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Chiller Energy Optimization using Artificial Intelligence : Experience in Hong Kong

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ABSTRACT

Air-conditioning has contributed to around 30% of Hong Kong's total electricity consumption by End-use in 2021, according to the Hong Kong Energy End-use Data 2023 compiled by Electrical and Mechanical Services Department (EMSD) of the Hong Kong Special Administrative Region (HKSAR) of the People's Republic of China [1]. To achieve carbon neutrality, a roadmap was set out by the government in the Hong Kong's Climate Action Plan ("the Plan") [2] addressing the goal to reduce the electricity consumption in commercial buildings by 30-40% by 2050, of which trimming down the energy use of air-conditioning system in particular its core component i.e. chiller plant would definitely be one of the key measures to attain the target. This paper aims to present the challenges and hurdles faced as well as the experience gained during the implementation of Artifical Intelligence (AI) chiller plant optimization in several in-service government and public buildings in Hong Kong. It elaborates the most favorable plant configuration for setting up AI and illustrates the optimization strategy by utilizing the artificial neural network (ANN) technique and particle swarm optimization (PSO) algorithm. The outcome outlines an encouraging achievement of 5–10% energy savings for the revitalized chiller plants with intelligence and vibrancy, which helps to step up the schedule towards carbon-neutral.

INTRODUCTION

The HKSAR has set out in the Plan to become net-zero carbon emission by 2050.*[2]* Updated in October 2021, the Plan outlined a path to carbon neutrality for electricity consumption in commercial buildings to be decreased by 15-20% by 2035 and 30-40% thereafter, relative to 2015. In view that air conditioning accounted for around 28% of the electricity consumption in 2019 according to the Hong Kong Energy End-use Data 2021 *[1]* (which is uplifted to 30% in 2021 as per the Hong Kong Energy End-use Data 2023), cutting down the amount of power used for air conditioning system in particular its core component i.e. chiller plant was part of the sure way for reaching the aforesaid net-zero carbon goal drawn in the timetable of the Plan. Riding on the corporate 5-year Strategy Plan "E&M 2.0 – a New Journey" launched since 2018, we developed a digitized asset management system covering major electrical and mechanical (E&M) assests inside government premises to facilitate consolidation and analysis on the operational and maintenance data of various E&M installations through a common platform for stepping up predictive maintenance and optimizing assests' operating performance. The digitized asset management systems were centralisely connected to the regional digital control centres (RDCCs) in EMSD Headquarters as shown in Figure 1, for remote monitoring the operating status and operational efficiencies of all E&M assets, and hence the exploration and implementation of AI tools using big data technologies and deep learning algorithms to derive specific real-time, continuous, and automatic optimization control strategies for the digitalized facilities in particular the chiller plants became simpler, easiler and faster.

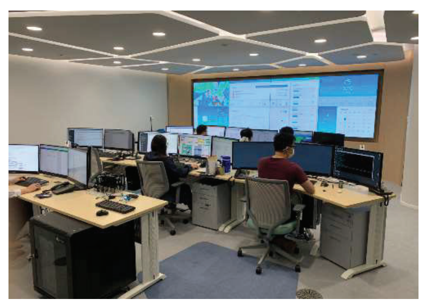

Figure 1 RDCC in EMSD Headquarters

CHILLER PLANT OPTIMZATION USING AI

With the innovative solution recognized, the framework and system requirements of chiller plant optimization using AI were constructed. EMSD currently operates and maintains thousands of chiller plants in in-service government and public buildings in HK, with around three quarters were air-cooled chillers. So, the most effective way to achieve the net-zero carbon goals was to pave the route to adopt AI optimization control in these air-cooled chiller plants. Figure 2 shows a typical hardware configuration of air-cooled chiller plant with AI optimization control adopted.

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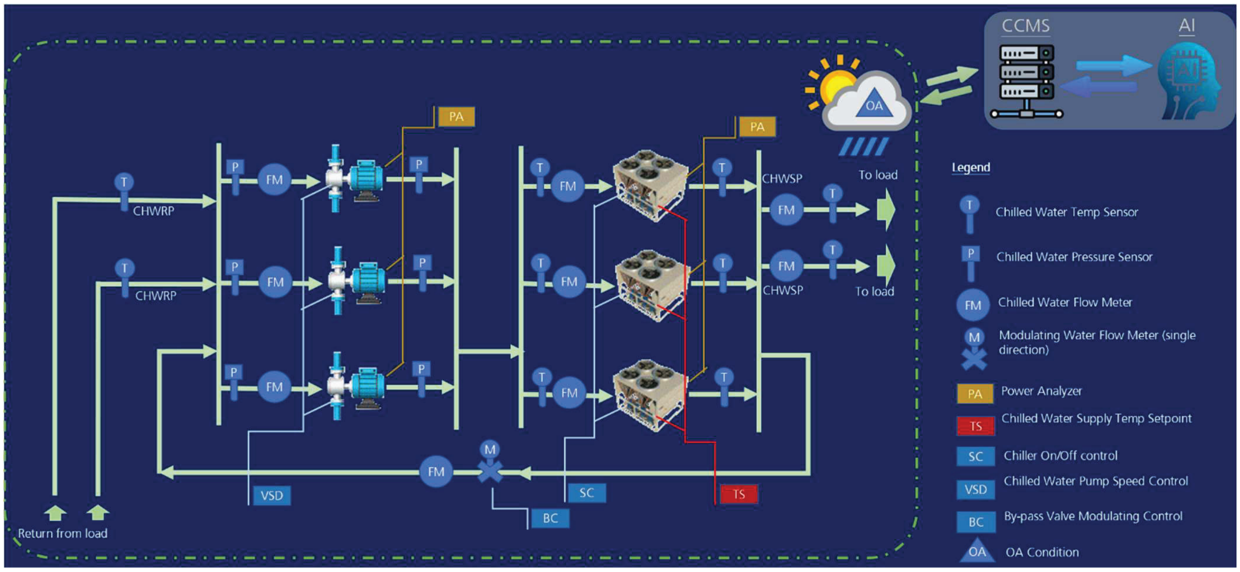

Figure 2 Air-cooled Chiller Plant with AI Optimization Control adopted

The core part for improving the energy performance of air-cooled chiller plant is to utilize the high part-load efficiency of variable speed drive (VSD) components that function in the most energy-efficient combination of chillers, pumps and associated accessories to satisfy the demand for building cooling loads. A specific hybrid predictive operational chiller plant control strategy was derived using AI as the data mining algorithm *[3]*, with big data analysis based on numerous actual performance parameters acquired from the operating equipment and consideration according to the unique characteristics of existing plant without the need for additional installation of large-scale and expensive apparatus. ANN modeling including one for the building cooling demand labelled ANN_TC and another for the power consumption of individual chiller in whole possible range of setpoints labelled ANN_CHx was used to predict future outdoor air conditions, building cooling load requirements and the associated power consumptions of the chiller plant. PSO algorithm was used to find the optimal chiller plant operating points including chiller sequencing, number of chillers in opration, chilled water supply temperature and chilled water pump running speeds. The workflow of a typical hybrid predictive operational chiller plant control strategy is illustrated in Figure 3.

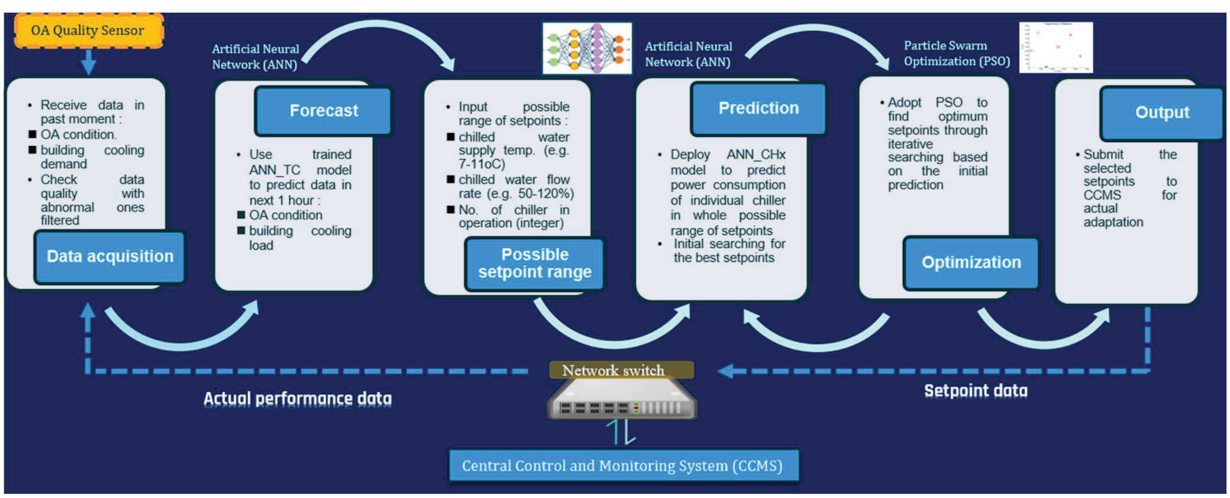

Figure 3 Hybrid Predictive Operational Chiller Plant Control Strategy

SYSTEM REQUIREMENTS FOR AI CONTROL

Upon establishment of the framework, a list of system requirements was worked out, which also helps the project officers to prioritize the implementation schedule by revisiting whether the chiller plant owning the most favorable configuration to work with AI in terms of both hardware and software, or so called "AI-ready". The system requirements include :

(a) The air-cooled chillers should be equipped with variable speed drive compressors. This allows the chillers to have a higher Coefficient of Performance (COP) under part load conditions. Remote control of the chilled water supply (CHWS) temperature setpoint is required.

(b) The chilled water pumps should also be variable speed driven. This enables the chillers to run at reduced flow for low building cooling demand situations and reduces power consumption by maintaining a lower pressure head. Remote control of the frequency of the VSD is required.

(c) It should be variable primary flow chilled water circuit type with bypass control valve modulated to maintain minimum flow through the operating chiller. All equipment and associated accessories should also be recommissioned without component failure.

(d) Sensors and meters for the chilled water side and electrical side of equipment should be available and properly calibrated. The completeness and accuracy of data are very important for accurate analysis and prediction.

(e) The operating parameters should be communicated with standardized data protocol and labelled according to unified equipment naming convention to simplify the integration and enable diffusion of AI to other systems.

(f) The central control monitoring system (CCMS) should be furnished with trend-log mechanism, while the chiller sequence, number of chillers in opration and CHWS temperature setpoints should be allowed for high level interface and remote control.

(g) The chiller plant fault protection logic in original CCMS should be maintained. The AI chiller plant optimization should NEVER directly command CCMS, but only send instruction to CCMS for execution while its commands shall not overwrite the manual control.

HURDLES ENCOUNTERED

(a) Common Hurdles on Hardware Side

- *Conventional chiller plant design without VSD gears.* It always happened in aged in-services buildings. To benefit from the energy saving of chillers and pumps at part load condition, the existing air-cooled chiller plant with constant speed drive gears should be upgraded to or replaced with variable speed type. Likewise, the existing chilled water system should be retrofitted to variable primary flow type. It should be noted that the energy saving of chillers and pumps at part-load condition is attributed to the benefit for the brake horsepower varied as the cube of the rotating speed in accordance with Affinity Laws.
- *Lack of sensor, measuring stations or control elements.* In certain chiller plants, some apparatus was found missing or still using century-old models. To make the energy systems more connected, intelligent, efficient, reliable and sustainable, proper instruments should be added, modified or upgraded.
- *Faulty equipment, device not calibrated or no network connection.* A no. of components necessary for the implementation of AI control were found faulty, setpoint drifted or disconnected, requiring replacement or re-calibrated. Issues in data acquisition will highly affect the usefulness of the energy management actions.
- *No provisions for high level interface or remote control.* One of the controlling parameters by AI is to reset the setpoint of CHWS temperature. For some aged chillers, such provisions were not available and required to equip by the chiller suppliers adequately.
- *Simple rule-based chiller plant control.* Some of the strategies only aimed to meet building cooling demand and setpoint of CHWS temperature by turning on and off of individual chiller through either manual or automatic operation in local CCMS. For most of the time, the plant might not run in the best efficiency mode and upgrading should be conducted.

(b) Common Hurdles on Software Side

- *Proprietary communication protocol and naming convention.* In aged chiller plants, such protocol was normally proprietary made while naming convention was unsystematic. To facilitate big data analysis and predictive operational control by AI, a coherent platform with same communication property should be built for the interoperability among cooperating building automation devices in the plants.

- *Missing M&V records, inaccurate operating logs, incomplete manufacturer's performance information and missing commissioning records.* Incomplete plant design parameters or equipment performance data from manufacturer like system performance curve; missing commissioning records such as chiller part load performance were always observed, in particular for those maintenance offices having been renovated or relocated previously. Without this information, it unavoidably pro-longed the time spent by the project officer to recognize the plant configuration and its operating condition.

- *Insufficient monitoring and control points.* Some of equipment were not facilitated with required monitoring and remote-control points such as the remote-control points for pumps. Being one of the controlling parameters by AI, it is important to obtain such provisions.
- *Lack of trend-log mechanism.* Some of the chiller control dashboard only displayed the instantaneous performance data but no trend-log details. It might be due to the limitation of processing power and storage capacity at the time of procurement. To serve analysis by AI, proper modification, upgrading or replacement of CCMS with trend-log facilities should be carried out.

IMPLEMENTATION STRATEGY

(a) Hardware Intallation

- *Retrofit existing air-cooled chiller plants with VSD gears and variable primary flow chilled water configuration for high-level interface and remote control.* Considering the possible service interruption and cost effectiveness, we put forward the re-vitalization task in line with the replacement schedule of aged or failure chiller. In particular, it should be paid attention on the impact of prolonged suspension for those chiller plants without proper resilience or provision of isolating valves.

- *Recalibrate, repair, modify, replace and add measuring devices, sensors, wiring and control elements.* Check within the chiller plant was essential. These included firstly, to rectify all defective instrumentations and secondly to re-vitalize the control gears. We needed for example the temperature sensors to be accurate down to 0.1 degree. It should always be reminded that sensors with drifted setpoints or poorly performed flow switch might offset all the efforts spent in the implementation of AI control.
- *Retro-commission chilled water circuits and ensure all equipment in normal conditions without component failure.* It was another important step, especially the plant having been operated for certain period of time or the served building having been undertaken with major addition, alternation and/or improvement. This acted for 3 purposes. First, re-assured the setpoints and system devices properly adjusted. Second, assisted later on establishing the energy baseline for the measurement and verification process. Third, underpinned the development of fault detection system with more accurate and healthy performance data.
- *Connect to mini-computers next to local CCMS or EMSD RDCCs via VPN tunnel and firewalls, with specific AI programmes.* On one hand, we expected AI to assist in optimizing the plant operation. On the other hand, we wished to have the existing CCMS maintaining its built-in control strategy, such as automatic changeover for chillers or pumps. To solve, we put the AI programme in a mini-computer in early stage and EMSD RDCCs in current stage for better isolation to minimize the impact to each other in case of break-down.

(b) Software Installation

- *Use high-level programming language.* We adopted proprietary type i.e. MATLAB in early stage and open-source type i.e. Python in the development of specific AI chiller plant optimization programmes. Subject to the applications, other types of high-level general-purpose programming language may be expored.
- *Utilize common communication protocol.* For reliable and consistent communication among different devices, a standardized protocol based on ASHRAE Standard 135, i.e. the Building Automation Control Network (BACnet) was utilized.
- *Adopt unified equipment naming convention with object-oriented abstraction for code portability and extensibility.* In our AI development, the unified equipment naming convention is referenced to BIM-AM Standards and Guidelines Version 3.0 released by EMSD.
- *Develop hybrid predictive operational chiller plant optimization model with selection of "just-fit" input time-series.*

Its workflow was sequenced with data collection from existing CCMS, data processing through hybrid predictive control strategy, and data output of optimized setpoints. To ensure proper and stable operation of chiller plant, the AI programme would review the plant operational data from CCMS every 10 minutes and send updated recommendation at pre-determined intervals for different parameters. In the pilot projects, the updating intervals for chiller sequence, CHWS temperature and pump speed were set at 50 minutes, 25 minutes and 10 minutes respectively.

- *Modify local CCMS for interface with AI control, without allowance for overriding chiller plant fault protection mechanism e.g. chiller & pump fault changeover.* The CCMS was upgraded for proper interface with AI, including the release of remote-control function with all the built-in safety features maintained and new operating functions added. The AI programme included a time stamp on each of its instructions for the users to identify whether the air-cooled chiller plant operated correctly and in accordance with the optimal setpoints. The operators may override the AI control in the event of irregularity of AI or other considerations such as ad-hoc events, failure, or scheduled maintenance of chiller plant equipment by pressing a dedicated button in the AI user interface added in the existing CCMS for switching back to CCMS automatic or manual control as needed.

CASE STUDY

Since January 2022, the EMSD has progressively launched the AI chiller plant optimization control in several pilot sites including local large healthcare facilities.

(a) Implementation of AI Chiller Plant Optimization in a Local Public Hospital

To illustrate, one of the chiller plants in a local public hospital with configuration shown in Figure 4, which consists of 6 air-cooled VSD chillers with each about 1,200 kW cooling capacity, 7 VSD chilled water pumps and variable primary flow chilled water circuity, is deliberated.

Measuring devices, sensors, wiring, and control elements were updated, replaced, and re-commissioned while the existing configuration was being tuned to align with the system "ready" requirements as outlined in Section 3. This pre-AI applied preparatory measures included verifying the pump operating in accordance with the manufacturer's characteristic curve, and re-calibrating and re-adjusting the water commissioning valve at each chiller for accurate water flowrate. The working pressure of the chilled water system was restricted to the range between the maximum and minimum speed of the chilled water pumps in order to protect the air-conditioning system's pipework and equipment. Similarly, the power analyzers of pumps and chillers were adjusted to make sure the readings to be reliable and correct.

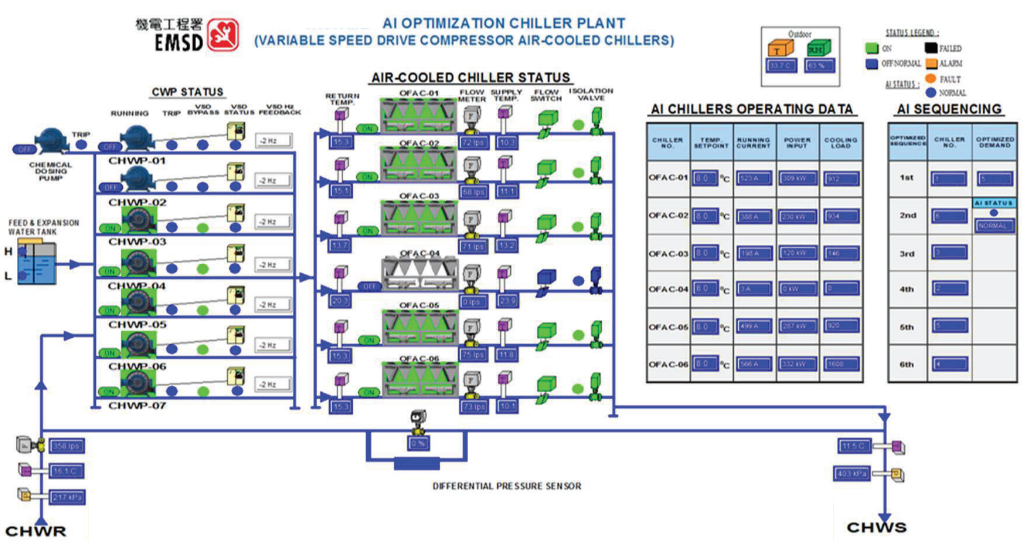

Figure 4 Configuration of Air-cooled Chiller Plant in a Local Public Hospital

(b) Benchmark Model of Existing Chiller Plant under Conventional Control

Baseline	All 6 chillers in operation		Existing Control Strategy		Creation of Baseline Model			
Date	Outdoor temperature (°C)	Total Cooling Load (kWh)	Total Power Input (kWh)	System COP	Total Power Input (kWh)	System COP	Error in kWh	
25/10	25.1	23,526	7,706	3.05	7,677	3.06	-29	-0.38%
26/10	24.9	54,215	16,357	3.31	15,706	3.45	-651	-4.15%
27/10	25.3	69,479	18,924	3.67	19,042	3.65	118	0.62%
28/10	25.1	70,647	19,059	3.71	19,226	3.67	168	0.87%
29/10	25.2	69,437	18,809	3.69	18,943	3.67	134	0.71%
30/10	24.2	65,973	17,564	3.76	17,549	3.76	-16	-0.09%
31/10	23.9	60,780	15,983	3.80	16,135	3.77	153	0.95%
1/11	24.0	25,076	6,584	3.81	6,644	3.77	60	0.90%
21/11	22.8	55,875	14,483	3.86	14,542	3.84	59	0.41%
22/11	19.2	34,433	8,779	3.92	9,121	3.77	342	3.75%
23/11	15.8	34,515	8,531	4.05	8,350	4.13	-181	-2.17%
24/11	18.5	52,412	12,623	4.15	12,410	4.22	-213	-1.72%
25/11	20.1	63,497	15,317	4.15	15,515	4.09	198	1.28%
26/11	21.1	71,372	17,670	4.04	17,731	4.03	61	0.35%
27/11	21.0	43,731	10,949	3.99	10,773	4.06	-176	-1.64%
Baseline	22.4	794,970	209,337	3.80	209,364	3.80	27	0.01%

Figure 5 Benchmark Model

Since the system could not be operated in both AI and conventional modes simultaneously for direct comparison, it was challenging to assess the energy savings related to the contribution by AI. To help, a mathematical model was created as a benchmark to determine the operating performance of existing chiller plant under conventional control by making use of a full set of historical data, including outdoor air condition, total building cooling load demand, total power input, and system coefficient of performance. As shown in Figure 5, its average error was very minimal and considered acceptable.

(c) Creation of AI User Interface in Existing CCMS

To satisfy the demand for building cooling load, the existing CCMS of chiller plant in the local public hospital was upgraded to receive instructions from AI such that its equipment could be maneuvered in the most energy-efficient manner possible. Should there be other considerations like ad-hoc events, failure or scheduled maintenance of the chiller plant equipment or irregularity of AI, the operators may override the AI control by deactivating the “Enable” button in the AI user interface added in the existing CCMS and switch back to CCMS for automatic or manual control, as shown in Figure 6.

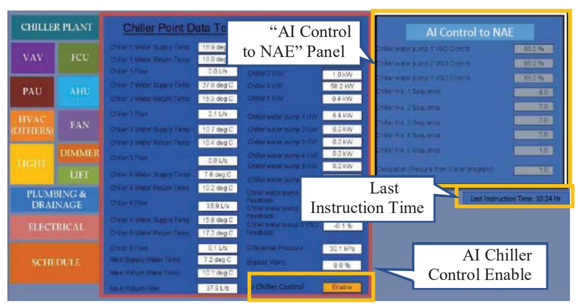

Figure 6 AI User Interface Created in Existing

(d) Creation of AI User Interface in Existing CCMS

Since January 2022, the AI chiller plant optimization control was initiated and operated steadily with improvement of Coefficient of Performance (COP) and reduction of energy consumption, as illustrated in Figures 7(a) and 7(b).

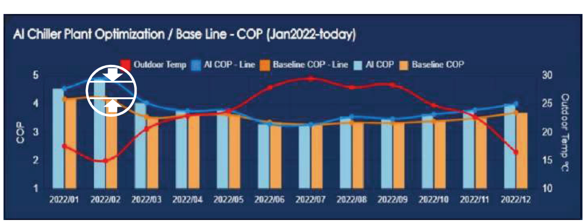

Figure 7(a) Improvement of COP Using AI

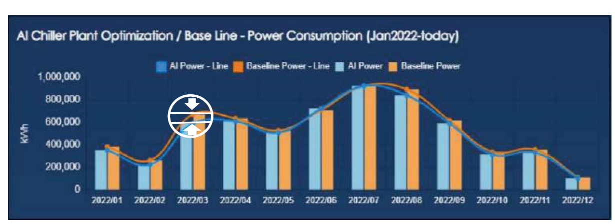

Figure 7(b) Reduction of Energy Consumption Using AI

The orange bar depicts performance under conventional control, whereas the blue bar depicts that under AI control. There was significant energy saving during seasons other than summer while less or even no energy saving during summer, May to July of 2022. It was because in hot and humid summer in Hong Kong, the building cooling demand was almost equal to the total cooling capacity of the installed chiller plant, of which the chillers were running at their maximum operating conditions and hence no benefit from the high part-load efficiency could be obtained. On the contrary, in seasons other than summer, the building cooling demand always less than the total cooling capacity of the chiller plant and the chillers could be driven in part-load conditions, enjoying their high efficiency operating ranges. Based on the total cooling load production of 22.53MWh with average COP improved from 3.52 to 3.74 or energy consumption reduced from 6.39MWh to 6.02MWh, the overall energy saving of chiller plant was around 6% per annum. This estimation may be varied depending on the accuracy of the chilled water temperature sensors, chilled water flow meters and digital power meters which having an important role of calculating the system COP. Nevertheless, as the saving was derived against the baseline chiller plant operation model built using historical data, the common uncertanties such as sensor deficiency or drift of set-points have been inherently covered and the implication to COP change due to operation uncertainity was minimized.

The system COP against the total cooling load under AI control and that under conventional control are illustrated in Figure 7(c). The orange dots represent the system COP under conventional control, while the blue dots depict that under AI cotntrol. It's interesting to note how different AI decisions were from the way regular humans think. For instance, it was traditionally recommended that the chiller plant should be operated with lesser chiller units with each unit running at its maximum ouput as far as possible and practicable. AI, however, performed differently, which always directed the chiller plant running at its highest system COP and lowest overall energy consumption as indicated in Figure 8. Similar operational patterns were also observed in other re-vitialized chiller plants.

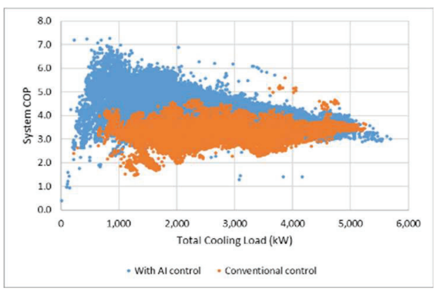

Figure 8 Overlaying of System COP under AI by that under Conventional Control

To sum up, with accurate outdoor condition and building cooling load prediction, the real-time, continuous and automatic operation of chiller plants with chillers, pumps and associated accessories became more stable, timely and efficient. It in turns reduced the temperature fluctuations in the served areas and uncomfortable feeling by the occupants, in particular the patients in the hospital. The AI chiller plant optimization measure at other pilot sites revealing an achievement of 5–10% energy savings would be a good example for the industry to follow or get inspiration for exploring other innovative solutions in reaching the goal of net-zero carbon emission by 2050.

WAY FORWARD

With the promising results found in the pilot sites, a rolling schedule to exlarge the application of AI optimization control to the "AI ready" chiller plants in a wide spectrum of in-service government buildings and healthcare facilities is under consolidation. The RDCC and digitization of chiller plant provide an excellent foundation and possibilities for AI applications for the purpose of energy optimization, early fault detection and predictive maintenance. The big data analytics, data mining, etc. also provide useful data for future chiller plant design toward carbon neutral. In near future, AI optimization will be extended to the air-side equipment for which a great opportunity to minimize the "un-used" treated air and thus the energy used, as well as the optimization of cooling tower performance.

AI Data Standardization Guidelines *[4]* is now being compiled in parallel with some pilot trials collabated with the partners in the Guangdong-Hong Kong-Macao Greater Bay Area. The guidelines share information on AI data standards and protocols, machine learning algorithms, case studies on AI model for predictive maintenance and energy optimization applications, as a reference for the industry.

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