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Demystifying District Cooling Systems in Hong Kong

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Abstract

According to the Hong Kong's Climate Action Plan 2050, the Government strives to achieve carbon neutrality before 2050 and one of the key strategies is "Energy Saving and Green Buildings". District Cooling Systems (DCSs) which have been widely adopted overseas are essential energy efficient infrastructures for New Development Areas (NDAs) to support this strategy. Hong Kong's first DCS has been put into operation in the Kai Tak Development since 2013. This paper aims to promote the benefits of DCS in terms of reliability and sustainability as well as demystify its applications with an in-depth elaboration on the misbelief on service risks. Strategic and holistic considerations in design, construction and operation of DCS can outperform other individual air-conditioning systems installed in individual buildings in a more reliable and sustainable manner. Moreover, trends in technological advancements such as artificial intelligence, global navigation satellite system, new refrigerants, etc. will also be covered in this paper.

1.0 Introduction

DCS is a low-carbon and energy efficient infrastructure designed to promote energy conservation and efficiency. It functions as a district-wide air-conditioning system, distributing chilled water from a central source to multiple buildings within a designated area in a reasonable distance. The major components of DCS include:

(a) Central chiller plant with the associated circulation pumps;
(b) Seawater pipework and the associated pumps (for seawater-cooling only);
(c) Fresh water cooling towers (CT) for heat rejection and the associated condensing water pumps (for fresh water cooling only);
(d) Underground chilled water distribution pipe network; and
(e) Substations in consumer buildings with heat exchangers and energy meters.

With the Hong Kong's Climate Action Plan 2050 set in place, the Government strives to achieve carbon neutrality before 2050. Among the four key strategies, "Energy Saving and Green Buildings" and "Zero-carbon Electricity Generation" are closely correlated as energy saving can help reduce the carbon emission for electricity generation. The Government established a first-of-its-kind DCS in Hong Kong at Kai Tak Development (KTD) so as to save energy consumption by air-conditioning in buildings. Following the successful implementation of DCS for KTD since 2013, the Government has continued to incorporate DCS in Tung Chung New Town Extension (East), Kwu Tung North New Development Area, and an expansion of DCS at KTD by constructing an additional plant to support the new development of Kai Tak Sports Park and other facilities nearing completion. DCS at Hung Shui Kiu/Ha Tsuen New Development Area is also under design development. The Government is exploring the feasibility of adopting DCS in Kau Yi Chau Artificial Islands and will accelerate the incorporation of DCS in other New Development Areas including the Northern Metropolis.

In addition, the People's Republic of China (China) has also actively promoted DCS especially for the southern region so as to echo the dual carbon goals (i.e. carbon dioxide emissions peak by 2030 and carbon neutrality before 2060). Thus, Hong Kong as the Special Administration Region of China, has an aligned policy in the development of DCS with China. According to the Xinhua News of August 2023, it is indicated that over 150 DCS have been put into operation currently. Besides, the largest DCS in Qianhai which is under development has the capacity of about 3 times of that for DCS at KTD. In view of the energy efficient features of DCS, it is not surprising that other tropical countries such as Singapore, Malaysia, India, United Arab Emirates, etc. have also been developing DCS actively. Benefits of adopting DCS may include energy saving/efficiency, reduction in installed capacity of central chiller plant because of cooling load diversification, release of roof areas for green roofs/ photovoltaic (PV) panel installations, mitigation of heat island effect, reduction of refrigerant consumption, flexibility building design, reduction of upfront capital cost for the provision of chiller plant and its associated plant rooms by building owners, reduction in noise/vibration pollution, etc. Some of these benefits which may be neglected by others will be elaborated in this paper.

To ensure the effective implementation of DCS, it is of utmost importance that chilled water supply to the buildings must be reliable so as not to affect the building operations.

Besides, in view of the recently uprising trend of extreme weather conditions including heaviest rainfall and super typhoons, due considerations should be taken to enhance the system resilience of DCS in response to such adverse climate impacts. Therefore, this paper also aims to explain how the system resilience of DCS can be enhanced to maintain a highly reliable service to the consumer buildings. Moreover, trends in technological advancements such as artificial intelligence, global navigation satellite system, new refrigerants, etc. will also be covered in this paper.

2.0 Description of District Cooling Systems

DCS is designed to generate chilled water from the central chiller plant and convey chilled water at five (5) degrees Celsius to the consumers' substations of served buildings. The chilled water absorbs the heat collected from building internal loads via the heat exchangers installed at the consumer substation, and then returns to the DCS plant at thirteen (13) degrees Celsius for cooling again by the chiller plant. In general, heat rejection by means of either direct seawater condensers or fresh water cooling towers will be used.

The major equipment and components that support smooth DCS operation and their respective functionalities are summarised in the table below:

Item	Equipment	Function
1	Central Chiller Plant	A group of equipment based on the refrigerant cycle that absorbs heat from one heat reservoir (i.e. chilled water) and rejects the absorbed heat to another heat reservoir (i.e. condensing water or sea water)
2	Chilled Water Circulation Pumps	Electric power driven pumps that circulate chilled water to and from consumer buildings via DCS pipes and provide sufficient pressure to overcome fluid resistance and static head in the water circuit
3	Condensing Water / Sea Water Pumps	Condensing water / sea water acts as a heat carrying medium for removing the heat from chiller and releases to the ambient environment (i.e. either ocean or

		atmosphere) Condensing Water / Sea Water Pumps are electric power driven pumps that circulate either sea water between the chillers and the shore or condensing water between the chillers and cooling towers and provide sufficient pressure to overcome fluid resistance and static head in the water circuit.
4	Fresh Water Cooling Towers	Specialised heat exchangers which brings atmospheric air and condensing water into direct contact with each other for removing the heat carried in condensing water and lowering its temperature (used in conjunction with fresh water cooled chillers only)
5	Chilled Water Distribution Pipe Network	Underground pipe distribution network dedicated for conveying chilled water from DCS plant to connected consumer buildings and returning the heated water back to the Central Chiller Plant.
6	Plate Type Heat Exchangers	A device consisting of a series of parallel steel plates for transferring heat between two fluids (i.e. DCS chilled water and secondary-side chilled water circuit of the consumer buildings) in the consumers' substations.

The working principle of DCS can be illustrated by the simplified schematic diagram below (Figure 1). Except for Plate Type Heat Exchangers (i.e. Item 6 in the above Table) which are installed in the consumer's substation of the respective building, failure and malfunctioning of any of Items 1 to 5 in the above summary table could potentially lead to different level of interruption to DCS service. By strategic planning and design of DCS, the potential service disruption can be minimized. In this connection, different features and measures enhancing resilience and reliability have been incorporated into the design, construction and operation and they will be discussed in the Section 4 below.

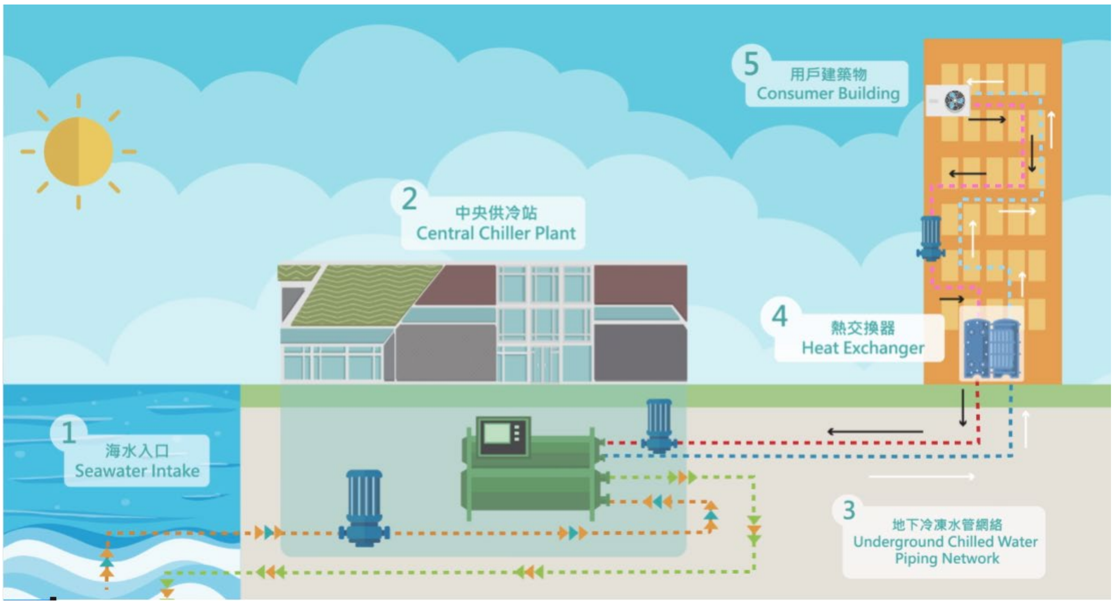

Figure 1: Simplified Schematic diagram for District Cooling System Working Principle

3.0 Benefits of District Cooling Systems

3.1 Sustainability of DCS

In general, DCS using seawater as heat rejection mean can consume less electricity by 20% to 35% as compared with individual conventional centralized water-cooled air-conditioning systems and air-cooled air-conditioning systems respectively. The total installed capacity of chiller plant for a building is determined based on the block cooling load plus spare capacity for standby and future expansion. Since there are different cooling load profiles for various types of buildings, DCS can make use of the load diversification factor to reduce the total installed capacity of the DCS chiller plant as compared with the sum of installed capacity of individual chiller plants for consumer buildings. This in turn can reduce the refrigerant charging requirements in the same proportion. According to the UNEP [1], the typical annual leakage rate of refrigerant for chillers regardless of their capacity ranges from 2 to 4%. Indeed, refrigerant leakage is generally attributive to malpractice and non-adherence to manufacturers' instruction during chiller maintenance. With a well-trained and competent operation and maintenance team for DCS plant, the overall refrigerant leakage rate can be largely reduced.

Adoption of DCS can not only allow more flexibility for building design but release the roof area for other purposes. For instance, when air-cooled chillers and heat rejection equipment are not required to be installed at the roof, PV panels or green roof can be provided in roof area. In this respect, the overall greening ratio and use of renewable energy in a new development area can be obviously increased to create a more sustainable living environment. By adopting DCS, consumers no longer need to accommodate heavy equipment of the air-conditioning systems including chillers, cooling towers, and cooling tower make-up water tanks, etc. Since the structural load requirement of the building superstructure can be lowered, this can not only consume less building materials but reduce the construction waste. Together with the reduced scale of electrical and mechanical installations (i.e. chiller plant equipment), the required transportation of materials and equipment is also diminished. In light of above, the overall carbon footprint of the building including the embodied carbon can be reduced to enhance the sustainability of the new development area.

When DCS plant is strategically located away from major residential and/or commercial zones, the adverse effect originating from heat generated from refrigeration equipment could be minimised. The adoption of DCS removes the heat rejection equipment that would otherwise be installed in individual buildings, which helps to mitigate urban heat island effect in the development area.

3.2 Financial Viability / Benefits

Currently, the Government is delivering the DCS project through a design-build-and-operate mode. This is a construction procurement method where a contractor designs, builds the facility and then operates it for a period of time as agreed in the contract. To decide if the DCS project should be put forward or not, the financial viability should be ascertained based on the following two criteria:

(a) Both the capital and operating costs of the DCS can be recovered from building owners or their authorized agents over the project life; and

(b) The DCS tariff should be set at a competitive level, comparable to the cost of individual water-cooled air-conditioning systems using cooling towers, which is one of the most energy-efficient air-conditioning systems available in the international market.

The charging mechanism has two components (i.e. capacity charge and consumption charge). The capacity charge is calculated on the contract cooling capacity and the capacity charge rate applicable to the building. The consumption charge is calculated based on the actual cooling energy consumption of the building in the month and the consumption charge rate applicable to the building. The effective rates are provided in the District Cooling Services Ordinance (Cap. 624) and will also be shown in EMSD's website. Therefore, according to the charging mechanism, the building developers can save the upfront capital cost for installation of the chiller plant and the associated facilities and construction of plant rooms as well as pay less based on the results of lifecycle cost analysis (i.e. accumulative payment of capacity charge and consumption charge is less than the CAPEX and OPEX over the project life).

4.0 System Resilience of District Cooling Systems

The DCS which has been developed by the Government is a highly reliable infrastructure with diverse features for enhancing system resilience. In general, there are three elements in the framework of system resilience for DCS, namely (1) hardware, (2) software/control and (3) administration, which work together for ensuring continuous and uninterrupted district cooling services.

Hardware

Standby units in "N+1" arrangement are provided for all critical equipment in the DCS plant which contribute towards the reliable production/generation of chilled water. Such equipment includes:

- Chillers
- Chilled water pumps
- Sea water / condensing water pumps; and
- Cooling Towers (applicable for fresh water cooling only)

For DCS pipes, the underground DCS distribution pipe network has a three-pipe arrangement operating in a hot standby mode. In this respect, the third pipe which is normally used as a supply water pipe can be switched to the return pipe to ensure the service continuity if the duty return pipe is damaged. Besides, as far as practicable, ring-main circuit is provided in the pipe network of each DCS plant. As such, should there be a pipe damage somewhere in the network, the chilled water can still be conveyed to consumer buildings when the damaged pipe section is isolated. To further enhance the reliability, interconnection between two ring-main circuits at the strategic locations will be provided wherever practicable and feasible.

To ensure the continuous operation of DCS, reliability and resilience features are integrated into the power supply design [2]. These features include:

- In the High Voltage (HV) 11kV side, each pair of 11kV 7MVA supply feeders will be arranged from two different sources (namely source A & B) so that in case of failure of source A 11kV feeders, source B 11kV feeders will take up 100% of the connected loads by closing the tie section breaker (Figure 2); and

- In the Low Voltage (LV) 380V side, power transformers are sub-divided into groups of three (3). In case of breakdown of any one transformer within the same group, the rest two transformer can stand ready to take up 100% of the connected loads of the faulty transformer. In addition, the dual power supply sources (e.g. Source A and Source B) to the three (3) transformers is arranged in the form of either "Source A – Source B – Source A" or "Source B – Source A – Source B" (Figure 3). This can further enhance the system reliability on low voltage power supply.

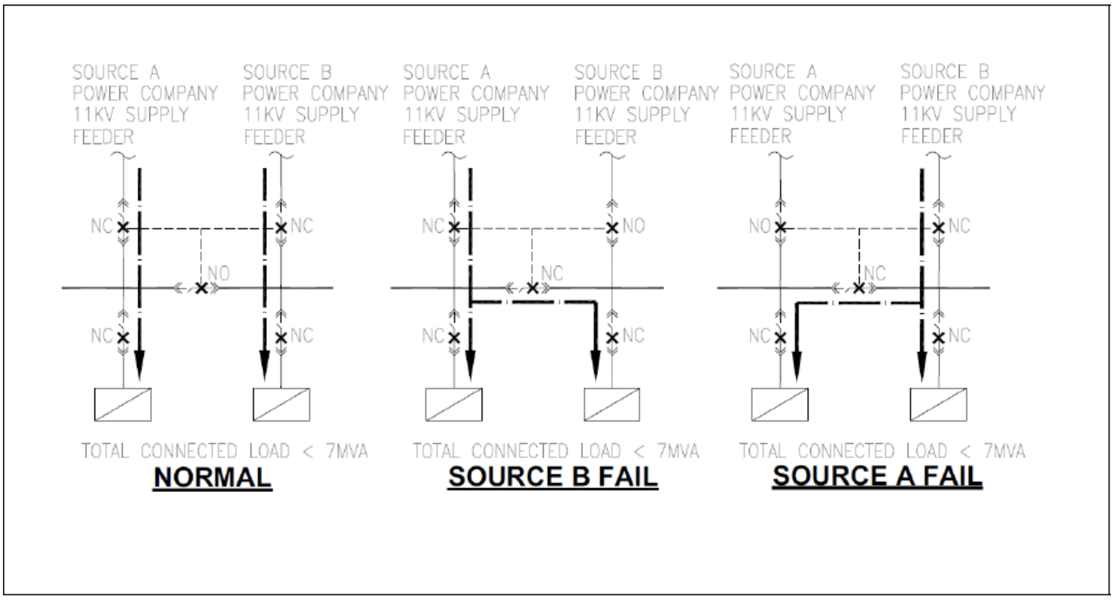

Figure 2: 11kV Supply Arrangement

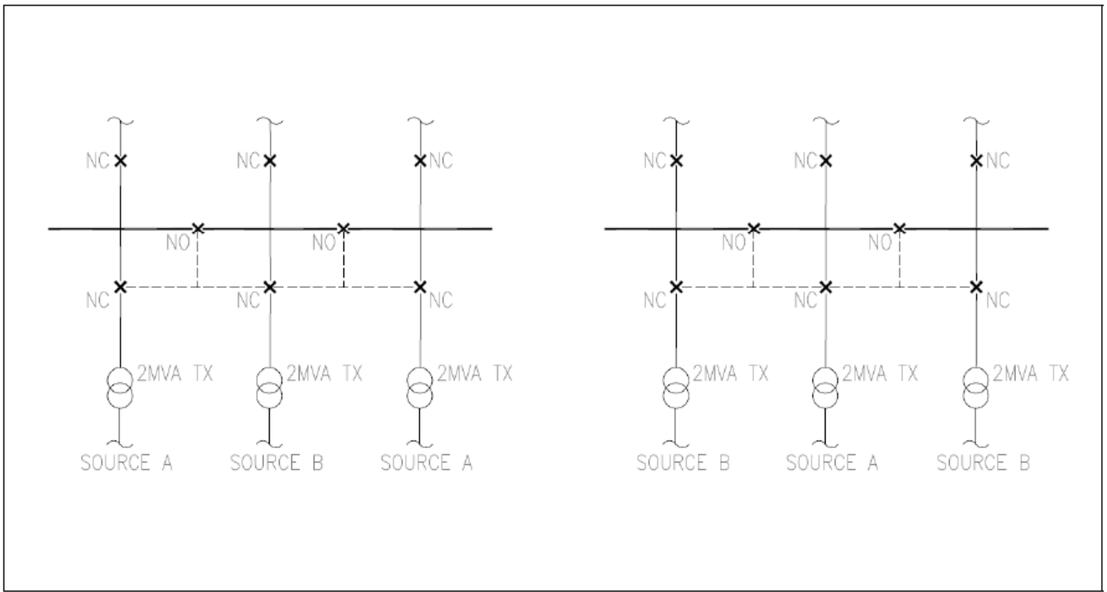

Figure 3: 380V Supply Arrangement (under normal conditions, each transformer undertakes 33% (⅓) of the total load; should any one of the transformer malfunctions, one of the two operating transformers would undertake 67% (⅔) of the total load)

Software/Control

The District Cooling Instrumentation, Control and Communication System (DCICCS) is provided for controlling and monitoring the whole DCS. DCICCS consists of optical fibre network for data transmission and automatic computerised monitoring system for central control and remote monitoring. The DCICCS which comprises substations, servers, switches, network controllers, remote processing units, etc. acts as the brain and nervous system behind DCS and performs data analytics based on the data collected from the field devices to perform systems functions such as on/off control, pump speed modulation, chiller sequencing, chilled water temperature reset points, etc. To avoid service disruption arising from single point of failure, DCICCS is provided with a complete hot standby system which includes all necessary backup computer processing units, servers, network switches and optical fibre network, enabling full back-up, instant switchover and operation in case the duty DCICCS system malfunctions.

Administration

Operator team staff is on 24/7 shift duty monitoring the DCS around the clock, ensuring DCS plant proper operation as well as continuous and undisrupted DCS service. DCS operator are contractually obligated to maintain DCS service at a predetermined level of which is governed and monitored by a series of key performance indicators (KPIs) and his performance is regularly monitored by EMSD on a monthly basis. Besides, both incentive and penalty provisions are allowed in the operation contract such that the DCS operator is encouraged to keep improving his performance level.

In addition, special management policies in response to extreme weather are put in place to ensure DCS service not to be disrupted under special circumstance, which includes:

- Under extreme climate conditions including strong typhoon and heavy rainfall, maintenance team are on high alert, monitoring the status of DCS assets, safeguarding underground facilities from flooding risk and making report to the Employer (EMSD) at regular intervals until extreme climate conditions is alleviated;

- In the event of any incident affecting the DCS service, operator is contractually obligated to report the incident to the Employer (EMSD) within a predetermined timeframe according to the incident severity. The respective response and operator's rectification action (if applicable) would be closely monitored by the Employer (EMSD).

With the above-mentioned system resilience features of DCS, it is obvious that in terms of reliability and resilience, DCS can outperform individual conventional central air-conditioning systems for a typical commercial building as shown in the Table below:

	District Cooling System	**Conventional Individual Air-conditioning System**
Chiller Plant Standby Provision	● Chillers ● Chilled water pumps ● Sea water / condensing water pumps; and	● Chilled water pumps; and ● Sea water / condensing water pumps

	● Cooling Towers (for fresh water cooled chillers)	
Chilled Water Distribution Network	● 3-pipe network with standby chilled water supply/return pipe; ● Ring-main network adopted	● Standby chilled water pipes normally not available; ● Other than critical facilities such as hospitals and data centres, ring-main chilled water network is usually not adopted
Power Supply Network	● Dual source power incomer; ● Grouped transformer arrangement for LV distribution	● Other than critical facilities such as hospitals, airports and data centres etc., dual source power incomer is usually not adopted; ● Grouped transformer arrangement for LV distribution is normally not adopted
DCICCS/BMS/CCMS Standby Provision	● Hot Standby System available	● Hot Standby System usually not adopted
Operator Team Management	● Staff on 24/7 shifts, allow for rapid, on-site response	● 24/7, 365 day emergency call out available;

5.0 Future Development of DCS

For the continuous pursuit of DCS reliability, resilience and energy efficiency, EMSD is proactively seeking feasible and viable technical solutions to enhance DCS performance, so as to provide better service to DCS consumers and to benefit the society as a whole. Several potential solutions including (1) adoption of artificial intelligence for operation and maintenance of DCS, (2) use of global navigation satellite system (GNSS) for pipe settlement monitoring and (3) smart maintenance of heat exchangers by clean-in-place approach are identified and will be discussed below.

5.1 Adoption of Artificial Intelligence (AI) and Machine Learning (ML)

One of the challenges of DCS is the ability to match cooling supply to the consumer building demand. As the cooling demand of consumer building changes, there is a time difference (lagging effect) for the central plant to receive the signal and react. Mismatches between cooling supply and cooling demand would lead to energy wastage and reduced consumer satisfaction. There exists a potential energy saving opportunity when the DCS plant is capable of matching its operation with consumer cooling demand. This can be achieved by using artificial intelligence technology to 1) predict consumer building demand, 2) determine the possible range of operating set-points of DCS plant, 3) predict the plant the Coefficient of Performance (COP) of individual chillers and the overall electricity consumption in the possible range of operating set-points, and 4) determine the optimal operating set-points. The overall workflow is illustrated in the Figure 4 below.

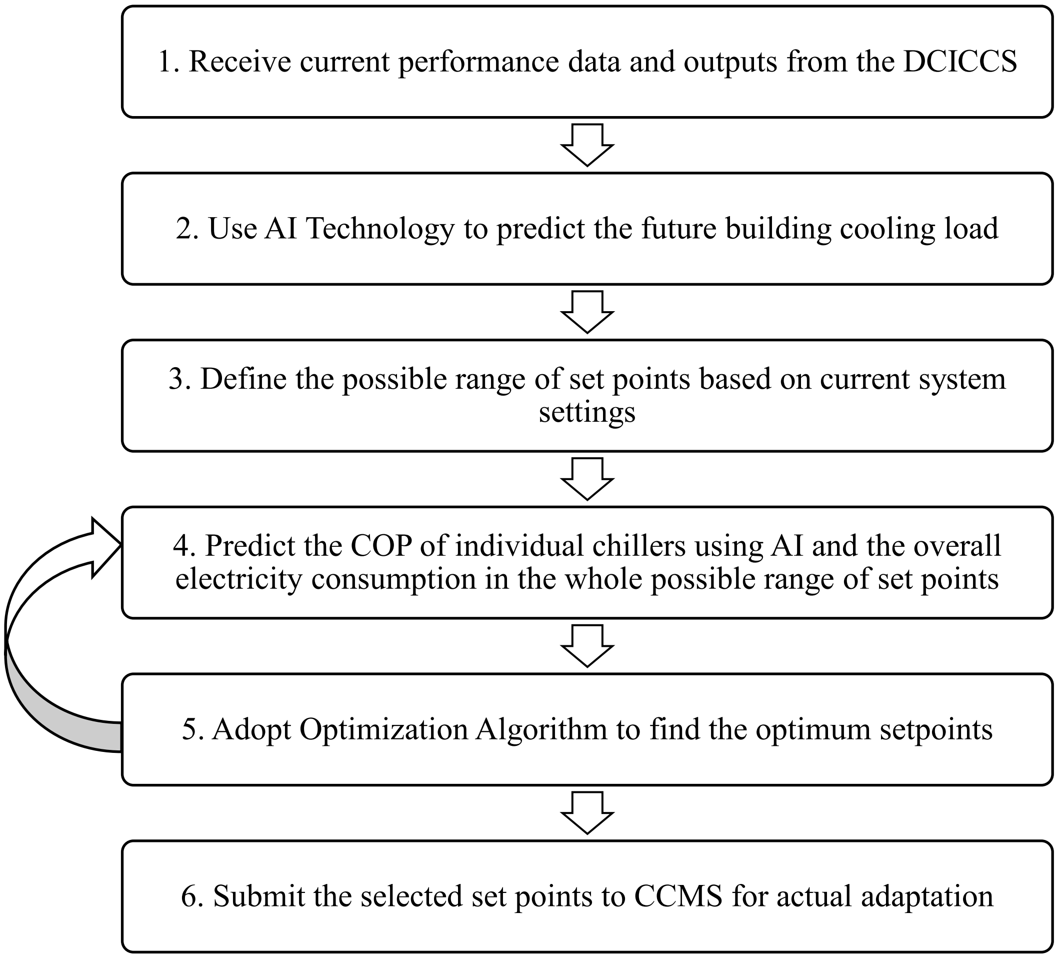

Figure 4: Workflow of DCS Chiller Plant Predictive Operational Control Strategy

Apart from energy optimization, AI/ML could also be used for Predictive Maintenance to further enhance reliability and resilience. Condition-based maintenance, involving performance monitoring and equipment condition monitoring during regular operations, reduces the chances of a breakdown. Executed with AI/ML, since the machine breakdown can be predicted, maintenance efforts can be planned ahead of time, effectively reducing down-time long-term repair costs, enhancing the reliability and benefitting to the plant operation financials.

5.2 Global Navigation Satellite System (GNSS) Application for DCS Pipe Settlement Monitoring

With due consideration of ensuring the longevity of DCS pipes and protecting them against external effects from soil movement / conditions, the ability to monitor the alignment and invert level/depth of buried DCS pipes in real time could much benefit DCS operation by allowing the operator to monitor pipe asset against unforeseen underground conditions, to efficiently locate pipe sections required for repair and inspection and to facilitate underground spatial coordination with other utility providers. Global navigation satellite system (GNSS) is indeed a proven technology to provide a viable solution for this purpose. By using GNSS receiver and survey grade antenna, operators would have the ability to map the location and depth of DCS pipe assets with high accuracy. This allows operator to monitor pipe assets and to be alerted in case of any pipe movement particular due to settlements which could lead to pipe burst. EMSD has conducted a trial installation (pictures below) for the purpose of "proof-of-concept". Early results were positive but technical issues such as reduced reception under metallic manhole cover, limited battery life, etc. needs to be further resolved prior to district-wide adoption.

	Pair of manholes accommodating GNSS equipment (Manhole with solar panel cover encloses GNSS receiver and battery, remaining manhole houses GNSS antenna)
	Manhole acccommodating a water-tight casing enclosing GNSS receiver and battery unit

	Manhole acccommodating GNSS Antenna

Figure 5: Trial Installation of Settlement Monitoring System by GNSS

According to the initial measurement findings, the measurement difference between manual surveying and such GNSS method range from 4 to 6 mm only. Such level of accuracy is sensitive enough to facilitate the current maintenance protocol of three response levels (i.e. 12 mm for alert, 18 mm for action and 25 mm for alarm)

5.3 Implementation of Clean-in-Place equipment for Plate Type Heat Exchangers

Plate type heat exchangers (PHE) require regular maintenance to operate at peak performance. In the absence of regularly scheduled maintenance, the efficiency of PHE's declines due to plate fouling and reduced thermal transfer. However, the maintenance work itself is a tedious, labour intensive and time consuming process that involves opening the plate pack, removing plate one by one, cleaning and flushing each HE plate, replacing any deformed plate during the process, replacing plate gaskets, and reinstating the plate pack, etc.

With Clean-in-Place (CIP) equipment as shown in the Figure 6, various kinds of debris collected in PHE can be flushed out over time. Although CIP cannot entirely replace above-mentioned manual cleaning process, it can lengthen maintenance intervals, allowing PHE to operate at a high level that benefits energy efficiency whilst minimising downtime which benefits to the reliability of DCS. By continuous monitoring of heat exchanger conditions such as pressure differential, flowrates, temperature differential, cooling demand, previous cleaning date, etc. with AI application, together with its capability to learn the maintenance window during part load periods (i.e. winter seasons), the smart maintenance system can create maintenance scheduling for all heat exchangers and set the priority for operator's actions.

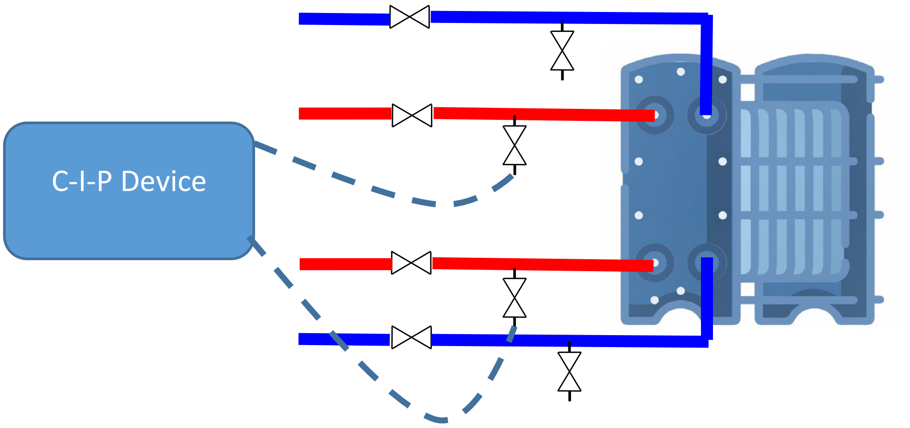

Figure 6: Maintenance of Heat Exchangers by Clean-in-Place Approach

5.4 Low GWP Refrigerant

In Q2/Q3 2023, Environmental and Ecology Bureau conducted a consultation exercise [3] regarding a proposal to regulate and phase down hydrofluorocarbons for Implementation of the Kigali Amendment to the Montreal Protocol. The Kigali Agreement to the Montreal Protocol is an international agreement that aims to phase down the annual production and consumption of hydrochlorofluorocarbons (HFCs), a synthetic gas primarily used as refrigerants in air-conditioning and refrigeration equipment, with high global warming potential (GWP).

Following the acceptance of the Kigali Amendment (the Amendment) by the Central People's Government in June 2021, Hong Kong is obliged to phase down the local production and consumption of eighteen (18) HFCs controlled under the Amendment to fulfil its international obligations under the Montreal Protocol. In terms of the schedule of production and consumption of HFCs phasedown, Hong Kong as a developed party is required to phase down the use of HFCs by 85% from the baseline by 2036 (Figure 7). However, it should be borne in mind that reductions in production and consumption of HFC are 40% and 70% in 2024 and 2029 respectively. This will lead to significant challenges for planning the DCS in near future.

Therefore, EMSD will actively liaise with the industry to identify suitable alternative refrigerants which may not be limited to hydrofluoroolefins (HFO) with due consideration in its flammability, toxicity, operation pressure, space requirement for refrigeration equipment using alternative refrigerant, cost, etc. to develop the DCS according to the phase-down programme.

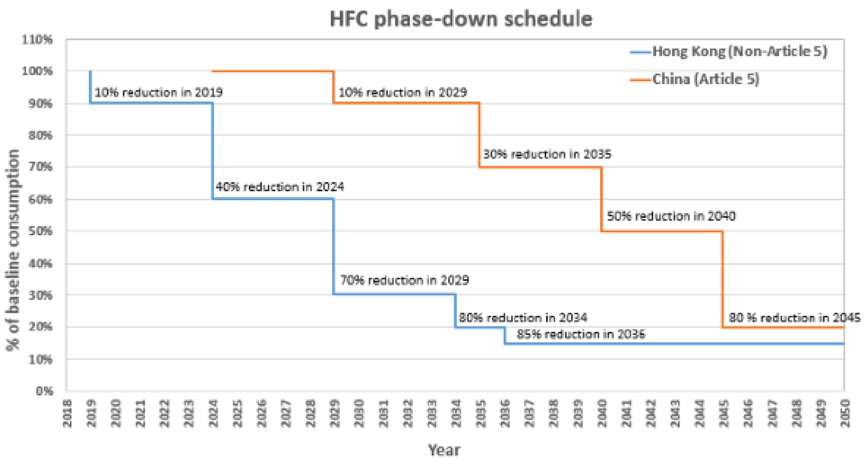

Figure 7: Phase-down Schedule of HFCs under Kigali Amendment

6.0 Conclusion

To combat climate change and achieve the target of carbon neutrality before 2050, it is of utmost important for Hong Kong to reduce energy consumption and enhance the energy efficiency. As adoption of district cooling system is considered as one of viable strategies for energy conservation and efficiency, DCS has been widely developed all over the world with some major recent developments in Asian countries including China and Hong Kong. Apart from the inherent benefits on sustainability, DCS should be duly designed to incorporate different features for enhancing the system resilience so as to minimise services disruption affecting the operation of consumer buildings. Finally, for the sake of continuous improvement, advanced/innovative technologies should be explored to enhance the energy performance of DCS and make its maintenance more effectively and efficiently.

7.0 References

[1] UNEP Ozone Secretariat, 2015, Fact Sheet 10 – Water Chillers for air-conditioning

[2] Lo, S.K., Chung F.W., Lau, K.P., No Date, Engineering Design for Power Supply to District Cooling System at Kai Tak Development

[3] Environment and Ecology Bureau (2023) Consultation Document – Proposal to Regulate and Phase Down Hydrofluorocarbons for Implementation of the Kigali Amendment to the Montreal Protocol