generation to the power companies at an attractive rate. Also, the requirements for engineering, building structure, land use and business registration of roof-top PV panels are clearly defined by the HKSAR Government to facilitate the adoption of roof-top PV panels. Thereby, more and more customers have installed the PV at their premises, and related voltage fluctuation issues require attention from the planning stage to daily operation.

Moreover, the deployment of EVs can be an important means of supporting low-carbon community transition, since the use of EVs is essential to reduce the use of fossil fuel on the roadside. However, the integration of the large-scale of EVs will bring challenges to the capacity of the network, including transformers, cables, and lines [4].

These two issues, voltage fluctuation and capacity of network caused by high penetration of PV and EV charging, are addressed by the project of LV smart grid. The details of the project are elaborated in Section 3, and then the results are presented to verify the effectiveness of the proposed project in Section 4. The conclusion and way forward are presented in Section 5.

3. LV SMART GRID PROJECT

The project aims to enable more RE (mainly FiT) and facilitate more EV charging connections to support low-carbon community transition while uplifting asset utilisation, voltage stability and supply reliability through automated network optimization algorithm. It is the first LV smart grid in Hong Kong, which continuously optimizes the asset and network performance by AI algorithms.

3.1 The Architecture of LV Smart Grid System

The architecture of the LV smart grid system is illustrated in Figure 1, which consists of an LV smart grid controller, a BESS, an LVR, a PV system and a micro-weather station.

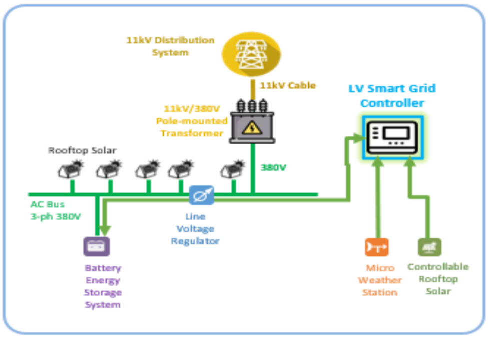

Fig. 1 - The Architecture of LV Smart Grid

3.2 LV Smart Grid Controller

The LV smart grid controller, as shown in Figure 2a, is the brain of the LV smart grid. It performs the functions of optimal dispatching and automation. The optimal dispatching consists of five modules: electrical network modelling, real-time data acquisition, AI (neural network) based generation and load forecasting, real-time calculation and optimization, and supervisory control. For the electrical network modelling module, the LV distribution network model is established in the Open Distribution System Simulator (OpenDSS) according to the actual information, including network topology, line parameters and transformer parameters, which will be updated with the latest data. In the real-time data acquisition module, the voltage of LVR and the voltage and State of the Charge (SoC) of BESS are acquired in real time for further assessment. In the AI neural network module, Deep Neural Network (DNN) is used to build the PV generation and load consumption forecasting models, acquiring the historical data from local weather station (See Figure 3) and smart meters, which will be described in detail herebelow. After acquiring these three types of data, the network state is assessed according to calculation results in OpenDSS in the real-time calculation and optimization module. Lastly, the control signals for LVR and BESS are determined using the embedded smart algorithm and then issued to respective devices to achieve smart control. The control logic of the controller for LVR and BESS is illustrated in Figure 2b.

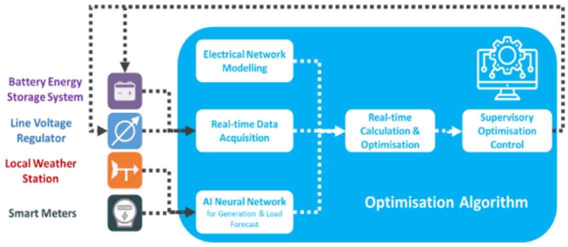

Fig. 2a - LV Smart Grid Controller

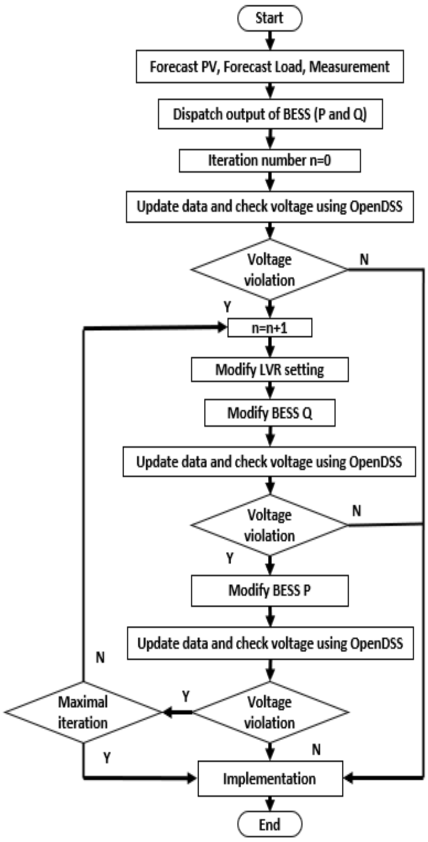

Fig. 2b - Control Logic of LV Smart Grid

Fig. 3 - Micro-weather Station

As illustrated in the figure, after acquiring the forecast data and real time measurement data, the outputs of BESS active power (P) and reactive power (Q) are optimally dispatched according to the economic dispatch strategy. The planned dispatch order requires to be further verified before implementation, in terms of voltage limits using power flow function in OpenDSS. If voltage violation occurs, the control logic containing the iterative process is triggered and starts to modify the following parameters in sequence to regulate the voltage along the LV circuit within the pre-defined limits, (1) LVR setting (steps in LVR), (2) generate/consume reactive power of BESS (BESS Q), (3) discharge/ charge active power of BESS (BESS P). The iterative process will exit once the adjustment of a specific parameter is effective for voltage regulation or the iterative process has reached the pre-configured maximal iteration number. After the iterative process finished, the control signals will then be sent to the field devices of LVR and BESS for operation.

The key function modules of the AI-based forecasting system include: (1) historical data storage, (2) real-time/forecast data collector, (3) AI model training and tuning; (4) self-adaptation of AI models with auto updates; (5) operation instruction output. The forecast system can provide multi-timescale forecast in 15 minutes ahead, 1-hour ahead, 4-hour ahead and 24-hour ahead. The flowchart in Figure 4 below illustrates the functioning of DNN [5].

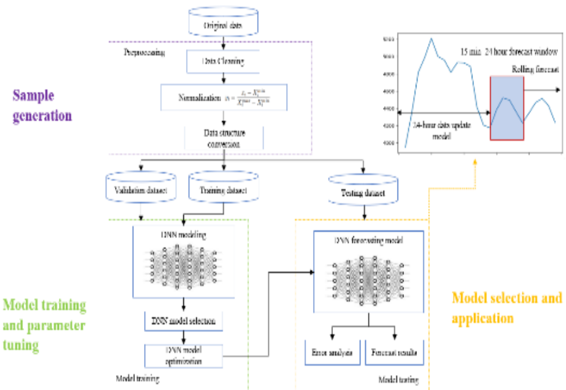

Fig. 4 - The Flowchart of the DNN for PV/Load Forecasting

After collecting the original data like historical PV generation and real-time weather information, the data preprocessing is conducted, which contains data cleaning, normalisation and data structure conversion. Then the data is divided into two categories for different purposes: one for model training and the other for model testing. In model training process, the dataset is further divided into two categories: training dataset and validation dataset, both of which are applied to model, select, and optimize the DNN forecasting model. Then the trained DNN can be deployed to forecast the PV generation and customer load according to the testing dataset, which is further analyzed.

Taking the forecast of distributed PV output as an example (See Figure 5). The AI-based forecast system first collects historical PV actual output data and the irradiation data of the past 4 days from weather information. Then, the collected data is classified into two categories, training data and testing data for DNN training. Finally, the DNN forecasting model is constructed to forecast the PV generation with a resolution of 15 minutes, and further optimized to search for the best hyperparameter set for better forecast accuracy.

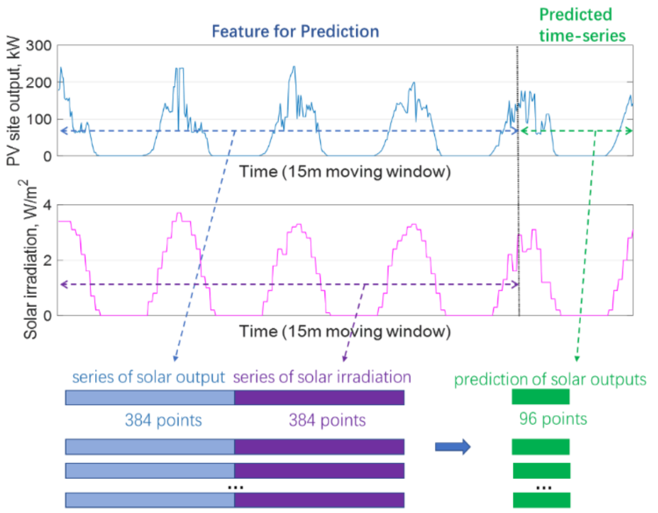

Fig. 5 - The Forecast of Distributed PV Output using the DNN Algorithm (for Illustration)

3.3 Line Voltage Regulator (LVR)

The function of the LVR is to regulate the voltage profile according to the pre-defined limits at the LVR installation location.

When the real-time voltage on the load side violates the pre-defined limits, LVR is triggered to regulate the voltage with a tolerance band to avoid hunting. Thereby, LVR has the ability to maintain the voltage on the line between the installation location and remote end [6]. The deployed LVR is shown in Figure 6, which can achieve 6% voltage regulation with 1.5% change at each step, totally 9 steps. See details below.

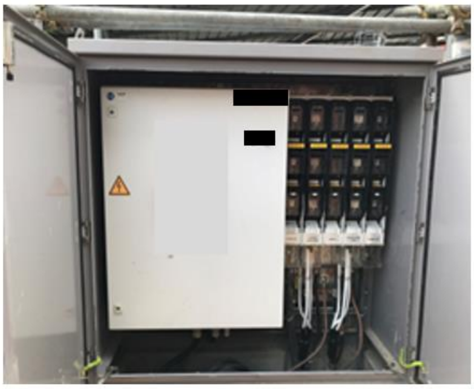

Fig. 6 - Photo of LVR

The principle of realizing voltage regulation is to switch two transformers connected in series with selected transfer ratios on and off. The details can be found in Figure 7, where the 6% voltage regulation is a linear combination of the 1.5% voltage regulation and 4.5% voltage regulation, corresponding to 9 steps with 0.94, 0.955, 0.97, 0.985, 1.0, 1.015, 1.03, 1.045, and 1.06. For example, a 3% voltage reduction can be achieved by a linear combination of a reduction in 4.5% and an increase in 1.5% of respective transformer in LVR.

Step	Transformer 4.5%	Transformer 1.5%
+6 %	+4.5%	+1.5%
+4.5%	+4.5%	0 %
+3%	+4.5%	-1.5%
+1.5%	0 %	+1.5%
0%	0 %	0 %
-1.5%	0 %	-1.5%
-3%	-4.5%	+1.5%
-4.5%	-4.5%	0 %
-6%	-4.5%	-1.5%

Fig. 7 - Nine Voltage Steps of the LVR

The LVR can achieve smooth voltage regulation without current surges, voltage dips and harmonics due to an important component, the thyristor with intelligent switch function.

3.4 BESS

The installed BESS is illustrated in Figure 8 where the capacity of the BESS is 240kWh, and the maximal charging and discharging power is 50 kW. The main function of the BESS is to store energy during the daytime, which could absorb some extra PV power from the grid, and discharge to the grid at night, especially during the peak time, to achieve the peak shaving and support EV charging.

The BESS comprises four major components, including Power Conditioning System (PCS), Energy Storage System (ESS), Battery Management System (BMS) and Grid Connection Cubicle (GCC).

PCS is used to manage bi-directional AC/DC power conversion for battery charging and discharging at nominal rating 50kW while BMS monitors and manages battery operation. The ESS equips with 28 units of Lithium Iron Phosphate (LiFePO4) battery modules in total 240kWh capacity. Moreover, GCC is a ground-mounted stainless-steel kiosk for connecting between PCS and the LV network. It is pre-fabricated with one unit of 400/380V Isolation Transformer, one unit of 100A Fuse Cutout, one unit of LV distribution board comprises of one unit of 6-way distribution board, metering equipment and communication equipment.

Fig. 8 - Installed BESS

4. RESULTS

In this section, the simulation and testing results are illustrated to verify the effectiveness of the system.

In the simulation, the impact of LVR on voltage regulation is illustrated in Figure 9. Before the installation of LVR, the voltage sometimes drops below the limit during summer time, while after installing the LVR, the voltage is regulated within the limit. Thus, the LVR can improve the voltage quality and maintain voltage within the safe range.

Load comparison before and after using PV and BESS is illustrated in Figure 10. As shown in the figure, the customer load decreases from midnight to noon and then increase to the peak value at around 22:00. The PV panel injects power into the grid during daytime. The BESS is dispatched to charge and discharge, which achieves the peak shaving and minimise the load variance. Therefore, the BESS can reduce peak demand and further increase the host capacity to allow more EV and PV connections.

The voltage regulation by LV smart grid controller during the 25-31 March 2023 is presented in Figure 11. The figure shows the maximum and minimum voltages are both within the voltage limits during the operation of the LV smart grid controller. Based on the existing setup, the system performance from the testing results is positive, which could accommodate more PV and EV. Moreover, Figure 12 shows the actions taken by the system on load levelling and peak shaving. As exhibited in the figure, the BESS can smooth the load, especially to achieve peak shaving, meanwhile considering the impact from PV generation.

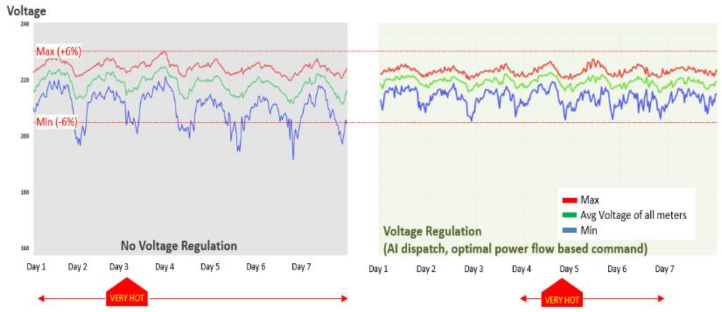

Fig. 9 - Voltage Comparison Before and After the Installation of the LVR in Simulation

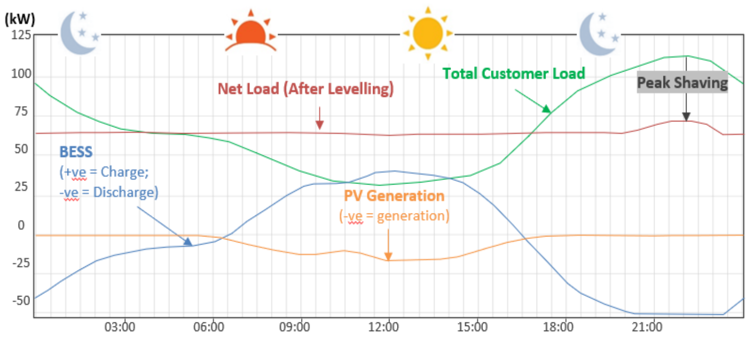

Fig. 10 - Load Comparison Before and After Using PV and BESS (For Illustration)

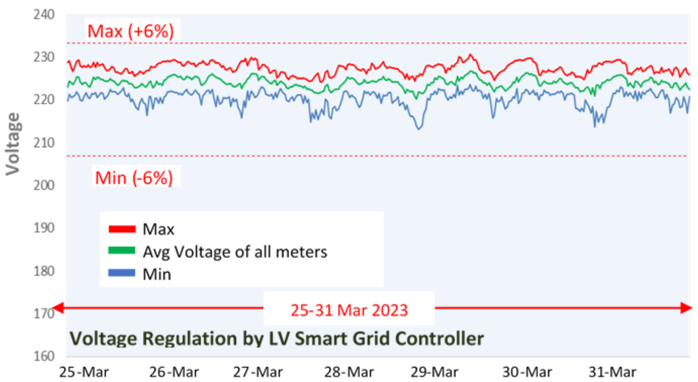

Fig. 11 - The Voltage Regulation Results by LV Smart Grid Controller during 25-31 March 2023 (For Illustration)

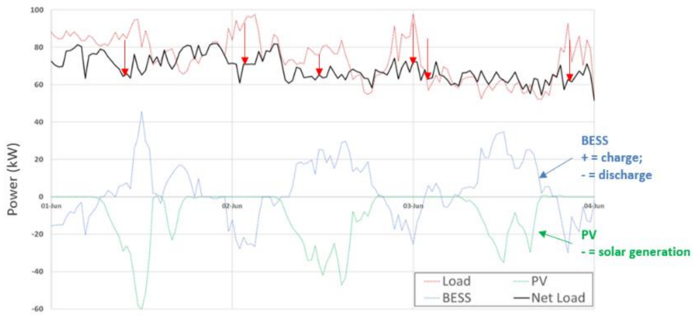

Fig. 12 - LV Smart Grid Actions on Load Levelling (For Illustration)

5. CONCLUSION AND WAY FORWARD

The AI-based LV smart grid system can regulate the voltage within limits in the distribution line and achieve peak shaving, which can enable more PV and EV charger connections and at the same time maintain the power quality standards.

In the future, the potential evolution of the system architecture of LV Smart Grid is illustrated as Figure 13, where the LV smart grid will be integrated to the Advanced Distribution Management System (ADMS) for SCADA monitoring and DER management. Additionally, visibility of LV network could be improved by deploying real-time Internet of Things (IoT) sensors. With support of more real-time data, the control algorithm of the smart grid controller can be further enhanced to achieve more accurate control for facilitating DER integration.

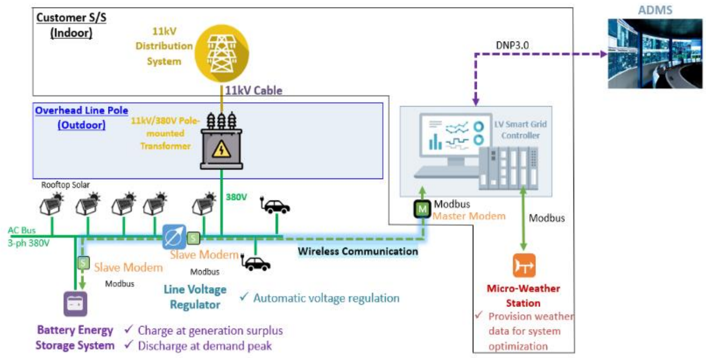

Fig. 13 - Future System Architecture

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Paper No. 7

ROAD TO CARBON NEUTRALITY WITH MICROGRID IMPLEMENTATION

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ROAD TO CARBON NEUTRALITY WITH MICROGRID IMPLEMENTATION

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ABSTRACT

Microgrid is an energy system that operates in parallel with or independently from the main grid, consisting of distributed energy sources (e.g., renewables, conventional, storage) and loads, and is a promising solution for achieving carbon neutrality and ensuring reliable energy supply. Its implementation has to ensure reliable energy for commercial, industrial, and consumer applications while reducing greenhouse gas (GHG) emissions, which is particularly relevant for critical infrastructure, geographical islands, and campuses.

There are several challenges that need to be addressed, including resilient and network-synchronized system, the efficiency of the system by means of smart use of renewable energy systems and distributed energy resources control, and the connection to the utility grid which involves generation and load forecast. To overcome these challenges, specialized hardware and software systems control, i.e., Microgrid Management System (MGMS) and Microgrid controller (MGC) for optimal performance, are essential for Microgrid implementation.

In this paper, we will discuss the challenges and solutions for Microgrid implementation, and also examine real-world Microgrid projects implementation in various countries to showcase the effectiveness of microgrid implementation in achieving carbon neutrality and ensuring reliable energy supply.

1. INTRODUCTION

In the pursuit of a sustainable future, the world is embarking on a transformative journey towards carbon neutrality. As societies grapple with the urgent need to mitigate climate change and reduce greenhouse gas emissions, innovative solutions are emerging as key enablers of this transition. Among these solutions, the implementation of microgrids stands out as a promising avenue for achieving carbon neutrality while ensuring reliable and resilient energy systems.

Microgrid serves several specific geographic areas such as campuses, hospitals, business centers, or neighborhoods, possess the ability to operate autonomously or in coordination with the main power grid. It is characterized by the capability to connect and synchronize with the main grid at a point of common coupling, ensuring compatibility and exchange of electricity under normal conditions. In times of emergencies, natural disasters, or grid outages, microgrids can seamlessly disconnect from the main grid and function as independent islands, relying on their local energy generation units to provide uninterrupted power to the connected loads.

2. KEY DRIVERS

Motivated by the imperative of decarbonization and policies aimed at reducing fossil fuel usage and addressing environmental concerns, the integration of a significant amount of renewable generations at the transmission level and distributed energy resources (DERs) at the distribution level are beginning to impact system planning, operational controls, and maintenance decisions. Additionally, there is a growing demand for integrating charging infrastructure into the grid to support electric vehicles, as well as the electrification of other industries.

Research conducted by RWTH Aachen University on the power flows and grid utilization in the European transmission grid for 2020 reveals an escalating trend in energy traffic, which is projected to worsen by 2050, resulting in heavy congestion on the energy roads. See Figure 1 [1].

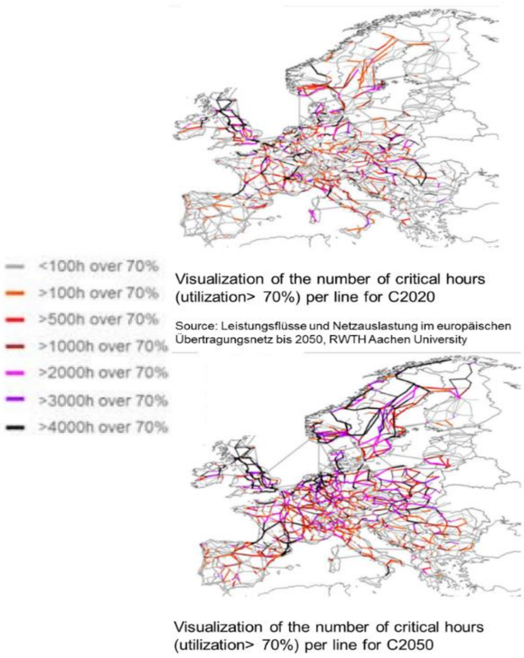

Fig. 1 - Visualization of the Number of Critical Hours in European Transmission Grid for 2020 and 2050

The unpredictability of renewable energy source outputs further compounds the challenges of effectively balancing supply and demand within electric grids.

As a result of the significant transition from fossil fuel to sustainable energy sources, decentralization with microgrid implementation has become a crucial necessity, serving as a driving force for many utilities worldwide.

3. MICROGRID CONTEXT AND STRUCTURE

A microgrid can be described as a collection of interconnected loads and distributed energy resources (DERs) that operate within specific electrical boundaries. It functions as a unified and controllable entity in relation to the main grid. The microgrid typically interacts with the external grid at a designated point known as the point of common coupling (PCC). In cases where multiple points of contact exist, only one of them is typically managed to facilitate the integration of the microgrid. The microgrid has the capability to connect or disconnect from the main grid, allowing it to operate in both grid-connected and islanded modes. It also usually characterized as a microgrid control system, capable of automatically integrating and coordinating generation, storage, controllable loads, and the grid intertie equipment within the microgrid required to interact with the larger grid as an aggregated single system.

A microgrid control system incorporates various control functions that establish the microgrid as a self-managing system. It enables the microgrid to operate autonomously or in a grid-connected mode, allowing for seamless connection and disconnection with the main distribution grid to facilitate power exchange and the provision of ancillary services. The microgrid control system serves as the exclusive interface point for any DERs device, DER management system (DERMS), and/or energy management system (EMS). It is designed to perform real-time control and energy management functions in the following scenarios:

a) Operation in both grid-connected and islanded modes

b) Automatic transition from grid-connected to islanded mode - facilitating a controlled shift to islanded mode for microgrid loads during abnormal bulk power system conditions and planned interruptions of the system

c) Re-synchronization and reconnection from islanded mode to grid-connected mode

d) Energy management to optimize both real and reactive power generation and consumption

e) Ancillary services provision, support of the grid, and participation in the energy market and/or utility system operation, as applicable.

The microgrid control system includes software, hardware, or a combination of both, and can be implemented in various physical configurations, such as centralized or distributed setups. As such, the term microgrid control system could be used in place of Microgrid Controller (MGC), with control functions distributed.

The typical microgrid control system could be specified in three levels: operator level, field device automation level (Core functions for microgrid control system) and asset level of its function stack as shown in Figure 2. For example, the physical requirement to disconnect under certain voltage and frequency conditions will involve the core functions and the low-level functionality of individual asset/devices, including breakers and disconnects. Any microgrid control system shall implement and meet these minimum requirements. These implementations are commonly used in commercial and industrial installation.

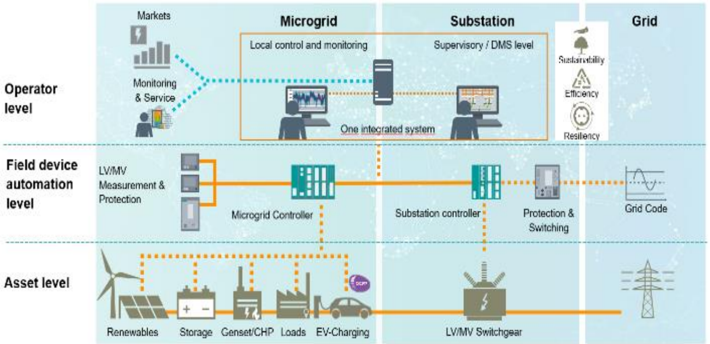

Fig. 2 - Microgrid Control System Framework on Distribution Grid

The microgrid controller serves as the primary interface at the field device and automation level, plays a crucial role in the operation of the microgrid. It is responsible for controlling various components such DERs, PCC, loads, battery storage, and conventional generators.

Additionally, the microgrid controller is designed to support different industrial communication protocols, enabling effective communication and control of these elements. It also gathers data from the microgrid and reports it to the upstream local microgrid control human-machine interface and the distribution management system (DMS). An example is shown at Figure 3, as a visual representation of the typical configuration of the microgrid controller in the context of these functionalities.

The newest MGC offers the modular design and platform-independent interfaces, enables the flexibility and customization capability for the control components and algorithms development. This approach ensures the users can accommodate various functionalities without imposing limitations. It paves the way for adaptability and customization in the control system, allowing for seamless integration of different components and the implementation of specific control strategies tailored to the microgrid's requirements.

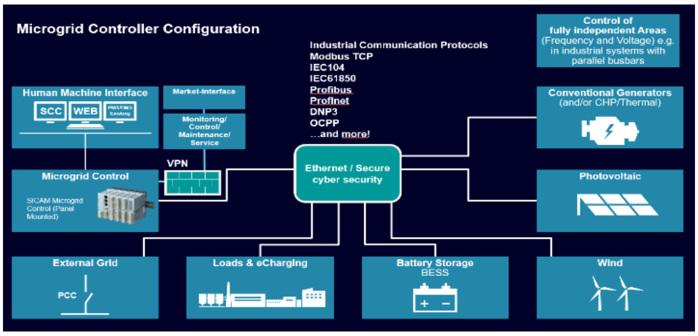

Fig. 3 - Microgrid Controller Configuration

4. MICROGRID CONTROL FUNCTIONS

The microgrid control functions of microgrid controllers have been established based on the guidelines outlined in the IEEE 2030.7 Standard for the Specification of Microgrid Controllers.

The newest generation of MGC equips the standard microgrid logic template that adheres to the specifications set forth by the IEEE 2030.7 standard. This template simplifies the implementation process for end users and promotes standardized microgrid system designs. By utilizing the standard logic template, end users can avoid the need to develop customized, non-standardized logic, leading to time savings during the microgrid implementation process.

Figure 4 shows a comprehensive depiction of the functional overview of microgrid control applications, following the design principles outlined in the IEEE 2030.7 standard. It offers a clear representation of the various components and interactions involved in the microgrid control system as specified by the standard. By referring to Figure 4, one can gain a deeper understanding of the key aspects and functionalities of microgrid control applications in accordance with the IEEE 2030.7 standard design.

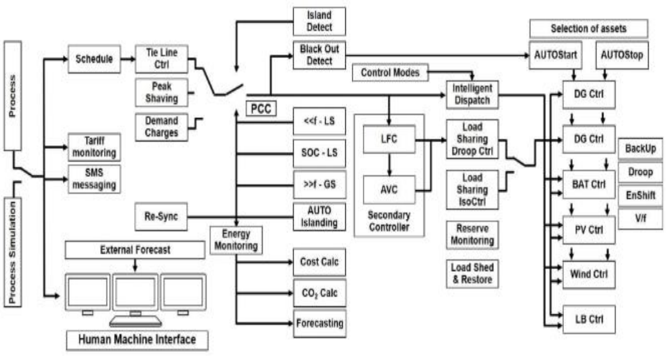

Fig. 4 - Microgrid Control Functions Overview

The core microgrid control functions encompass the management of system transitions from grid connection to islanding. These transitions should be considered in the following sequences, which are associated with the transition function [2]:

a) Unplanned islanding (T1)

b) Planned islanding (T2)

c) Reconnect (T3), as applicable

d) Black start (T4)

The transition function plays a crucial role in determining the logic for switching the dispatch function between different operational modes within the microgrid. These modes include the four transition modes (T1 to T4) and two steady-state modes, namely the connected mode (SS1) and the islanded mode (SS2), as illustrated in Figure 5 [2].

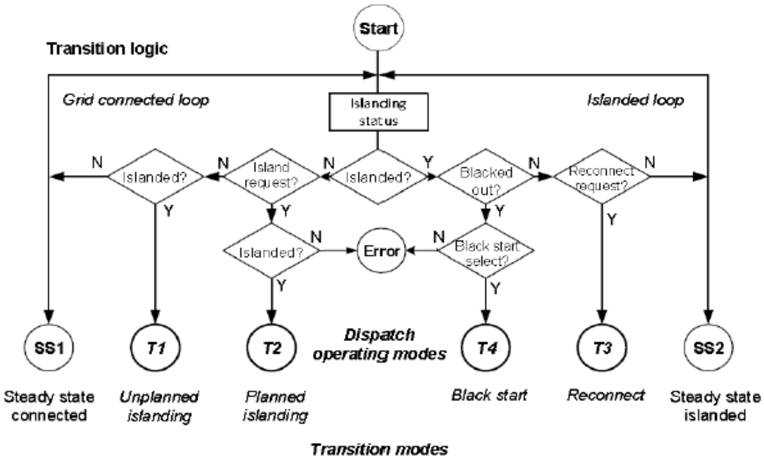

Fig. 5 - Sequences Associated with the Transition Function

Under steady state conditions, the dispatch function shall carry out the operations described below for the two states of the microgrid, grid connected (SS1) and islanded (SS2) transitions, it receives information about the nature of the transition to be carried out and executes required operations. The transition modes include unplanned islanding (T1), planned islanding (T2), reconnect (T3), and black start (T4).

There are different microgrid grid logic functions implemented in the new generation microgrid controller while the transitions from grid connection to islanding.

4.1 Control and Increase Share of Renewables

Operation modes can be selected with economic, reliable, or low emission (green) objectives. Table 1 [3] shows that the behavior of assets will be different in grid interconnected or islanded modes for a selected operation mode.

Asset	(A) Interconnected Mode (B) Island Mode		
	Economic	*Reliable*	*Green*
Battery Set Mode	(A) Energy Shift (B) Energy Shift	(A) Backup (B) Backup	(A) Energy Shift (B) Energy Shift
Renewables Penetration	(A) 100% (B) 70%	(A) 100% (B) 30%	(A) 100% (B) 70%
Diesel Set Mode	(A) Off (B) On	(A) On (B) On	(A) Off (B) On
Loads	(A)Warning if actual tariff > tariff limit (B) Tripping if necessary	(A) none (B) Tripping if necessary	(A) Warning at low renewable production (B) Tripping if necessary

Table 1 - Operation Mode - Interconnected Condition

4.2 Island Detection - For Unplanned Islanding (T1)

The information whether the microgrid is in grid-connected or islanded mode is crucial for many functions of the microgrid controller. A logic should check the status of the circuit breaker at the PCC. In OPEN position the microgrid is supposed to be in islanded mode. In CLOSE position the microgrid is interconnected [3].

4.3 Automatic Intended Islanding - For Planned Islanding (T2)

This function should provide the possibility to isolate an interconnected microgrid from its external grid. The sequence should be as follows: [3]

a) Initiation of islanding at Human Machine Interface/DMS.

b) Reduce Active Power (P) and Reactive Power (Q) at point of common coupling to zero.

c) Check whether load frequency control and automatic voltage control modules are running.

d) Open circuit breaker at point of common coupling.

4.4 Re-Synchronization to External Grid - For Reconnect (T3)

This function provides the possibility to resynchronize an isolated microgrid to its external grid and finally close the circuit breaker at the PCC.

The synchronization itself is not done by the MGC but by an external protection relay with synchro-check function. To have equalized voltage and frequency, the microgrid controller should temporarily use the real-frequency and the real-voltage of the external grid as reference. The approach of equalizing the values of the microgrid with the reference values should use the load frequency control and automatic voltage control functions.

Prerequisites for the re-synchronization function are: (a) it must be possible to measure frequency and voltage at the internal and external side of the point of common coupling. (b) an extra synchro-check relay needs to be installed which is eventually releasing the CLOSE command [3].

4.5 Blackout Detection - For Black Start (T4)

This function checks the voltage at the PCC. In case a blackout has been detected, other functions like auto-start of diesel generators should be triggered.

The sequence should be as follows: [3]

a) Check voltage at PCC

b) If under voltage detected, then blackout is detected

c) Open circuit breaker at PCC

d) Open all circuit breakers at loads

After detection of a blackout, the auto start function can optionally initiate a black start of diesel generators and other energy sources.

In addition to the core microgrid control function, Figure 4 illustrates other features and functionalities that result from specific system and component design approaches and choices made during the planning and implementation stages. These extra features are aimed at enhancing the resilience, energy security, and reliability of the microgrid.

The specific control system functions may vary depending on the requirements and preferences of the end user and the characteristics of the microgrid system. These functions can be tailored to meet the unique needs of the microgrid and its components.

5. IMPLEMENTATION AND CHALLENGES

The electric power grid plays a critical role either as an enabler or bottleneck on the microgrid implementation. Microgrid implementation involves installing the DERs and storage as well as control system to manage the flow and balancing of electricity. It requires coordination among energy providers, hardware suppliers, engineers and local authorities, who to push and speed up in order to break the barriers of challenges, as detailed below.

5.1 Cost

Microgrid projects typically have high upfront capital investment due to the multiple components involved, such as DERs, BESS and control system. Securing funding for such projects can be challenging, especially for smaller-scale installations. With the technology advancement, the costs are expected to decrease over time, making microgrids more financially viable in the coming future. Another option would be utilizing the advanced controller, equips with future proof technologies – modular design, programmable logic control and open communication capabilities, such to serve the purpose of remote control and monitoring as the general remote terminal unit (RTU), also the connectivity of DERs and microgrid implementations as MGC. Capital investment could be optimized.

5.2 Control Complexity

Microgrid requires sophisticated control systems to optimize their operations and seamlessly switch between grid-connected and islanded modes. Developing and implementing these control systems can be technically challenging. However, ongoing research and development efforts are focused on addressing this challenge by improving control algorithms, communication protocols, and automation technologies.

5.3 Energy Storage Limitation

Energy storage technologies, such as batteries, are essential for storing excess renewable energy and ensuring a reliable power supply during periods of low generation or grid outages. However, current energy storage capacities are still limited, which constrains the amount of renewable energy that can be stored and utilized within a microgrid. Continued advancements in energy storage technologies are needed to overcome this limitation.

5.4 User Adoption

Educating and engaging customers in the transition to a localized grid and promoting behavioural changes for flexible demand-side management can be challenging. It requires raising awareness about the benefits of microgrids, providing clear communication, and incentivizing participation. In addition, public outreach programmes, financial incentives, and supportive policies can encourage user adoption and facilitate the necessary behavioural changes.

5.5 Resiliency During Outage

Microgrid is expected to provide increased resiliency during extreme weather events or main grid disruptions. However, comprehensive testing and evaluation of microgrid reliability under such conditions are still ongoing. Developing standard resilience metrics and conducting rigorous testing will help assess and improve the performance of microgrids during critical situations.

Continued research, development, and innovation, along with supportive policies and financial mechanisms, will contribute to overcoming these barriers and accelerating the widespread implementation of microgrids.

6. REAL WORLD MICROGRID PROJECTS

Two microgrid projects are to be studied in this section. The first location in Blue Lake Rancheria (BLR), USA, would be focusing on the energy exchange at the PCC of a grid-connected microgrid, reduce net site load power draw from the utility, and replaced by the renewable energy sources within the microgrid in the managed manner. The second location in Madeira, Portugal would be seeing with the high portion of the renewable energy in an islanded microgrid, how the use of microgrid control can help increase the reliability and stability of the power system.

6.1 Blue Lake Rancheria (BLR) Native American Reservation

Located at Blue Lake Rancheria California, USA, a federally recognized Indian reservation with approximately 100 acres of trust land, 400 employees and roughly 2000 visitors daily. A collaborative microgrid solution is used to tackle the challenge of integrating the renewable energy sources, energy storage, and other controllable loads. The target is to replace traditional fossil fuel energy consumption by 680 MWh per year [4], with no compromise on the power system stability and power quality, which is necessary for powering a certified Red Cross Shelter in the reservation.

The controllable elements consist of the power sources with 1,000kW diesel generator (G), 175kW biomass fuel cell (FC), 420kW solar panels (PV), and with battery energy storage system (BESS) with capacity 950kWh and maximum output of 500kW, 5 controllable load groups with 700kW peak or 500kW on average [4]. With a variety of controllable assets, it opens the possibility for optimization by using a microgrid control system.

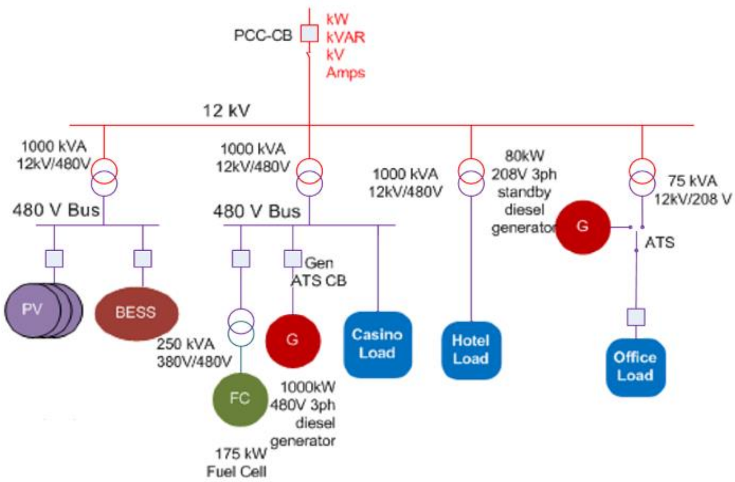

Fig. 6 - Single Line Diagram of BLR Power System under Microgrid Control

During grid-connected operation, the local weather data, historical load and generation data are fed into the microgrid control, for which the loads and renewable generations can be forecasted. Then the combined load profile is projected for optimization and scheduling. Control commands are issued accordingly to the renewable generations and the battery system, or even the diesel generation if needed. Real time measurements are feedback to the microgrid control which the optimization is adapted to the actual load/supply situation.

In most of the scenarios, the solar PV, as a renewable energy source, provides the best to output at its maximum capacity. The battery system could quickly adjust the power outputs on command, and is able to switch between charging and discharging states, contributes as a crucial element to secure the system stability and power quality and flexibility to apply different optimization strategies. Examples are keeping the targeted state-of-charge (SoC) at 100% for the maximum energy reservation; or setting the SoC target at mid-range leaving room for the battery to be discharged and charged which will be useful to maintain the power quality during islanded operation. By balancing the power output of renewable generations and the state of the battery system, the energy exchange at the PCC can be controlled by the microgrid control.

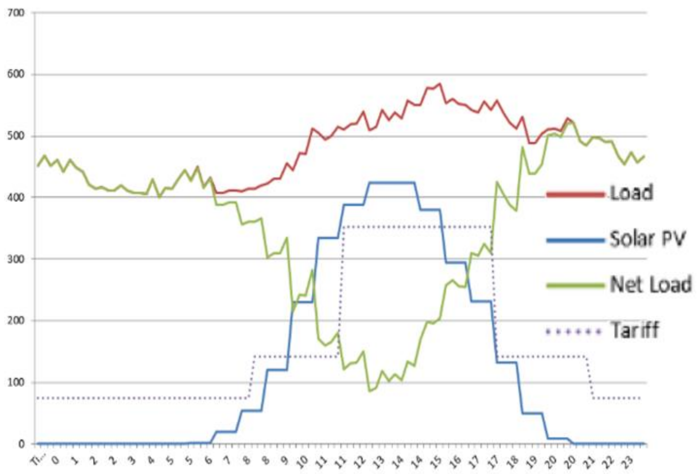

Fig. 7 - Typical Load Profile of a) Gross Load, b) Solar PV Supply, c) Net Load, which Equals Gross Load - Renewable Energy Sources

Although BLR has not joined to the utility demand response programme, the controls demonstrate the microgrid ability to reduce the net site load by utilizing the BESS. The demand response is realized by two other programmes from the local utility Pacific Gas and Electric Company (PG&E). The first programme is a Base Interruptible Programme (BIP). With a 30 minutes notice before the demand reduction period begins, the utility can request participating users to reduce the electricity consumption to a predetermined level when the energy supplies are falling short. Each event has a maximum 10 events per month, and a total of 120 hours per year [5].

Since the load profile is forecasted, any shortfall between the net load and the target reduced energy demand can be compensated by preparing the battery system such as increasing the SoC of the battery system. The microgrid is capable of managing the spinning reserve during the notification period, then to utilize the reserve during the energy demand reduction period.

The second programme is a Demand Bidding Programme (DBP), in which the energy reduction events are opened for bidding a day ahead and is not obliged to participate in every event [5]. The microgrid control can manage the energy consumption in the same manner as the previous programme, with the benefit of active planning and fitting the bidding event into the forecasted load profile, which allows more room for the reduction. The control of the battery system charge/discharge and the energy consumption at the PCC can all be done through schedulers in the microgrid control. The planned demand response events can be executed with minimum effort.

If BLR is participating in the utility's demand response programmes, it would help release the demand pressure on the larger power grid, preserving the system stability and reliability in bigger picture.

Other than grid-connected operation, the multiple distributed energy resources with microgrid control is playing an important role in the community in the event of a natural disaster or any other emergency when operating in islanded operation and continue to help reduce the carbon emission by minimizing use of the diesel generator and maximizing the use of renewable energy sources while maintaining the power stability and quality. Accompanied by load shedding scheme, which is also performed by the microgrid control, maximizing the fuel conservation is ensured during harsh disaster event, which as in a real-life test the system can supply uninterrupted electric power for at least 7 days. After the main grid is restored, the microgrid control can seamlessly re-synchronize the islanded microgrid with the external grid and be ready for reconnection [6].

The overall deployment of the microgrid solution helps Blue Lake Rancheria Native American reservation save 570 MWh out of the 3810MWh total 2017 gross site load in 2017, reduce its peak demand from 754kW to 652kW by 17%, and reduce 159 tons of CO_2 emissions annually, which also creates clean energy related jobs for the locals [6].

6.2 Autonomous Region of Madeira

Madeira, the remote islands on the North Atlantic Ocean, is one of two autonomous regions of Portugal, is becoming the EU's showcase for renewable energy.

As solar and wind energy sources are fluctuating as nature is, a battery energy storage system is being implemented in the form of a 22.5MVA / 15.6 MWh outdoor battery storage plant. In order to support the clean energy transition and retain the grid resilience, the BESS must be integrated into the microgrid and be working alongside with other controllable assets. With an area of 741 km^2 and population of 260,000 inhabitants, and without any external support of energy source, the power grid in Madeira may be considered as one islanded microgrid.

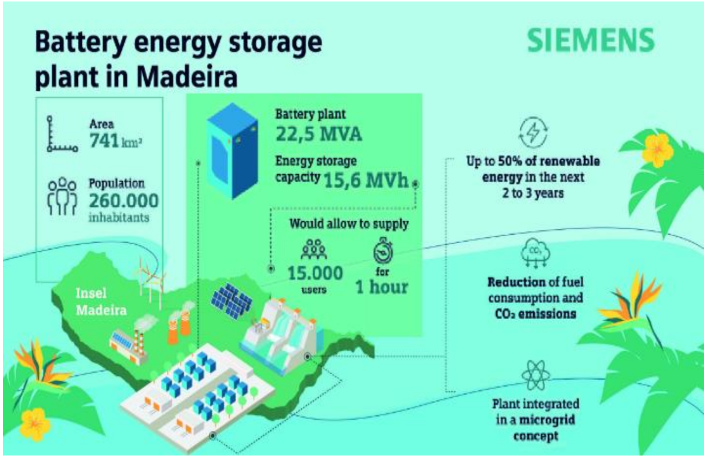

Fig. 8 - New Battery Energy Storage Plant on Madeira [7]

In islanded microgrid operation, the objective is to maintain the system reliability and availability of power distribution, smoothing the fluctuating renewable energy sources which would cause supply demand imbalance, and to minimize the use of the fossil fuel generations. Features of the islanded microgrid concept could be potentially beneficial to the energy system.

To address the power quality concern, the microgrid control can monitor the power system quality and command accordingly the output of the BESS to compensate for any drift in system frequency or voltage. The basic principles lay on the fact that the imbalance between active power load and supply will affect the system frequency. With more active power load than supply, system frequency will decrease. In reverse if more active power supply than load due to fluctuation of renewable energy sources or disconnection of a large load, the system frequency would increase. The reactive power and system voltage have a similar relationship in which voltage sag is often associated with insufficient reactive power supply [8]. These are not usually a critical concern for the grid-connected system since the larger grid offers much more power reserve to balance the demand. However, it would become a realistic issue for an islanded system. Two single-in-single-out feedback control modules are used for the Load Frequency Control and the Automatic Voltage Control and issue active and reactive power setpoint commands to the BESS to help adjust the power supply in order to maintain the frequency and voltage of the power quality [3].

On a remote island's self-dependent power grid, backout may sometimes be just unavoidable. The microgrid control with blackstart feature can utilize the BESS to resume the generators. The thermal power plant, once in outage, requires external electric power to operate the power plant in order to restore the generation. The necessary power could now be supplied by the BESS. Loads are disconnected during the beginning of a blackstart. An intelligence dispatch of energy storage or conventional generation ensures the success of the blackstart. Smart load restoration per each load group guarantees a smooth transition from BESS back to conventional generations when needed.

In the case of Madeira, the new battery storage plant is located next to the Vitória Thermal Power Plant, which it is already integrated to blackstart a part of the 60kV power network and help restore the grid services in case of an outage. This would significantly reduce the downtime of an outage event, thus increasing the system reliability [7].

The Madeira's power grid as reported by the first half of 2022 had generated 893 GWh, 33.0% of which came from renewable energy sources [9].

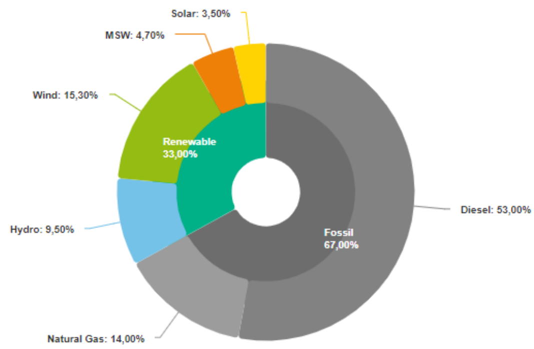

Fig. 9 - Combination of Energy Supplies on Madeira in the First Semester of 2022

Integrating battery energy storage systems into the microgrid concept enables critical control for greater renewable penetration and enhances the grid stability and reliability. This allows the microgrid to be integrated with more diversified energy sources. The energy provider in Madeira is intended to reduce the number of fossil fuel generations and bring in more renewable energy sources without increasing the risk of blackouts. This further improves the island's sustainability by reducing the CO_2 footprint with a target to increase the share of renewable energy sources to around 50% over the coming years. Increasing its energy independence without scarifying the power quality or grid stability.

7. CONCLUSION

The implementation of microgrids has emerged as a promising and effective solution on the road to carbon neutrality. As the world grapples with the challenges of climate change and the urgent need to reduce greenhouse gas emissions, microgrids offer a viable pathway towards a sustainable and resilient energy future.

The microgrid technology provides a decentralized and localized solution to energy generation, distribution, and management. By integrating renewable energy sources such as solar, wind, and biomass, microgrid reduces reliance on fossil fuels and promotes the use of clean, renewable energy. This transition not only mitigates the environmental impact associated with traditional energy systems but also enhances energy efficiency and reduces overall energy consumption.

One of the key advantages of microgrids is the ability to operate autonomously or in coordination with the main grid. This flexibility ensures a reliable and uninterrupted power supply, even in the face of disruptions or outages. Additionally, microgrids empowers communities and businesses to take control of their energy production, fostering a sense of energy independence and resilience.

Furthermore, the implementation of microgrid promotes the integration of energy storage technologies, such as batteries, which enable the efficient capture and utilization of excess renewable energy. This not only addresses the intermittent nature of renewable energy sources but also allows for the optimization of energy usage and load balancing. The combination of microgrids and energy storage systems creates a more stable and sustainable energy infrastructure, capable of meeting the demands of a rapidly evolving energy landscape.

However, the successful deployment of microgrid requires a collaborative effort from all stakeholders. Governments, utility companies, businesses, and communities must work together to create supportive policies, regulations, and incentives that encourage the adoption and integration of microgrid technologies. Investment in research and development, as well as infrastructure upgrades, is crucial to overcoming technical and financial barriers and ensuring the widespread implementation of microgrids.

In conclusion, the road to carbon neutrality is paved with the implementation of microgrid. With the ability to harness renewable energy sources, enhance energy efficiency, and promote energy independence, microgrids offer a sustainable and resilient solution to the challenges of climate change. By embracing microgrid technologies and fostering collaboration among stakeholders, we can accelerate the transition towards a carbon-neutral future and create a world powered by clean and renewable energy.

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Paper No. 8

A STATE-OF-THE-ART ENVIRONMENTALLY FRIENDLY TRANSFORMER OIL FOR EXTENDED TRANSFORMER LIFE CYCLE

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ABSTRACT

According to the UN, more than two thirds of the global population will be living in urban areas within 30 years. The impacts of climate change (floods, droughts, heatwaves, wildfires, storms) are being felt on a global scale. The global climate change is driving decarbonisation and the adoption of renewable energy generation and battery storage. Electricity utilities are seeking to balance budgets, maximise asset use and availability while addressing sustainability criteria set out in UN Sustainable Development Goals.

Synthetic ester transformer liquid was introduced in the 1970's to replace PCB's. Natural esters were introduced in the 1990's. Both ester types reduce the risk of human harm from fire events, which can be demonstrated by experiments. This enables substation innovation when guidance in standards such as IEC 61936 and AS2067 or industry guidance such as FM Global Loss Prevention Data Sheets 5-4 can be adopted.

Esters can underpin environmental risk reduction initiatives as they are readily biodegradable, non-toxic and non-volatile. They have been shown in studies to present low risk to marine and freshwater environments, enabling easy adoption in floating wind and solar applications as well as protecting vulnerable aquatic locations in general. It can now be shown that synthetic esters do not lose biodegradability in service. The use of renewable crop sources for natural esters and the circular potential of synthetic ester offer benefits to different parts of the full life cycle of esters in transformer applications and ester use demonstrates alignment with the UN Sustainable Development Goals.

Esters are now an established alternative liquid to mineral oils in all transformer applications. Recent research demonstrates that all ester types protect cellulose insulation, while field data can show robust performance after decades of service. Extending asset life also enables transformer owners to use limited capital and maintenance budgets in the most effective way.

Although it is accepted that esters are more expensive than the traditional mineral oil option, adopting esters from initial design can yield significant project cost and total cost of ownership savings, and enable full lifecycle sustainability benefits for substations. Similarly, retrofilling existing mineral oil filled transformers has been demonstrated to fit well with strategies for companies seeking to address continuity challenges, demonstrate corporate social responsibility or achieve significant risk reduction.

Ester transformer fluids are proven in thousands of applications where a zero-compromise approach is necessary, such as urban dense locations, underground, industrial facilities, and near environmentally sensitive receptors. If prevention is better than cure, the benefits of further adoption of ester transformer liquids will facilitate substation project design and delivery, with full lifecycle benefit for transformer owners.

1. INTRODUCTION

According to the UN Department of Economic and Social Affairs [1], by 2030 the world is projected to have 43 megacities (i.e. more than 10 million inhabitants). There are already 23 such cities in the Asia Pacific region. The UN also reports that global population living in urban areas will increase from 55% to 68% by 2050. Increasing urban density puts pressure on designers to reduce the footprint of new substations that may need to be located close to, within or even underneath places where people live and work. Transformer operators will need to manage the increasing risks as the land around existing substations is consumed by new residential, commercial, and industrial buildings.

There are also many remote, rural and island communities in both developing and developed countries that are more vulnerable to extreme weather events and often physically closer to environmentally sensitive areas, but also require access to clean, safe, and reliable energy supplies. This places challenges on existing and future electrical infrastructure as acknowledged in UN Sustainable Development Goal 7. These locations are often suited to renewable energy generation and microgrid development, substation design therefore requires a bespoke and robust approach to maximise efficiency, availability and reliability of energy supply whilst safeguarding the local environment.

Major weather events are becoming more common and are putting generation and transmission systems under increasing stress. Kern reported on the increasing wildfire risk in Europe, but every continent has experienced major wildfires [2]. In addition to the external risks from wildfires, extreme weather also presents an internal risk to electrical networks. Some utilities in the US are reported to have set new demand records ahead of the normal peak in high summer [3]. Likewise, the impact of storms such as typhoon Noru and extreme cold weather such as that experienced in East Asia in 2023 can create surges in networks. As the global impacts of climate change are being experienced, substation designers need to build in network reliability to enable robust performance that can cope with new norms and future extremes.

Electrical power is an essential feature of modern life for lighting, heating, cooling, refrigeration, electronics, transport, healthcare and industrial equipment, and transformers are a critical component in electrical grids allowing generation, transmission and distribution of electricity efficiently at the required voltages. Transformers have traditionally been filled with mineral oil due to its good dielectric performance, thermal properties and availability. Although worldwide experience has shown that the probability of well-maintained transformer failures leading to a fire is low, Berg included an analysis of data in the OECD FIRE Database showing that of 438 fire events from nuclear power plants, 8% were in oil filled transformers [4]. Bartley reported that 3% of the failure insurance claims were due to the transformer being a victim of fire [5]. CIGRE concluded that the probability of a transformer fire is approximately 0.1% per year, however over a 40-year service life the average probability is 4% so this risk cannot be ignored [6]. As transformers typically contain thousands of litres of dielectric liquid, the consequences of these catastrophic failures are not insignificant with potential outcomes include extended outage times, logistical challenges of procuring replacements and transporting heavy equipment, human and environmental harm, and millions in fines from regulatory non-compliance. Therefore, the risk from mineral oil filled transformer fires is far from negligible, and substation designers and operators need to consider the potential impacts.

Traditional transformer mineral oils sometimes carry warnings of human toxicity or environmental hazard and are not biodegradable. As such, substantial secondary containment and discharge controls to mitigate and manage any release are required in regulations. Sustainability factors including land use, consumption of abiotic resources and emissions throughout the entire life cycle from procurement to end of life are now being taken into account as part of environmental management and sustainability strategic objectives and corporate social responsibility over recent years.

A widely accepted methodology, the hierarchy of hazard control for eliminating or reducing hazards in workplaces starts with the controls perceived to be most effective and moves down to those considered least effective, as follows:

- Elimination – physically remove the hazard.
- Substitution – replace the hazard.
- Engineering controls – isolate people from the hazard.
- Administrative controls – change the way people work.
- Personal protective equipment– protect the worker with PPE.

Extensive engineering controls including increased separation distances to other assets, fire or blast walls, rock ballast to account for pool fires, deluge systems, larger containment designs, and containment discharge controls, etc., are commonly added to manage the inherent fire safety and environmental risks from mineral oil filled transformers, leading to increased substation project costs. Most secondary mitigation systems require additional administrative controls such as periodic maintenance and testing to ensure that they operate on demand, which further add to the total cost of ownership.

2. FIRE PROPERTIES & BEHAVIOURS

There are two basic scenarios by which a transformer can become involved in a fire event – as a source or as a victim. As a victim of an external fire event, the contribution from the transformer will be influenced by the ignitability of the liquid dielectric. However, if the main tank does not rupture due to being engulfed in flames, the likelihood of the liquid becoming involved is reduced. For the development of transformer risk assessments as the source of fire due to a fault leading to tank rupture, ignitibility is still important, but the behaviour of the liquid ejected from a transformer and away from the ignition source is equally important, especially considering this may be a fine spray when the internal pressure caused by a fault is released.

A substance's fire behaviour is typically discussed in terms of the flash and fire point. The fire point is defined as the lowest temperature at which vapours of the liquid will ignite and continue to burn, even after the ignition source has been removed. For insulating liquids used in transformers, if the fire point of the liquid is equal to or greater than 300°C, it is considered as "less flammable". The liquids can then be sub-classified according to the net calorific value (low heat value), with more energy available from combustion to sustain a fire indicated by a higher value.

Although natural esters have a higher fire point, the low net calorific value of synthetic esters further reduces the fire risk. Table 1 shows typical properties and classification of some dielectric liquids.

Dielectric Liquid	Flash Point ISO 2719	Fire Point ISO 2592	Net Calorific Value	IEC 61039 Classification
Mineral Oil	150°C	170°C	46.0MJ/kg	O1
Natural Ester	316°C	360°C	37.5MJ/kg	K2
Synthetic Ester	260°C	316°C	31.6MJ/kg	K3

Table 1 - Fire Properties Hazard Classification of Dielectric Liquids

A much greater temperature change is required for less flammable liquids like esters to reach their fire point. Assuming a typical operating temperature of a liquid filled transformer of 105°C and no heat loss from the transformer, Table 2 summarises the amount of energy required to raise the liquid temperature to this dangerous state, demonstrating that for the high fire point liquids, the energy input required is about four times higher than that of mineral oil.

Dielectric Liquid	Mass of 1000 litres	Specific heat capacity	Temperature change	Energy to raise liquid temperature to fire point
Mineral Oil	880kg	1860J/kg °C	65°C	106MJ
Natural Ester	920kg	1848J/kg °C	255°C	433MJ
Synthetic Ester	970kg	1880J/kg °C	211°C	385MJ

Table 2 - Comparison of Energy Required to reach Fire Point of Dielectric Liquids from 105°C

The assumption of no heat loss will not hold in reality, so a laboratory experiment was undertaken using an oxy-acetylene torch directed at the surface of a shallow pan of liquid to demonstrate the liquid behaviour in another way. The bulk liquid temperature away from the liquid surface was measured by a thermocouple. It can be seen in images taken from video footage of the experiment on mineral oil (Figure 1) that after only three minutes the liquid surface has started to flash and after four minutes the oil surface is burning at a bulk liquid temperature well below the flash and fire point.

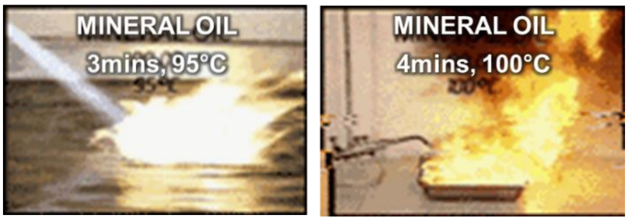

Fig. 1 - Images from Mineral Oil Pan Fire Experiment

In stark contrast, the images taken from the synthetic ester experiment (Figure 2) show that even after 70 minutes of heat from the torch burning at over 2,000°C there is no ignition. This test demonstrates how difficult it is to raise an ester liquid to its fire point.

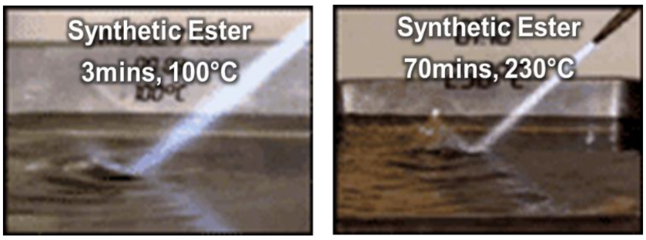

Fig. 2 - Images from Synthetic Ester Pan Fire Experiment

Transformers are often installed close to other assets or third-party property for technical or economic reasons and are therefore vulnerable to causing or becoming victim to fire spread to or from such adjacent installations. This potential often leads to expensive fire walls to isolate the transformer and the dielectric liquid must be retained in fireproof containment to avoid fire spread and limit the fire pool. Allianz used a sacrificial 630kV transformer containing 365kg of synthetic ester to understand how the liquid behaved in an external fire scenario [7]. To make both the convective and radiant heat act wholly on the transformer, and to prevent any effects from the flow of supply and discharge air drawn through the test room, a "corner" was erected around the transformer (Figure 3), consisting of two walls and a roof with an apron hanging down to approximately 60cm.

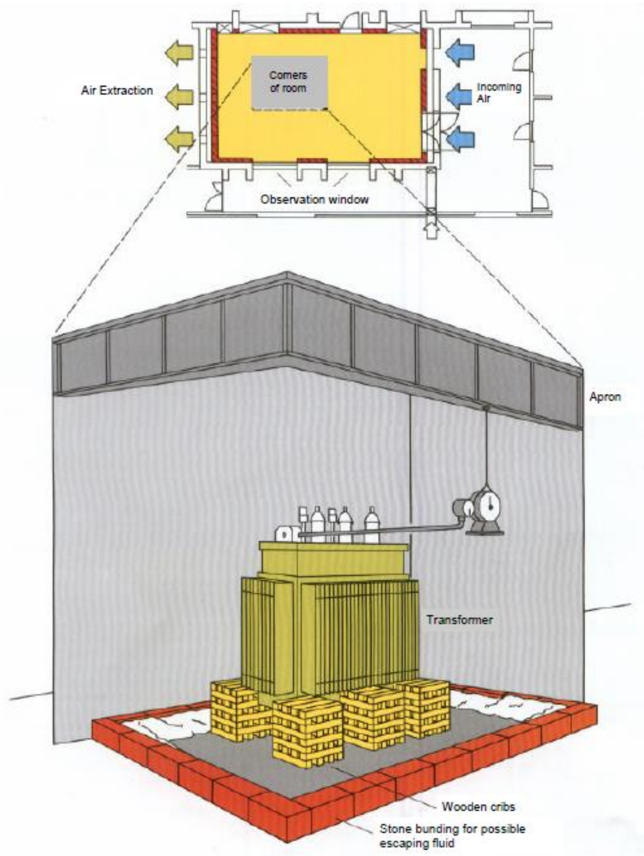

Fig. 3 - Transformer Victim Experiment Set Up

Twelve thermocouples were used to measure temperatures inside the transformer, recording changes automatically, and 180kg of pre-dried wooden cribs underneath the radiator fins around the transformer tank provided the fire load. The wood burned for about 70 minutes after ignition (Figure 4a) during which the transformer internal temperatures peaked at 180°C at the bottom and 204°C at the top, well below the ester flash point. The gases escaping from the pressure relief device could not be ignited, nor did the transformer leak at any point throughout the duration of the fire. No dangerous operating state arose on or in the transformer (Figure 4b) and the synthetic ester did not contribute to the fire. Additionally, it was found that the transformer was still in an electrically working condition when subsequently tested in the transformer manufacturer's factory.

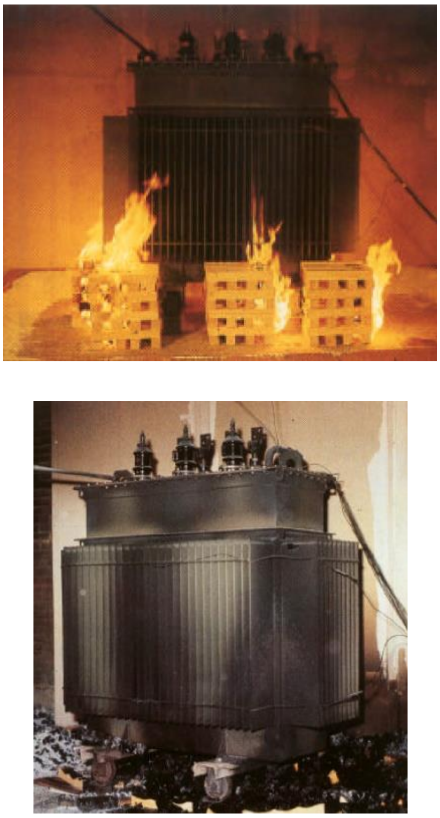

Fig. 4 - Transformer Victim Experiment (a) In Progress and (b) After

3. SUBSTATION AREA REDUCTION

Using mineral oil in transformers usually makes it mandatory to use either extended separation, fire walls, fire rated walls on nearby buildings, and often fire suppression systems where smoke or heat are a residual risk. The installation of these mitigation measures adds to project capital costs, and also leads to an increase in the spacing required around the transformers. The increased distances consequently require extra cable lengths, cable trenches, marshalling boxes, internal roads, etc as well as compromising the placement of any future equipment as part of later site developments.

Unsurprisingly, insurance companies have taken note of the use of less flammable liquids and the lower risk of using high fire point liquids as reflected in their advice.

For example, FM Global's Loss Prevention Datasheet 5-4, 2022 [8] outlines the measures required to ensure that risks are acceptable with different dielectric liquids. This includes a table of clearances between transformers and to adjacent equipment or structures. An example of an installation using these recommendations, for transformers containing 19,000 litres of liquid, typical of a medium power transformer, is shown in Figure 5. As the use of less flammable liquids considerably decreases the risk to nearby buildings and equipment, smaller separations can be used safely. If the transformer is also FM approved the clearances can be further reduced to 0.9m.

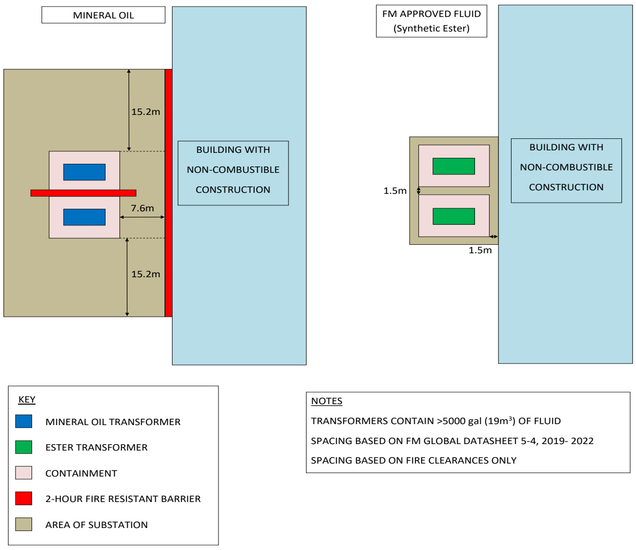

Fig. 5 - Example Transformer Installation to FM Global Guidelines

The risk reduction from less flammable liquids is also recognised by many international and domestic standards such as NFPA 70, IEC 61936-1, and AS2067. The National Electric Code, NFPA 70, allows similar reductions in spacing and the use indoors of transformers filled with "listed less-flammable liquids" up to 36kV, without the need for expensive transformer vaults. If a mineral oil transformer was specified, then a vault with a three-hour fire rating is mandated. IEC 61936-1 allows reduced spacing and protection for both outdoor and indoor transformers when filled with a K-class liquid (fire point greater than 300°C), while AS2067 adopted similar spacing and protection guidance as the FM Global Datasheet.

4. ENVIRONMENTAL RISK REDUCTION

Environmental legislation has become ever stricter over time and the environmental benefits of esters has extended their application. When evaluating any substance and requirements for a protection scheme for the environment, regulators will consider both the eco-toxicity and biodegradability. A substance, such as an ester liquid, which is both readily biodegradable and non-toxic will be viewed as less harmful. This may lead regulators to allow reduced concern for containment of this type of liquid over one which is not biodegradable or is potentially toxic to aquatic species.

There are some international standards that set out levels for biodegradation. For example, the IEC 61039 standard [9] assigns different levels for biodegradation of liquids as shown in Table 3, although the IEC standard only refers to the OECD 301C or 301F test methods, where the amount of oxygen used is measured. This is given as a percentage of the theoretical oxygen demand (ThOD), which is the amount of oxygen needed to totally break the substance down.

Classification	Biodegradation Result OECD 301C/F
Not Biodegradable	ThOD removed ≤ 20%
Slightly Biodegradable	40% ≥ ThOD removed > 20%
Well Biodegradable	70% ≥ ThOD removed > 40%
Fully Biodegradable	ThOD removed > 70%

Table 3 - IEC 61039 Biodegradation Classes

Different liquids used in the power industry have been tested for their biodegradability to one of the OECD 301 or equivalent OPPTS methods. It is important to take note of the period over which the biodegradation is measured, OECD 301 uses a period of 28 days and after this time the substance is assessed. Other methods can use longer periods, but a like for like comparisons should be made. The amount of biodegradation that occurs over 28 days in a laboratory cannot be compared directly to the amount of biodegradation in 45 days for example.

One direct comparison of different liquid types is shown in Figure 6, clearly demonstrating that ester-based liquids meet the readily and fully biodegradable requirements and will biodegrade much more rapidly than other liquids.

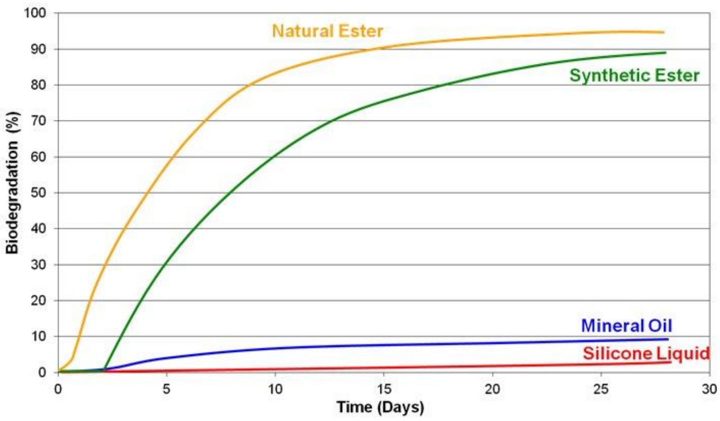

Fig. 6 - Comparison of Biodegradation Results OECD 301 [10]

Readily biodegradable substances are expected to biodegrade rapidly and completely, having little residence time to cause damage in the environment. Ester-based liquids are classified as non-toxic and through extensive testing and evaluation, such as used during REACH registration, esters have been checked rigorously to ensure that they do not pose a risk to aquatic life. Environmental safety has been studied in freshwater by the Bureau of Reclamation in the USA finding that esters did not produce a fathead minnow mortality at any of the doses tested [11]. The study asserted that the static tests done were also “extremely conservative in comparison to an environmental release downstream of a facility.” A further study by the Bureau of Offshore Energy Management, which concluded that synthetic ester could be recovered easily by mechanical means and is nearly 100% dispersible in the marine environment at the tested conditions [12, 13].

Ester liquids are being used increasingly for offshore transformer installations associated with windfarms where reduced requirements for environmental protection and fire mitigation measures over mineral oil can generate very significant savings in topside weight and therefore cost. Furthermore, ester liquids are enabling innovation regarding containment and management of environmental risks. One transformer manufacturer has reported the use of ester obviating the need for oil containment in the Poland’s lake district and operators such as National Grid are actively looking into the possibility to redesign substations for ester liquids and by removing deluge systems and simplifying the containment they could potentially deliver a more compact and lower cost substation [14].

5. ECONOMIC & SUSTAINABILITY BENEFITS ESTER DESIGN

The area required for an ester filled transformer substation could reduce by up to 90% if the design adopts the guidance in the FM Global datasheet. This switch can make further significant impacts on a substation design due to shortened distances for cable runs alongside the reduction in concrete needed for containment and the potential removal of fire suppression systems.

At the 2015 UN Sustainable Development Summit in New York the 2030 Agenda for Sustainable Development was adopted with its 17 Sustainable Development Goals. A switch to esters can influence Goal 11 Sustainable Communities and Cities through the reduction in risks from fire and to the environment highlighted above. When considering that the carbon footprint of concrete is about 72.5kgCO_2/tonne [15] and for copper it is 1.1 to 8.5kgCO_2/tonne [16] as well as the abiotic resource consumption required to produce these materials, the reduction in substation dimensions achievable when switching to ester filled transformers can be expected to lead to an improvement in the sustainability of a substation construction.

Procurement focussed project approaches may rule out ester filled transformers in favour of mineral oil equivalents, when a more holistic or total cost of ownership model might realise that the increased ester transformer capital is offset through the reduced civil infrastructure, elimination of fire suppression equipment, and shortened project timelines as well as lifetime savings, e.g. not needing to maintain fire suppression equipment. This same procurement lead thinking will also compromise the potential sustainability of the transformer and substation not only during the project phase but also throughout the remaining life of the asset.

In 2019, the benefits of switching to ester liquids for pole-mounted distribution transformers was evaluated by the Philippines utility Meralco [17]. This study included a cost benefit analysis that concluded that an average saving of 14% could be made by simply replacing the dielectric liquid, and a sustainability assessment that concluded that 1,776 tons of greenhouse gas emissions were avoided per annum. The results of their assessment justified a specification change for pole-mounted transformers to be ester filled.

SP Energy Networks of UK undertook a cost benefit analysis [18] that examined the case for choosing a synthetic ester filled transformer versus a conventional mineral oil filled transformer at 11kV secondary applications, 33kV primary and 132kV transmission. The analysis triggered by a policy change included fire walls and suppression, containment, capital and operational costs, and concluded that the absolute saving was around £235,000 per transformer for all classes.

It was identified that the amount of land needed for the substation could be approximately halved from a conventional GIS design with separate transformers by the use of compact switchgear and very close spacing of the transformers during the development phase of one particular project for National Grid in London. It was also clear that the risk of fire had to be all but eliminated to allow the proximity of the transformers to each other, the rest of the substation equipment and the land that was released for commercial and residential development. This coincided with the conclusions of a research project that gave National Grid the confidence to use synthetic ester for the three 240MVA 400kV transformers [19]. The land released has been developed to enhance the local area and capture significant economic benefits.

It is known that the use of esters can extend the life of the solid insulation in a transformer. Both IEC 60076-14 [20] and IEEE C57.154 [21] have published life expectancy curves for ester compared to mineral oils. The ageing rate of both natural and synthetic ester liquid filled systems have been shown to be equivalent and slower than mineral oil [22, 23]. This life extension in ester filled transformers not only enhances the financial benefits but adds to the sustainability credentials of an ester substation.

6. RETROFILLING

It is known that the risk reduction hierarchy can also be applied to existing assets, and it is possible to obtain similar fire safety, environmental, sustainability and economic benefits as for new installations using esters to retrofill existing mineral oil filled transformers. Indeed, retrofill projects can be driven by insurers concerned about the proximity of mineral oil transformers to critical or vulnerable assets, or by companies seeking to address business continuity challenges, demonstrate social corporate responsibility or manage available capital funds.

For example, the results of a pilot project at a rural substation in Australia were reported by Ergon Energy [24]. The site was faced with several constraints and the asset manager estimated there would be savings in both capital and operational costs. The project established that the cost for the new liquid, design modifications, resources for retrofilling and project timeframe with ester compared to the alternative containment, firewalls and site extension required for retaining mineral oil yielded a 6-7% saving (about AUD500,000). Additional benefits reported included increased fire safety and reduced environmental impact.

7. CONLUSION

The properties and behaviours of less flammable ester liquids in transformers can enhance fire safety, and their use can clearly address findings from multiple international surveys that mineral oil transformer fires are potentially catastrophic for people, assets, and business. The biodegradability and non-toxic nature of ester liquids present a significant environmental risk reduction, facilitating bioremediation and enabling innovation to containment requirements.

As both a potential victim of an event or trigger of one as a source, it is important for the fire and environmental hazards posed by transformers, and the options available to reduce the severity of the consequences and the likelihood of the hazard occurring in the first place to be thoroughly considered by substation designers and operators.

Although it is accepted that esters are more expensive than the traditional mineral oil option, adopting esters from initial design can yield significant project and total cost of ownership savings, and enable full lifecycle sustainability benefits for substations.

Similarly, retrofilling existing mineral oil filled transformers has been demonstrated to fit well with strategies for companies seeking to address continuity challenges, demonstrate corporate social responsibility or achieve significant risk reduction.

Where a zero-compromise approach is necessary, ester transformer fluids are proven in thousands of applications, such as oil & gas platforms, industrial sites, underground, nuclear facilities, and near environmentally sensitive receptors. As prevention is better than cure, the benefits of further adoption of ester transformer liquids will enable full lifecycle benefits, substation project design and delivery for transformer owners.

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Paper No. 9

CITY DATA REPOSITORY AND APPLICATIONS DEVELOPMENT FOR BUILT ENVIRONMENT

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ABSTRACT
In recent years, digital twin technology is being used increasingly to provide three-dimensional virtual replica of a city. A common digital twin platform can be set-up to integrate static and dynamics data of different urban facilities to enable visualization and representation of various aspect of city's information in a 3D environment. Combining with the latest state of the art technologies in 5G, photogrammetry, image processing, artificial Intelligence, sensing systems etc, a digital twin platform can enable a combination of both digital and physical world to support the whole life development, monitoring and analytics of various aspects in the built environment. This presentation will share the latest experiences and the approach of harnessing the digital twin platform to support data analytics, as well as planning and design for community, building and infrastructure.

1. INTRODUCTION

Realisation of the smart city can now be thought of as two-fold: data and application. Without data, applications will be unable to support decision-making processes. However, without application, data would be useless. The Digital Twin merges the data with application, where data is given meaning and can be manipulated to derive solutions.

1.1 The Digital Twin

What started out as a means of visualising parts in the aerospace industry has now become a staple in the construction industry. The digital twin's humble beginnings as a toolset for managing the performance of manufactured parts can now be commonly seen in the realms of construction, urban planning, city and building management. The ability to clone the physical city into the virtual environment and being able to manipulate this digital representation made it easier to simulate the impact based on urban designs and anticipate for changes caused by hazards. There is a visible evolution to the digital twin, starting with data capturing using embedded sensors and IoT, simulating existing and future environments, this technology has the potential to integrate upcoming AI and machine learning technologies to further support the decision-making process.

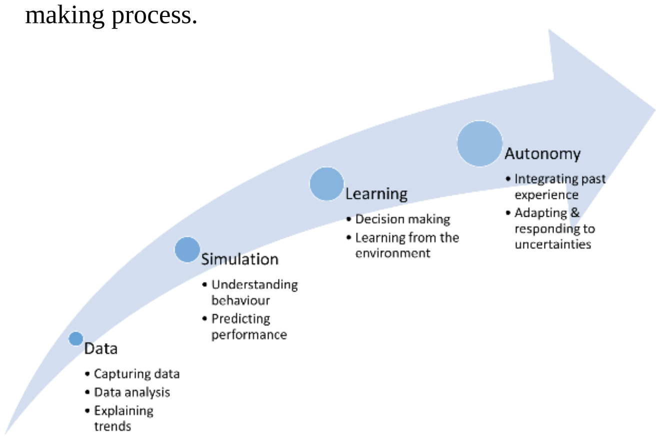

Fig. 1 - Adapted from "Digital Twin Maturity – Evolution of Digital Twins" [1]

Most notable country-scale Digital Twin, Virtual Singapore [1] has demonstrated the ways an accurate, reliable, up-to-date single source representation of the city can support management, planning and resilience efforts. The journey from data to virtual environment began from data. The Singapore Land Authority first planned for a national 3D mapping project, which served as a foundation to the digital twin, and included aboveground, underground and indoor spaces.

Hong Kong is also going through a similar journey, with the Government actively seeking to promoting smart city since 2017, though not specifically mentioning Digital Twin [2]. Hong Kong's Smart City Blueprint [3] and Hong Kong 2030+ [4] both paved way for the adoption of BIM, development of CSDI and 3D digital map, all components towards building a Digital Twin.

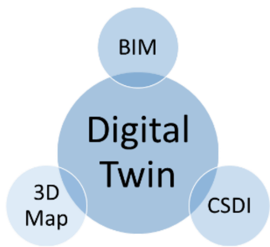

Fig. 2 - Components of Hong Kong's Digital Twin

[1] https://www.sla.gov.sg/geospatial/gw/virtual-singapore

1.2 Common Spatial Data Infrastructure (CSDI)

Spatial data supports virtually all applications across various sectors in the city. The CSDI becomes a single source of reliable data to encourage innovative solutions, application of city data, and creating value with data.

The establishment of a CSDI was first mentioned in 2017 under the umbrella of smart city and by December 2022, the CSDI was launched with over 500 spatial datasets from various government departments. See the HKSARG "Common Spatial Data Infrastructure portal and first 3D digital map open for use" [5]. It provided a platform to link people with data and provide reliable spatial data service. Data hosted on this platform are required to meet specific standards: Geo-tagging non-spatial data, which enables users to directly correlate with the physical alignment of the city; Data specification that ensures quality of data; Metadata about the data to provide information on the quality of data and data producer; Open and machine readable format to ensure data is not restricted to a particular application and equal access to all types of users; and Application Programming Interface (API) to allow software applications to easily share and gather data.

1.3 Building Information Model (BIM)

Capital Works Projects in Hong Kong is required to adopt BIM since 2019 to align with Hong Kong's Smart City Blueprint and support development of smart city. Prior to the mandatory adoption of BIM, the industry has developed BIM standards to promote its use.

A BIM Data Repository was set up to enable storage and sharing of BIM data and collaboration between works department on administrative and technical matters. The BIM Data Repository supports construction and building project lifecycle as well as enables update to 3D digital map with latest information. For improving convenience and as a standard for sharing, the "BIM Harmonisation Guidelines" [6] sets out how to structure the model, information required on BIM, and naming convention for BIM models to ensure the BIM is sharable and easy to use.

1.4 3D Map

The 3D digital map forms a major building block, facilitating sharing and opening government geospatial data and meeting the needs of digital map applications. Aside from providing a backdrop to visualise data, a 3D digital map allows users to virtually explore locations and with enough fidelity and level of detail, users can directly perform spatial analysis [7].

CityGML is the most common format adopted by cities to capture attributes and relations of the 3D model. It provides a standard model and mechanism for describing 3D objects and defines the levels of detail. A majority of European cities, such as Dresden, Berlin, Rotterdam, Lyon and Catalonia, as well as Singapore and New York adopted CityGML standards whereas cities in China mainly follow the Chinese National Standards, Industry standards or locally developed standards such as Sichuan, Nanjing and Chongqing. Hong Kong's approach to 3D mapping follows international trends, focusing on the use of open source data format, but also provides other typically uses.

2. HARNESSING DIGITAL DATA

2.1 Digital City Data Infrastructure

To integrate the physical world into the digital real, having a safe and reliable digital infrastructure is crucial. Data collected via sensors in the environment can be housed in the "sensing layer" which could be disseminated through the network into other platforms, infrastructure and applications.

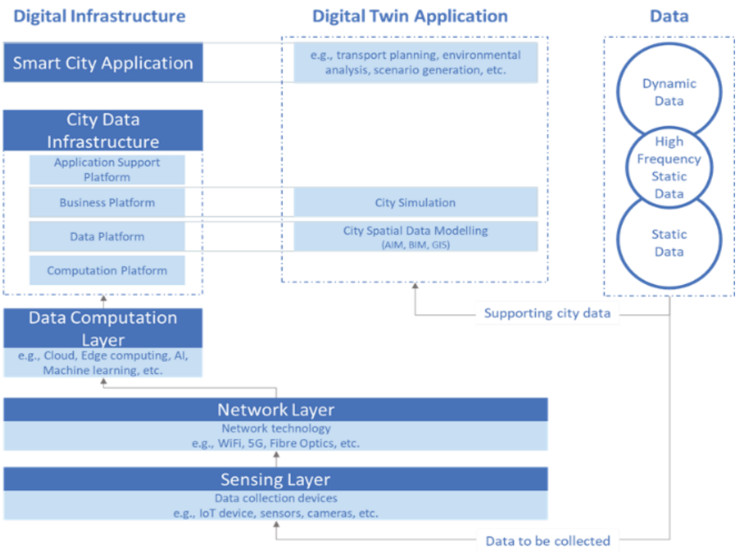

Fig. 3 - Digital City Data Infrastructure [8]

Ideally, data stored within the data warehouse would be standardised and in open format for it to be used by a variety of users and applications. Alongside data, there needs to be supporting applications to make use of data, and potentially contribute insights as data back into the data warehouse to be used by other applications or as foundation to further develop other analytical applications.

2.2 Built Environment Application Platform (BEAP)

The development of the Built Environment Application Platform was an essential component to support the use of spatial data. By tapping into the data and services provided through CSDI, it turns data into value-added solutions for shared use and to enable cooperation and co-creation between government, business sector, academia and the public.

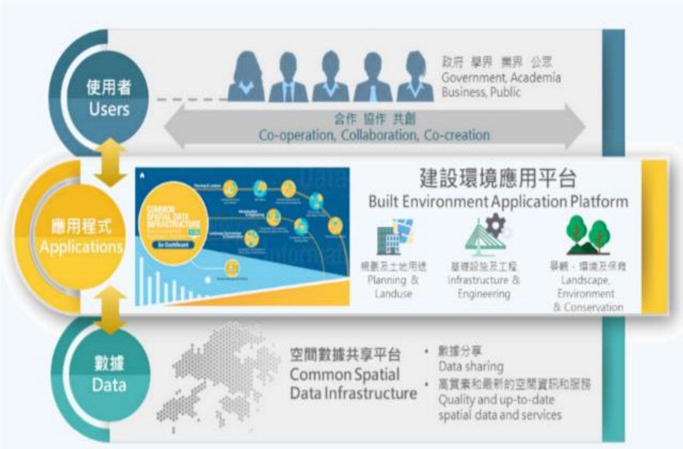

Fig. 4 - Creation of a Co-operate, Collaborate and Co-create Ecosystem through CSDI and BEAP [9]

The BEAP developed a set of territory-wide information product - actionable datasets - to enable applications to work responsively and seamlessly across the territory. It takes common spatial data from the CSDI to produce built environment specific spatial data. It also demonstrated how a collection of spatially and digitally enabled built environment applications and service embedded with actionable and dynamic data facilitated and enhanced the decision-making process by taking on a Digital Twin approach for interacting with the data.

Applications for Planning and Landuse (including Landuse Monitoring and Analytics platform, Site Search for platform, Scenario Generation for Planning and Development, Public Facilities and Open Space Analysis tool, Connectivity Analysis tool), Infrastructure and Engineering (including Visualisation and Analysis of Underground Space and Utilities, Compliance Checking tool for building plans), Landscape Environment and Conservation (including Visualisation and Analysis of Urban Green Infrastructure), and other applications (such as Built Environment Information Dashboard and Workflow Management Platform) aided the relevant government departments to provide efficient services to the land development process. Among them, three prototype applications, namely 'GIC Facilities and Open Space Analysis', 'Site Search' and 'Visualization and Analysis of Urban Green Infrastructure', were chosen as 'Quick-win Projects' for implementation in the short term.

The BEAP was internationally recognised, having won the 2020 International Data Corporation (IDC) Smart City Asia Pacific Awards under the Urban Planning and Land Use category, and a merit award at the Smart Cities Awards at the 2021 World Information Technology and Services Alliance (WITSA) Global ICT Excellence Awards, out of 100 entries worldwide.

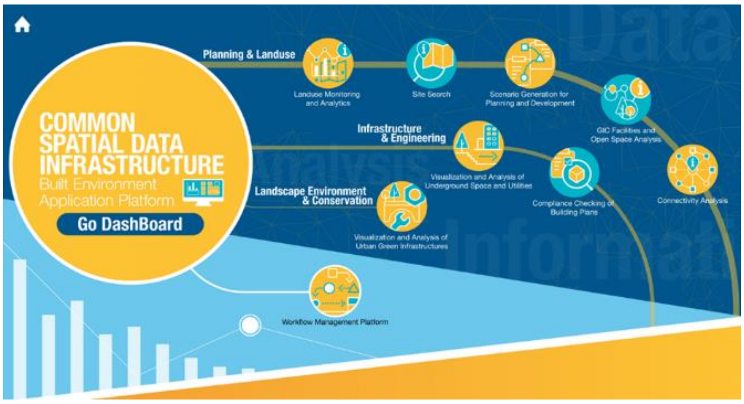

Fig. 5 - BEAP and 10 Use Cases

2.3 Hong Kong's first 3D Digital Map

The foundation of a Digital Twin could be found within a 3D Digital Map. It is set to act as the base map and container for the CSDI, covering both external areas, such as the terrain, and internal areas of the building. Data populating the 3D Digital Map for Hong Kong stems from a variety of sources, including traditional topographic survey, aerial imagery, LiDAR scans, mobile mapping, and close-range photogrammetry. While the full-fledged version will be covering the entire territory and providing a high photorealistic city mode, the pilot trialled in Kowloon East, spanning an area of 27 sq. km with around 6500 buildings and 284km of roads, set the basis for technical requirements including model standardisation and quality control.

The dense urban area of Kowloon East provided a challenge for creating the 3D map, with tall high-rise and tightly packed buildings. Aerial imagery may only capture the tops of buildings while ground-based mobile survey methods may only capture the base. The combined use of surveying techniques allows the production of detailed single models for buildings as well as tile-based model to visualise a building with its surroundings. Mapping Kowloon East into 3D took on two-staged approach, with Stage 1 focusing on the creation of individual models for buildings in infrastructure into formats commonly used, such as 3ds Max, FBX, gITF, DAE and KML; creation of tile-based models for visualisation into formats such as OSGB, OBJ and Cesium 3D tiles, and setting out the standard as well as refining the process of creating CityGML models to for ease of data sharing. Stage 2 focused on creating CityGML models for individual building and infrastructure while also extending the 3D Digital Map beyond the pilot area.

2.4 From Maps to Navigation

To give meaning to the 3D Digital Map requires application. Typical applications include urban planning, emergency management, environmental monitoring, navigation and transportation. The inclusion of both indoor and outdoor data into the 3D

Digital Map allows for seamless navigation between indoor and outdoor environments. Combining this information with ubiquitous positioning technologies provided accurate and reliable positioning services to support smart initiatives [10].

Currently there are many individual solutions for indoor and outdoor positioning in the market. Individual site owners may opt for certain technologies, such as use of Bluetooth sensors or Wi-Fi fingerprinting techniques. Datasets are rarely interoperable as definitions and structures differ. Sites may bring in 3D map data from outside, but rarely can outside source use site information, implying that trying to position and navigate between indoor and outdoor environments of different sites may become broken and may vary in accuracy and precision. To effectively provide ubiquitous positioning services, an infrastructure to bridge together different stakeholders and technologies applied in sites alongside standards to guide data dissemination is necessary.

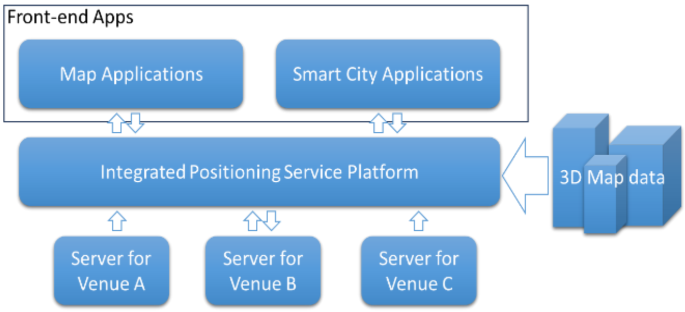

Fig. 6 - Infrastructure for Ubiquitous Positioning

Not all sites are willing to share information, as such, a service platform (e.g. lookup server) functions as an operator connecting the sites together and allowing the exchange of data. Developers can make use of this type of service to create applications on the front end without having to approach individual site owners for data access. Information can be brought in from external sources to augment data shared by sites and applied into particular applications.

3. MANAGING CITY DATA

Data is only useful if it is relevant, which can be in terms of purpose, timeliness or location. It is possible that not all data collected are useful or relevant. Collected data are often cleaned and classified to ensure they are useful to potential users. With the advent of BIM, it is possible to integrate BIM data directly into 3D map, providing there is standardisation to structuring. Map attributes can be updated using street view images or similar to update basic information such as building names [11]. Drone technology can be applied to capture building facades to update 3D building textures.

The rich data environment gives rise to a diversity in data quality, format, and means for data security and privacy. Existing location privacy protection strategies fall into four categories: regulatory, privacy policies, anonymity, and obfuscation [12] with the former two strategies mainly aimed at preventing the attacker from obtaining the location information of others through political efforts of mechanism designs and the latter two aimed at preserving location privacy technically. While an individual's data may be protected by local regulations and policies for data privacy, protection on the data themselves is also crucial to enable the use of data in planning and facilitate Smart City applications. Data encryption is typical to ensure transmission between source of collection and data storage is protected while accessibility management tracks and audits the physical usage of data.

4. DIGITISING FOR FUTURE

The evolution of technology brought about a change in the way data can be collected, disseminated and used. Spatial data, such as maps, evolved from being used as a source of background information, to visual backgrounds for supporting designs, and now imported as 3D data for analysis. Cities have also evolved, with sensors being embedded into the streetscape to collect data to facilitate city management. Connection between the digital city—the Digital Twin—and the physical world is therefore indispensable for the future.

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Paper No. 10

UNLOCKING DIGITAL POWER IN CONSTRUCTION AND BUILT ENVIRONMENT

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UNLOCKING DIGITAL POWER IN CONSTRUCTION AND BUILT ENVIRONMENT

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ABSTRACT

As we all know, the engineering & construction industry is one of the world's least digitized sector. Many companies spent several years of time and countless sum on trailing new software platforms and ways of working. However, dozens of attempts to streamline projects with digital solutions, such as 5D BIM, had failed to deliver. A few had succeeded in the pilot phase, but the company had struggled to apply those solutions at scale. Site and office workers grumbled about having to adopt yet more new technologies - before abandoning them and returning to their old ways of working. Overall, projects still hit delays and ran over budget as frequently as before, and productivity had barely budged upward. Referring to McKinsey report and analysis, the following characteristics of the engineering & construction industry make digital transformation particularly challenging: -

- Fragmentation in nature
- Lack of Replication
- Transience
- Decentralization

Swire Properties (SPROPS), one of major developer in Hong Kong, tried to break through these challenges and is conducting digital transformation in all stages of project development by introducing standardized BIM specification and requirement, enterprise-level common data environment, smart construction platform and digital twin. Those initiatives are targeted to streamline our design process, productivity, safety and maintainability and operation energy efficiency and final enhancement on user experience.

1. INTRODUCTION

1.1 Challenges on Digitalization at Construction Industry

Referring to Industry digitalization index (Figure 1) conducted by McKinsey Global Institute, the engineering & construction industry is one of the world's least digitized sector. Although there has been progress towards digitization, the construction industry still trails behind compared to other industries like retail and manufacturing. Many companies spent several years of time and countless sum on trailing new software platforms and ways of working. However, dozens of attempts to streamline projects with digital solutions, such as 5D BIM, had failed to deliver. A few had succeeded in the pilot phase, but the company had struggled to apply those solutions at scale. Site and office workers grumbled about having to adopt yet more new technologies - before abandoning them and returning to their old ways of working. Overall, projects still hit delays and ran over budget as frequently as before, and productivity had barely budged upward.

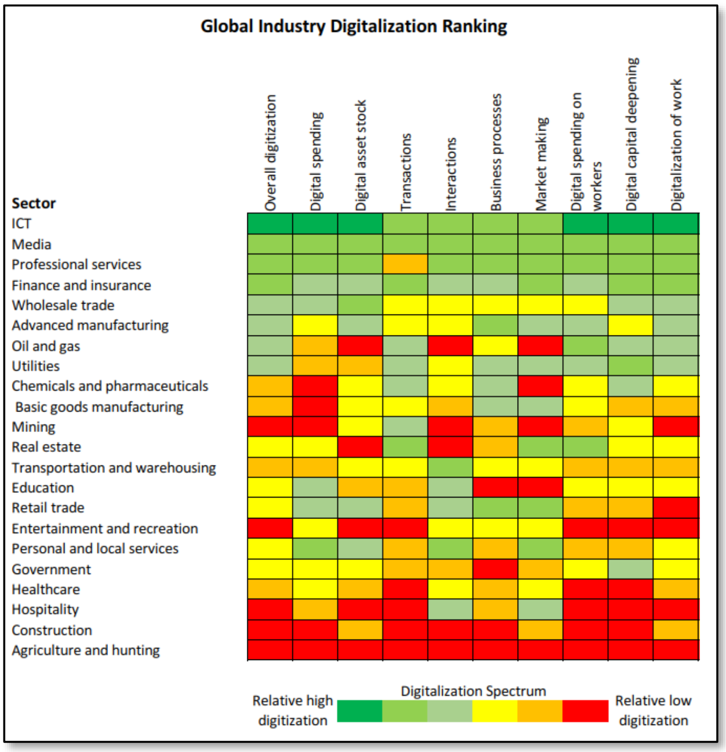

Fig. 1 - Global Digitalization Ranking among Different Industry. (Reference to McKinsey Global Institute Industry Digitization Index, 2017)

Referring to McKinsey report and analysis, the following characteristics of the engineering & construction industry make digital transformation particularly challenging: -

- Fragmentation in nature

Construction projects are typically fragmented along the value chain, with specialists generally operating in one or a small number of disciplines. Also each step in the value chain involves multiple layers of contractors and subcontractors. Implementing digital solutions across a project thus requires coordinating changes among organizations - a task that is especially hard, given the short-term and often adversarial nature of construction contracts.

- Lack of Replication

Construction projects are nearly always one-of-a-kind endeavors, with unique requirements that necessitate bespoke design and delivery approaches. Since these approaches are seldom repeated, it is harder to introduce changes across numerous projects, as full-scale transformation requires. The exceptions are multiyear major projects, on which companies can establish processes and reinforce them over time.

- Transience

Ordinarily, a new construction project will involve a new set of organizations working together. Project teams, too, are rarely consistent. Contractors face similar challenges at the enterprise level, at which workforce turnover is high. Transience at the project and company levels makes it difficult for engineering & construction companies and their subconsultants and subcontractors to establish new ways of working and build capabilities that carry over from one project to the next.

- Decentralization

Large companies tend to be highly federated, with business units and divisions following their own processes rather than standardized ones. Individual projects take place at sites that are far from a company office. And few sites are conducive to teaching workers how to work in new ways or use advanced technology.

These characteristics of the engineering & Construction industry make it harder for companies to develop digital solutions that they can apply to multiple projects.

1.2 Swire Vision

Swire Properties (SPROPS), a major developer in Hong Kong, tried to break through these challenges and is conducting digital transformation in all stages of project development by introducing standardized BIM specification and requirement, enterprise-level common data environment, smart construction platform and digital twin.

Those initiatives are targeted to streamline our design process, productivity, safety and maintainability and operation energy efficiency and final enhancement on user experience. Finally, these initiatives should be established a comprehensive building lifecycle digitization shown in Figure 2.

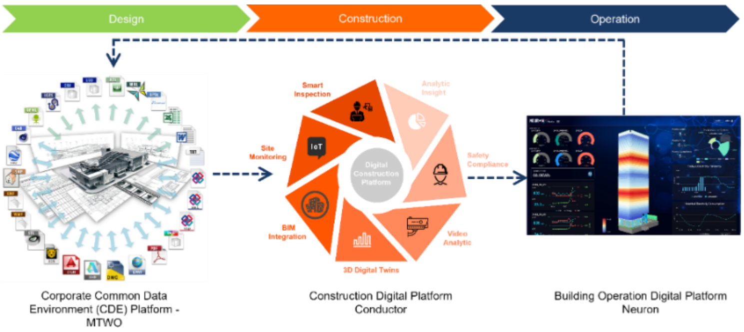

Fig. 2 - SPROPS Vision on Building Environment Lifecycle Digitization

2. IMPLEMENTATION

2.1 Standardization on Enterprise Level

As we all know, BIM acts as the core technology in digitization in Engineering & Construction industry.

Type	IDPD Standard / Year	IDPD 1.0 Hybrid IDPD		IDPD 2.0 Integrated IDPD		IDPD 3.0 LEAN IDPD	IDPD 4.0 AI IDPD
		2020	2021	2022	2023	2024	2025-2030
Investment Properties	Office	- >600k sqft - Schematic Design stage – Construction Stage	- >300k sqft - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Operation Stage	- All Projects - Schematic Design stage – Operation Stage
	Shopping Centre	- >600k sqft - Schematic Design stage – Construction Stage	- >300k sqft - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Operation Stage	- All Projects - Schematic Design stage – Operation Stage
	Hotel / Apartment	- >600k sqft - Schematic Design stage – Construction Stage	- >600k sqft - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Operation Stage	- All Projects - Schematic Design stage – Operation Stage
Trading Properties	Residential	- Club House (for project > 600K sqft) - Special area such as PTI - Schematic Design stage – Construction Stage	- Club House (for project > 600K sqft) - Special area such as PTI - Schematic Design stage – Construction Stage	- Club House (for project > 300K sqft) - Special area such as PTI - Schematic Design stage – Construction Stage	- Club House (for project > 300K sqft) - Special area such as PTI - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Construction Stage	- All Projects - Schematic Design stage – Construction Stage

Fig. 3 - SPROPS BIM Adoption Matrix

Swire, as pioneer in BIM adoption in Hong Kong, has rollout BIM adoption matrix along Swire projects and roadmap of BIM usage since year 2020. See Figures 3 and 4. BIM adoption matrix governs the type of nature of project to adopt BIM as design and project control tool while roadmap on BIM usage clearly identifies the application of BIM and progressive digital technology development.

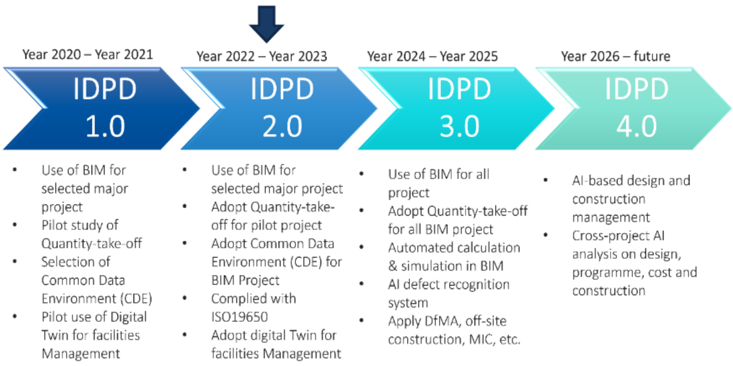

Fig. 4 - SPROPS BIM/IDPD Roadmap

Besides these two key governance documents, Swire also published their BIM specification in both consultancy agreement and main contract in Year 2020. We have clearly defined the role, responsibility, scope of work and deliverables for each consultant, designer and main contractor in BIM specification. In principle, all consultants shall prepare their own discipline BIM model and delivery a coordinated BIM model as their design package for tendering. The main contractor shall keep updating BIM model until the completion of projects.

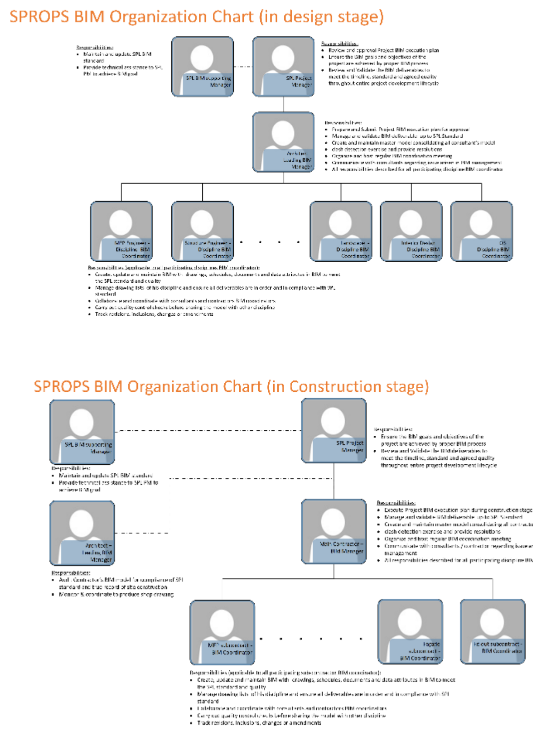

Fig. 5 - SPROPS BIM Organization Chart in both Design and Construction Stage

These control documents including BIM adoption matrix, roadmap on BIM usage and BIM specification standardizes BIM standard across all Swire projects. Such standardization allows all Swire staff and business partners familiar with Swire standard and requirement in BIM.

2.2 Common Data Environment (CDE) in Enterprise Level

Many organizations including Swire Properties recognise how a CDE can enable more effective collaboration across project team. A CDE forms a single source of information which creates confidence and helps to build trust among the project participants to capture a complete record of the project with a unique data ownership model that eliminates barriers to collaboration, increasing adoption and data sharing across the entire project team. This trust results in greater adoption, which yields more project data and insights. It also creates an unalterable audit trail, helping to reduce disputes and drive faster resolution.

Integration of BIM with CDE platform can further enlighten digital power across project team and enhance project participants.

With BIM adoption and implementation standardized in SPROPS, MTWO is appointed as CDE platform for all SPROPS projects since year 2021.

MTWO is a cloud base platform which provides the following functions: -

- BIM collaboration tool
- Project budget & cost control
- Quantity-take-off
- Contract document control with all SPROPS in-house workflows incorporated
- Variation order control with all SPROPS in-house approval procedures incorporated
- Construction planning and programme
- Quality control
- Performance dashboard

2.2.1 BIM collaboration in CDE platform

MTWO has full capacity on BIM collaboration. Their folder structure is fully flexible in the collaboration workflow proposed under ISO19650 “Organization & digitalization of information about buildings and civil engineering works, including building information modelling (BIM)”. With MTWO environment, BIM manager can conduct a comprehensive clash analysis among various BIM models. The comprehensive software tool for comment, mark-up and issue creation on BIM model and issuance of Clash analysis report during collaboration is available for use. The BIM manager is able to appoint particular consultant to update their BIM model with prescribed workflow and predefined timeframe.

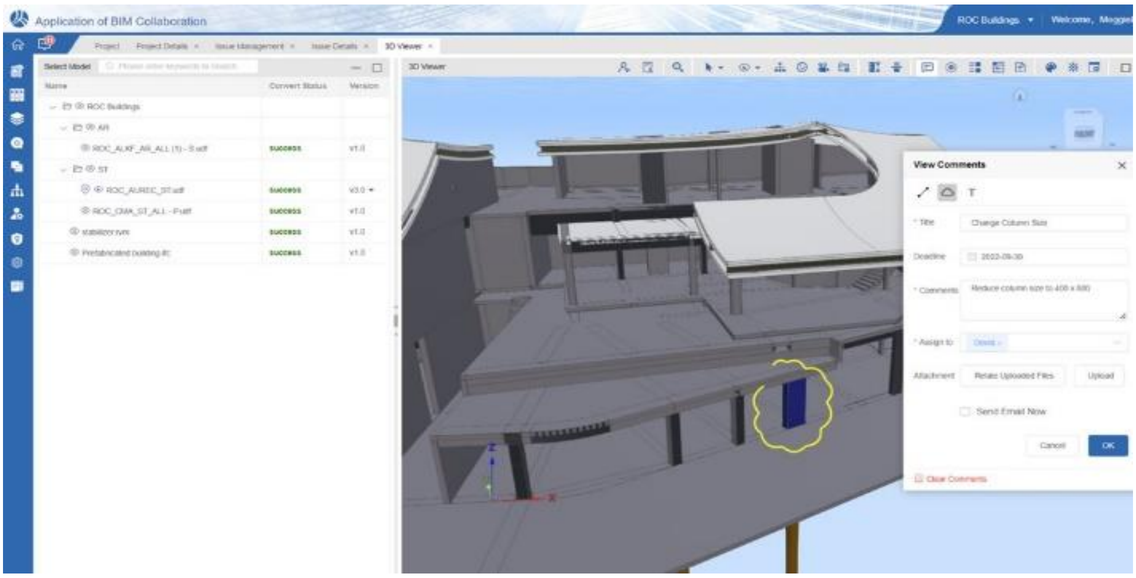

Fig. 6 - Snapshot on BIM Collaboration - Issuance of Comment on BIM Model

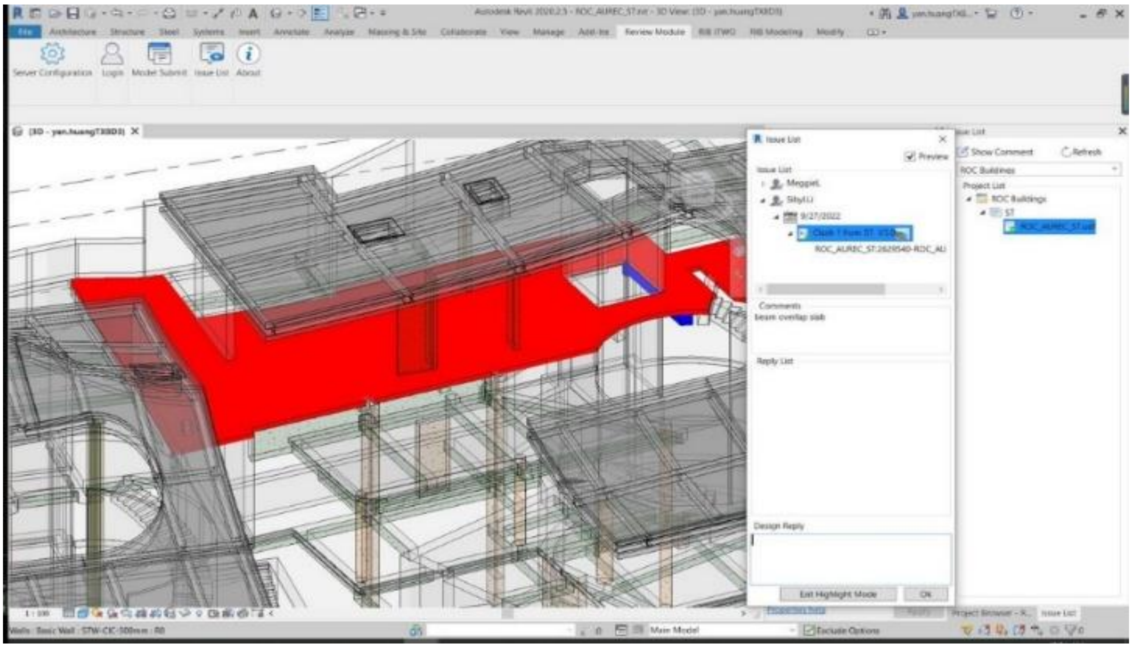

Fig. 7 - Snapshot on BIM Collaboration Plug-in Tool in REVIT

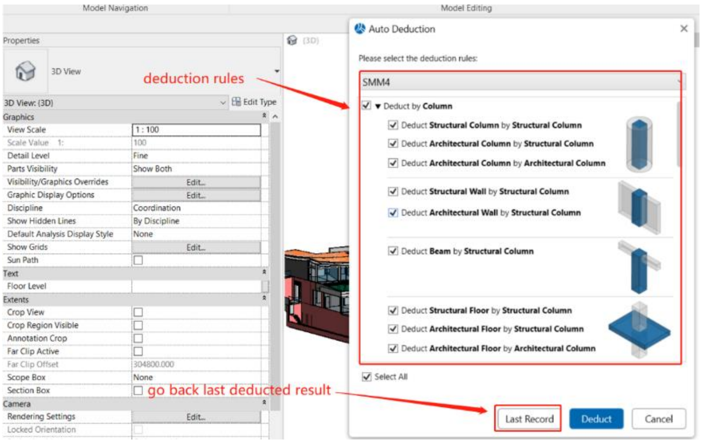

Fig. 8 - Sample of Automatic Function in REVIT Plug-in Tool

Besides these typical functions, MTWO provides plug-in tool in REVIT environment which facilitates all comment/issue/mark-up synchronization with actual REVIT model. This function enhances the productivity efficiency on BIM collaboration. In addition, it also provides additional automatic function on BIM model amendment after clash analysis. For example, MTWO plugin provides automatic deduction rules which can eliminate/resolve clashes between various BIM models.

2.2.2 Cost and programme control

In MTWO environment, BIM models are created and coordinated with SPROPS standard which can allow quantity take off on the model and create the bill of

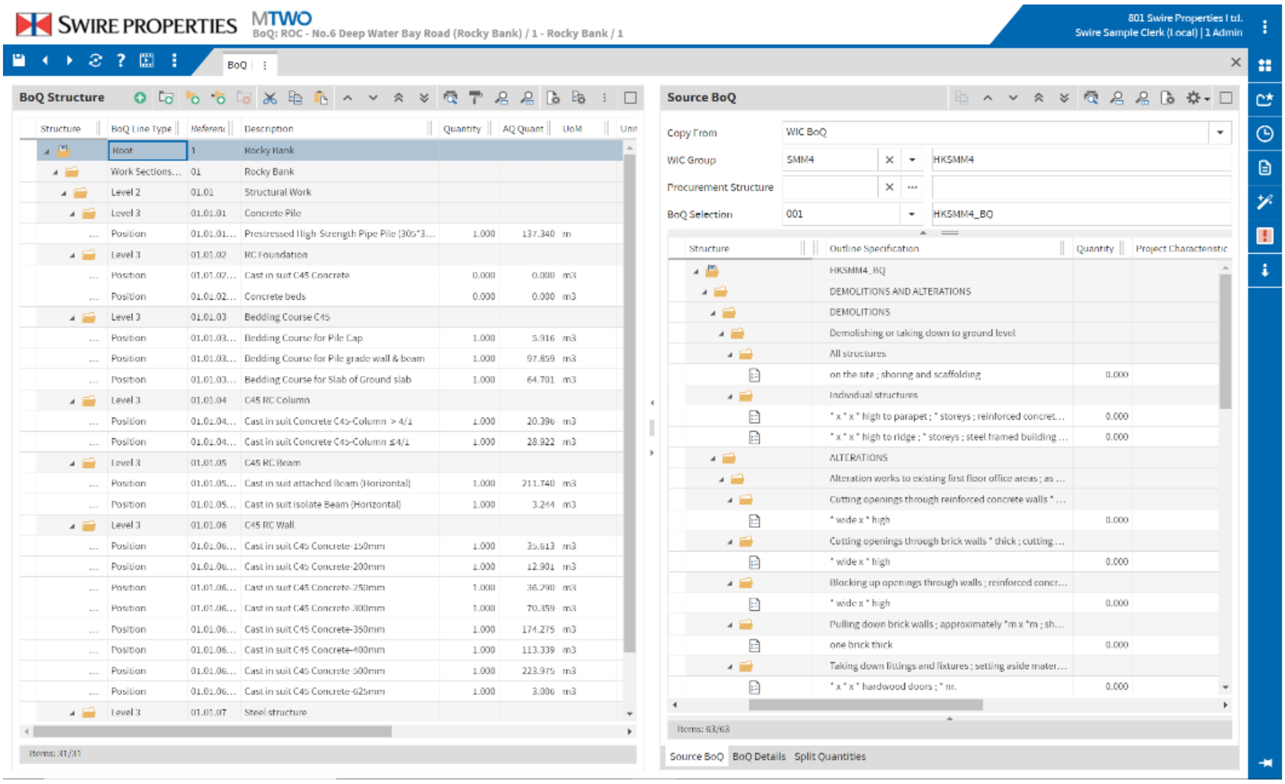

Fig. 9 - MTWO Creating Bill of Quantity

quantity which can enhance the quality of work and shorten the production time.

MTWO also allows the users to import the whole construction programme into the system and link with BIM model. 4D simulation on construction planning can be generated for construction programme risk management. Together with cost information, MTWO can also generate the whole simulation of construction with cashflow forecast. It not only provides detailed information on construction activities planning but also provides financial information on cost control.

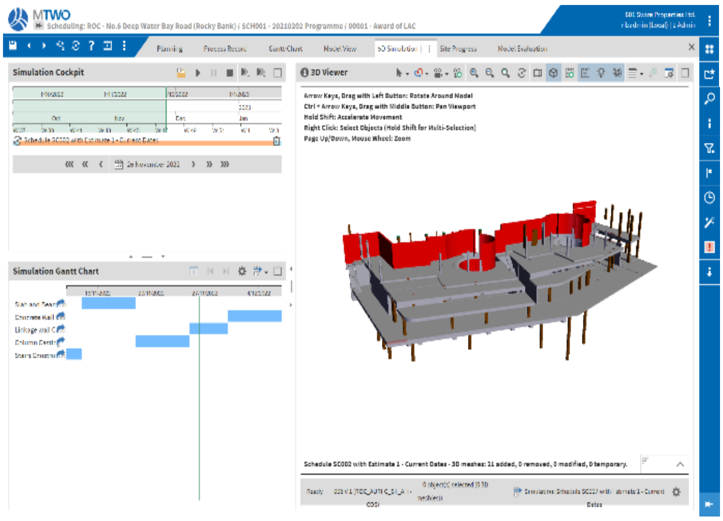

Fig. 10 - Construction Programme Simulation

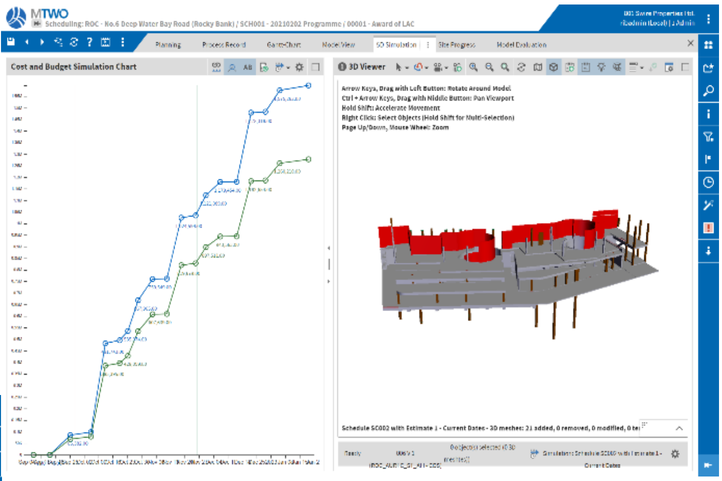

Fig. 11 - Construction Programme Simulation with Cashflow Forecast

2.2.3 Variation order control & Contract Document control

Variation order or architectural instruction is always a key topic on programme management and create a critical issue to threaten the programming control and budget control. In MTWO environment, SPROPS standard procedure on issuance variation order are incorporated in which all information on issuance of each variation order is properly recorded in the system. Instant review on cost implication on the overall budget can be performed for cost control and audit trail record can also be kept for future internal review.

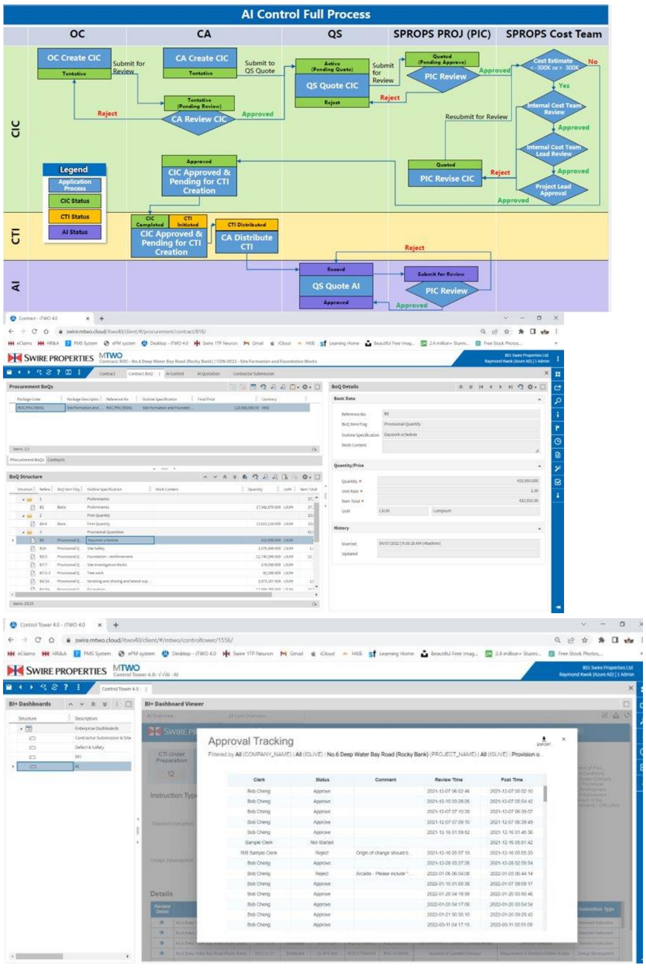

Fig. 12 - SPROPS Variation Order Workflow Incorporated into MTWO/Instant Review on Cost Implication after Issuance of Variation Cost/Sample of Audit Trail

Similar to variation order control, the workflow on contractor submission/consultant document are also incorporated into MTWO. The submission/document can link up onto building element in BIM model which allows locating the area easily in the model. The project development team can comment/reply/approval all submissions directly onto BIM model. The project manager also allows to oversee the project document and its approval status effectively. The comprehensive audit trail on each submission is fully recorded into the system.

2.2.4 Project performance dashboard

MTWO forms single source of information for each SPROPS project from design stage to construction stage. Project manager can extract all valuable information from MTWO platform to evaluate project performance, cost expenses against budget, site progress compared construction programme and various dashboard.

Beside single project level, the performance for various projects within enterprise can also be evaluated effectively.

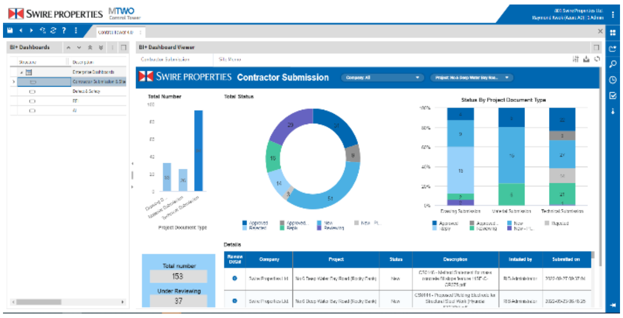

Fig. 14 – Sample of Performance Dashboard

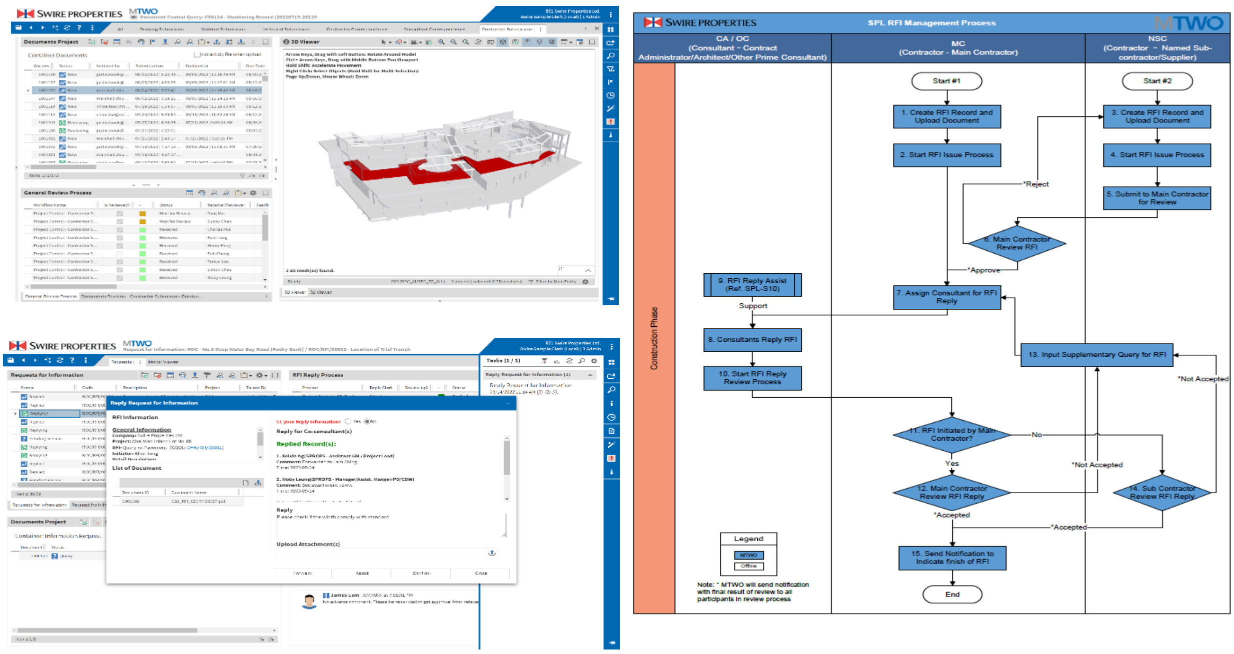

Fig. 13 - Contractor Submission Link onto BIM Model/SPROPS Standard Workflow on Contractor Submission incorporated into MTWO/ Sample of Contractor Submission Reply

2.3 Conductor as Smart Site Platform

To resolve the unpreferable nature of construction work including lack of replication and transience, SPROPS works together with Arup to develop a digital revolutionizing construction platform - Conductor.

Conductor integrates with BIM to enhance the building life cycle. It offers the Smart Site Safety System, Digital Work Supervision System, and Green Construction. The integration bridges the design and operational stages, enabling seamless collaboration and improved decision-making. Conductor leverages BIM data during the design stage for aligned design and material information. In the operational stage, it accesses BIM's repository for effective facility management. This real-time synchronization ensures stakeholders having up-to-date information, reducing errors and improving project coordination. Conductor and BIM create a powerful partnership, driving efficiency and success in the construction industry.

2.3.1 Smart site safety system

Conductor's Smart Site Safety System is a ground-breaking feature that prioritizes worker safety and reduces the risk of accidents on construction sites. By leveraging advanced sensors, real-time video analysis, and artificial intelligence, it constantly monitors the site environment and alerts workers and supervisors on potential hazards. From identifying unsafe conditions to tracking personnel movement, Conductor ensures proactive safety measures are in place, leading to a significant reduction in accidents and injuries. The integration with BIM allows Conductor to access critical safety information from the digital models, enabling precise hazard detection and prevention.

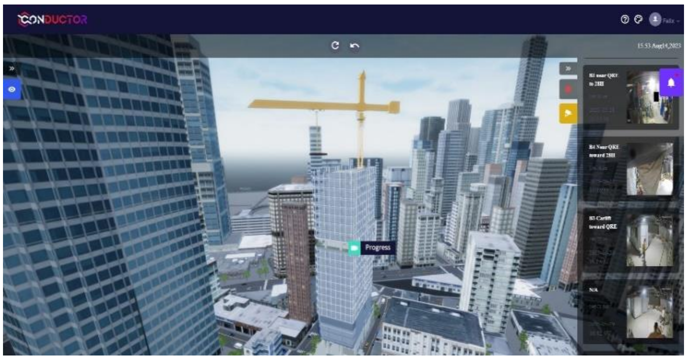

Fig. 15 - Sample of Conductor with Real Time AI Analyst CCTV

2.3.2 Digital work supervision system

Efficient project management is the cornerstone of successful construction endeavors, and Conductor's Digital Work Supervision System provides a comprehensive solution. By digitizing and automating various aspects of work supervision, this system eliminates manual processes, reduces errors, and enhances productivity. Real-time progress tracking, automated task assignment, and streamlined communication enable seamless collaboration among project stakeholders. With BIM integration, Conductor gains access to accurate and up-to-date project data, allowing supervisors to make informed decisions based on a holistic understanding of the building's design and construction status.

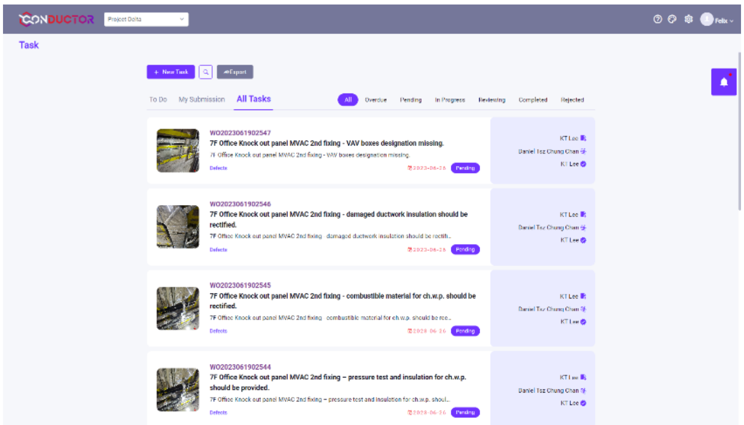

Fig. 16 – Sample of Defect Tracking and Reply Trail Record

2.3.3 Green construction: sustainable building practices

In an era where environmental responsibility is paramount, Conductor's commitment to green construction sets it apart. The platform promotes sustainable building practices by integrating eco-friendly features and monitoring environmental impact. From optimizing energy consumption to managing waste and water resources, Conductor ensures that construction projects align with sustainability goals. BIM integration enables Conductor to leverage the rich data stored in the digital models, facilitating precise analysis of energy efficiency, material usage, and carbon footprint, thus empowering construction professionals to make informed decisions that minimize environmental impact.

Fig. 17 - Sample of Dashboard on Environmental Performance on Construction Site

2.3.4 Linking BIM with actual site activities

One of the most significant advantages of Conductor's integration with Building Information Modelling (BIM) is its ability to bridge the gap between the design stage and the construction stage of a construction project. Traditionally, these two phases have operated in relative isolation, leading to inefficiencies and information loss. However, with Augmented Reality (AR) technology incorporated into tablet & wearable devices, Conductor is now working with BIM in tandem. The construction team can superimpose coordinated BIM model into the construction site with actual scale in which the instant information can be accessible seamlessly. Thus, the construction industry can achieve a holistic and integrated approach that maximizes the benefits of digitalization.

Fig. 18 - Snapshot on Tablet Screen for Superimposed BIM into Actual Site

2.4 Digital Twin for Built Environment

A digital twin is a digital representation of a physical object, system, or process. It can be a virtual replica of everything from a simple machine (or a not-so-simple spacecraft) to an entire city. The idea is to create a digital representation that mimics the real-world behaviour of the physical counterparts, providing opportunities to simulate and analyse performance, maintenance, and potential future scenarios.

As buildings become larger, more complex, and more integrated, the need for a digital twin that can provide an accurate real-time overview of the facility increases. An indoor mapping platform solves this challenge by providing building owners and occupants with an always up-to-date map of the facility, points of interest, and important information on building performance, usage, and optimization opportunities. As long-term partnership with Arup, SPROPS initialized digital twin idea since 2018 and worked with Arup to develop Neuron as digital twin for built environment. Empowered by the latest IoT, AI and Big Data technologies, Neuron Digital Platform serves as the foundation for the built environment and engineering plants to consolidate and connect data from disparate equipment and devices, providing customized insight and machine learning models to resolve and optimize engineering problems.

2.4.1Creating virtual environment with BIM-based digial twins

The integration of spatial data (BIM, GIS) with building real-time operation data from BMS system and IOT devices empowers a digital twins virtual environment to reflect the building environment with comprehensive visualization and fluent user experience.

Through a flexible user interface, the detailed information such as the energy performance, operational status, CCTV footages, resources distribution, etc. would all be accessible within a click. BIM/GIS's application in Neuron would provide a user-friendly building management interface and engage the operators with an immersive monitoring experience.

Fig. 19 - Snapshot on Neuron Screen

By navigating through the 3D digital twin model, detailed assets information such as cable trunks, pipe routes, lightings etc. can be visualized by layers. This function help building operator to swiftly understand the structure and hidden details of the building and improve the monitoring and maintenance process in future.

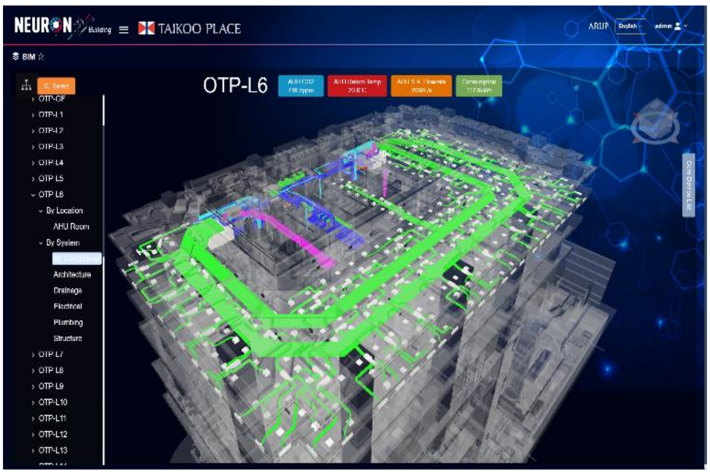

Fig. 20 - Snapshot for BIM Environment within Neuron

2.4.2 Integration of building system data & operation information

Neuron Digital Twin can connect data from different systems and combine it with the model to realize its visualization. This function can save developers a large amount of customized development work requested by the cross-system data connection in the process of digital twin implementation.

With Neuron scene editor, users can configure the front-end data dashboard and model component data resources and develop the business logic based on the interaction of data and model driven by their business needs. After configuring the data source, users can display the data in the corresponding locations on the scene with just a few simple mouse clicks. This easy operation largely reduces the cost and threshold of applying the digital twin, fully maximizes the user's flexibility on data selection and usage, releases most the digital twin value to the operator practical work.

To make use of BIM for building lifecycle management, the components data are managed through COBie (Construction Operation Building Information Exchange), which are further integrated with BMS data, equipment basic information including O&M manuals, design drawings and maintenance record in the database. Operators can locate core devices through shortcut buttons, specific parameters and statistics for the item to be visualised through interactive and responsive dashboards, making building performance data more transparent and insightful.

2.4.3 AI & ML on energy optimization

With numerous operation data collected via BMS system, smart metering system and IOT network, neuron developed with artificial intelligence and machine learning engine in chiller plant and AHU plant which offers automatic energy optimization function in those systems. It provides additional energy saving opportunity.

Fig. 21 - Snapshot for AI & ML Advice on Chiller Plant Operation after Energy Optimization

3. CONCLUSION

The digitalization of the construction & building industry is the general trend. New digital technologies such as BIM, common data environment (CDE), smart site platform and digital twin will cause revolution in this industry by enhancing quality of work, productivity, site safety and operation practice. They also provide additional opportunity in environmental performance such as minimizing resource for construction, energy consumption in building operation, etc.

These new technologies can also collaborate with each other and further improve the building lifecycle. Considering all the data are already standardized, the information from design stage in CDE platform can merge into smart site platform for construction and then flow into digital twin for operation.

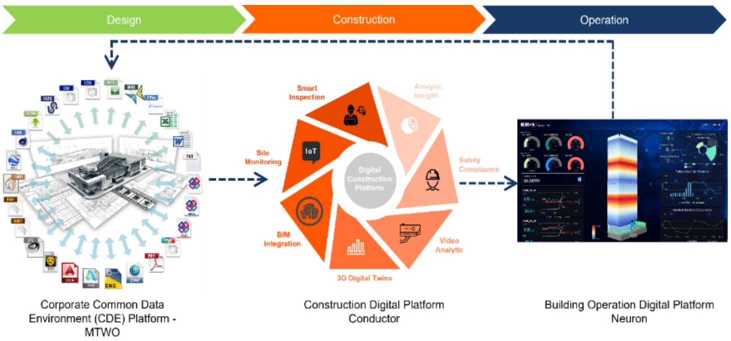

Fig. 22 - Data Flow from Design, Construction to Operation

In the future, we also foresee the information feedback from operation to design which form a closed loop of information throughout the whole building lifecycle. Imagine all data stored in CDE platform, smart site platform and digital twin, it eventually forms a data lake for the whole building. With technology in knowledge management and artificial intelligence, we can hunt all the useful knowledge such as potential design problem, potential delay in certain site activities, actual cost implication on design changes, frequency of system breakdown, etc. from the data lake and feedback into design stage of another new project. That knowledge can help to eliminate all the potential problems and enhance the quality of building.

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