Optimization and Renewable Energy Integration for Next-Generation District Cooling Systems

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Abstract. District cooling systems are increasingly viewed as an effective solution to meet rising urban cooling demand while reducing energy use and environmental impacts. This study evaluates three strategies to enhance the energy efficiency and sustainability of district cooling systems. Cooling loads and electricity demands for four representative buildings - office, hotel, retail, and hospital - were simulated. The baseline model represents a conventional district cooling configuration employing water-cooled chillers and thermal energy storage. Building on this foundation, the analysis investigates two key enhancement pathways: (i) improving operational performance through algorithmic control and optimization, and (ii) integrating onsite renewable energy systems to reduce dependence on the electrical grid. Three scenarios were assessed to quantify the energy-saving potential of various combinations of chiller optimization strategies, demand-side management techniques, and onsite renewable generation. Comparative results show that the implementation of a genetic algorithm–based optimization achieves a 5.59% reduction in energy consumption over a 25-year system lifespan. Additionally, installing a 3,530 kWp photovoltaic system further reduces electricity imports by 5.92%, resulting in an overall carbon emission reduction of 3,296 tons per year. Overall, the findings demonstrate the potential of coordinated optimization and renewable energy integration to improve the sustainability of district cooling systems.

1 Introduction

Cooling systems have become central to global energy and sustainability challenges, driven by rapid urbanization, rising ambient temperatures, and growing affluence. These trends continue to accelerate the demand for space cooling, with the global installed capacity of cooling equipment projected to triple by 2050 under business-as-usual conditions. Such expansion is expected to double electricity consumption and elevate greenhouse gas emissions to more than 6 billion tons of CO_2-equivalent annually by mid-century [1]. Addressing this trajectory requires a systemic transition toward sustainable cooling solutions that reduce environmental impact while safeguarding access to thermal comfort, food preservation, and economic productivity. The urgency is even more pronounced in tropical regions such as Singapore, where high humidity and year-round elevated temperatures drive

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substantial cooling needs. In 2019, cooling accounted for nearly 30% of the nation's total electricity consumption, and this demand is projected to increase by 66% by 2030 [2]. Singapore's reliance on imported electricity further heightens the importance of reducing cooling-related energy use and emissions in support of its 2050 net-zero targets [3]. Rising demand for cooling also poses significant challenges to power system reliability. Meeting future loads may necessitate major grid infrastructure upgrades unless demand growth is carefully managed. Recent assessments highlight the need for integrated strategies that combine effective electricity demand-side management with expanded onsite renewable generation. Approaches such as energy performance enhancement of cooling systems, load shifting and peak demand reduction along with onsite green electricity generation can alleviate stress on the power grid, enhance system resilience, and support the transition to a more sustainable national energy framework [4].

A study by Park et al. [5] found that the Sequential Uniform Part Load Ratio algorithm reduced cooling energy use by 24.5% in a specific climate zone by optimizing the number of chillers to avoid low Part Load Ratios. Other studies applied Particle Swarm Optimization to optimize capacity configuration and load distribution in a multi-chiller system, achieving an 11.3% energy consumption reduction [6]. Shejul and Harikrishnan [7] developed an energy scheduling system for food storage chiller plants using GA-enhanced Grey Wolf Optimizer and JAYA algorithms, achieving a 22% cost reduction, 10% energy consumption reduction, and efficient load shifting to low-price hours while maintaining temperature constraints. A Singapore case study found that combining District Cooling System (DCS) with a long-term thermal storage solution results in 4.1% cost saving [8]. For onsite electricity generation, much research has focused on integrating renewable energy into DCS, with photovoltaic (PV) systems being an obvious choice due to the high annual solar irradiation of 1,580 kWh/m²/year [9]. In a study conducted in Singapore, a combined DCS and PV system have significantly reduced electricity imports from the grid by 19.5% [10].

This study evaluates a set of complementary strategies to improve the energy efficiency and sustainability of centralized cooling systems serving multiple buildings. The baseline system considered in this study represents a conventional district cooling configuration consisting of electric-driven water-cooled chillers coupled with thermal energy storage. This configuration reflects current industry practice and serves as a reference case for assessing system performance. Based on this baseline, two complementary enhancement pathways are systematically investigated. The first pathway focuses on improving operational efficiency through advanced control and optimization strategies, including algorithm-driven scheduling and real-time performance optimization, to better manage cooling loads and reduce energy consumption. The second pathway explores the integration of onsite renewable energy resources to partially offset grid electricity demand, thereby enhancing system resilience, reducing lifecycle carbon emissions, and supporting the transition toward more sustainable district cooling systems. Together, these approaches provide a structured framework for advancing the performance and resilience of modern district cooling systems.

2 Modelling and simulation

2.1 Simulation of cooling load using eQUEST

Four representative building archetypes - office, hotel, retail, and hospital - located in the Orchard area of Singapore were selected to characterize typical urban cooling demand profiles. The geometric characteristics of each building, including footprint, height, orientation, and overall form, were extracted from Google Maps and modelled using SketchUp (Figure 1). The geometries were scaled to reflect real-world dimensions and subsequently imported into the eQUEST simulation platform for detailed building energy modelling.

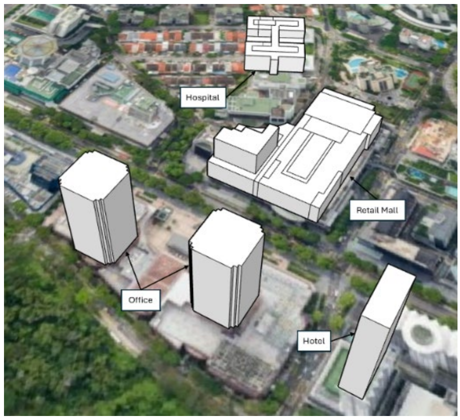

Fig. 1. Sketchup models of different building types

Annual simulations were conducted to capture the temporal variability of cooling demand under typical meteorological conditions. Singapore weather data were obtained from Climate.OneBuilding.Org [11] and used as inputs to the simulations. Key modelling assumptions and parameters adopted in eQUEST are summarized in Table 1. To enhance energy efficiency and reflect common design practice, Variable Air Volume (VAV) air-conditioning systems were modelled for the office, retail, and hotel buildings [12]. For the hospital building, a dual-duct reheat system was selected to provide stringent control of temperature and humidity in critical spaces such as patient wards and operating theatres. In addition, lower indoor temperature setpoints were adopted for hospital spaces, consistent with prevailing practice to mitigate bacterial growth (ASHRAE, 2019).
Building occupancy schedules, internal heat gains from equipment and lighting, and construction-related thermal properties were defined using default eQUEST inputs aligned with ASHRAE Standard 90.1. The resulting hourly cooling load profiles per unit floor area for each building archetype is presented in Figure 2.

Table 1. Parameters used for eQUEST simulation for different building types.

Description	**Retail**	**Office**	**Hotel**	**Hospital**
Number of buildings	4	6	6	1
Operating days	All week	Mon - Fri	All week	All week
Operating hours	10 am - 10pm	8am - 8pm	24 hours operation	24 hours operation
Required Indoor temperature	24°C	24°C	24°C	22°C

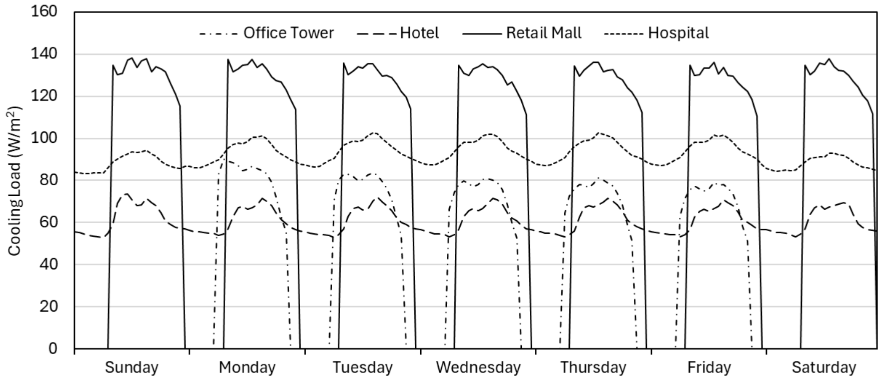

Fig. 2. Average weekly cooling load profiles for different building types.

2.2 Energy consumption calculation for chiller systems

The *k*-th cooling demand $Q_{c,k}$ (RT) of the consolidated chiller plant is obtained by adding cooling loads of all individual buildings as:

$$Q_{c,k} = N_{retail}Q_{retail,k} + N_{office}Q_{office,k} + N_{hotel}Q_{hotel,k} + N_{hospital}Q_{hospital,k} \quad (1)$$

where, N is the number of each building type and Q is cooling load of each building in RT. The total electrical power consumption of the entire chiller plant, denoted by $P_{p,k}$ (kW), associated with the *k*-th cooling demand $Q_{c,k}$ (RT), is calculated as:

$$P_{P,k} = Q_{c,k}(\eta_{c,k} + \eta_{CHWP,k} + \eta_{CDWP,k} + \eta_{CT,k}) \quad (2)$$

where, $\eta_{c,k}$, $\eta_{CHWP,k}$, $\eta_{CDWP,k}$ and $\eta_{CT,k}$ are the efficiencies in kW/RT of the chiller, chilled water pump, condenser water pump and cooling tower, respectively. Once $P_{p,k}$ is calculated, the chiller plant efficiency $\eta_{p,k}$ can be derived as:

$$\eta_{p,k} = \frac{P_{P,k}}{Q_{c,k}} \quad (3)$$

where $\eta_{p,k}$ is the chiller plant efficiency in kW/RT for the *k*-th cooling load.

2.3 Genetic algorithm

Genetic Algorithm (GA) Genetic algorithm (GA) is a search algorithm inspired by the process of natural selection, used to solve optimization and search problems. It works by evolving a population of candidate solutions through selection, crossover, and mutation over several generations to find the best solution to a given problem. MATLAB software was used to develop GA to optimize the operation of the chiller plant containing three different types of chillers *Chiller-1*, *Chiller-2* and *Chiller-3* of different part load efficiencies as shown in Eqs. (4) to (6).

$$\eta_{c1,k} = 2.98 \cdot {PLR_{1,k}}^2 - 4.36 \cdot PLR_{1,k} + 2.07 \tag{4}$$
$$\eta_{c2,k} = 2.98 \cdot {PLR_{2,k}}^2 - 4.96 \cdot PLR_{2,k} + 2.53 \tag{5}$$
$$\eta_{c3,k} = 2.98 \cdot {PLR_{3,k}}^2 - 5.55 \cdot PLR_{3,k} + 3.06 \tag{6}$$

where $PLR_{1,k}$, $PLR_{2,k}$ and $PLR_{3,k}$ are the part load ratio of *Chiller-1*, *Chiller-2* and *Chiller-3* respectively. $\eta_{c1,k}$ is the efficiency for *Chiller-1* under cooling load $Q_{c,k}$. Similarly, $\eta_{c2,k}$ and $\eta_{c3,k}$ are the efficiencies for *Chiller-2* and *Chiller-3* respectively.
Using GA, cooling demand $Q_{c,k}$ is assigned to different chillers. The purpose of GA is to optimally assign cooling load across different chillers such that the chillers are working near their best efficiency point.

$$Q_{c,k} = Q_{c1,k} + Q_{c2,k} + Q_{c3,k} \tag{7}$$

where $Q_{c1,k}$, $Q_{c2,k}$ and $Q_{c3,k}$ are the cooling load assigned to *Chiller-1*, *Chiller-2* and *Chiller-3* respectively. The part load ratios $PLR_{1,k}$, $PLR_{2,k}$ and $PLR_{3,k}$ of different chiller types are determined as follows:

$$PLR_{1,k} = \frac{Q_{c1,k}}{Q_{c1,rated}} \tag{8}$$
$$PLR_{2,k} = \frac{Q_{c2,k}}{Q_{c2,rated}} \tag{9}$$
$$PLR_{3,k} = \frac{Q_{c3,k}}{Q_{c3,rated}} \tag{10}$$

where $Q_{c1,rated}$, $Q_{c2,rated}$ and $Q_{c3,rated}$ are the rated cooling capacities in RT of *Chiller-1*, *Chiller-2* and *Chiller-3* respectively. The combined efficiency of the operating chillers $\eta_{c,combined}$ for the cooling load of $Q_{c,k}$ is defined as:

$$\eta_{c,combined} = \frac{\sum_{i=1}^{3}(Q_{ci,k} \cdot \eta_{ci,k})}{Q_{c,k}} \tag{11}$$

The optimized power consumption to operate the chillers $P_{combined,k}$ (kW) is the combined power consumption of different chiller types and is calculated as:

$$P_{combined,k} = \sum_{i=1}^{3}\left(Q_{ci,k} \cdot \eta_{ci,k}\right) \tag{12}$$

2.4 Thermal energy storage system

One of the key advantages of integrating Thermal Energy Storage (TES) into a District Cooling System (DCS) is its ability to shift electrical demand from peak to off-peak periods. By charging the TES during nighttime off-peak hours, when electricity tariffs are typically lower, and discharging it during daytime peak hours, when both cooling demand and electricity tariffs are high, significant operational cost savings can be achieved [13]. The total daily cooling demand of the DCS is determined by aggregating the cooling demands during off-peak and peak periods, denoted as Q_{OP} and Q_P, respectively. The cooling production of the chiller plant within the DCS is formulated in Eq. (13), which explicitly accounts for TES charging during off-peak hours to alleviate the cooling load on the chiller plant during peak demand periods.

$$Q_{day} = (Q_{DCS,P}\, h_P) + (Q_{DCS,OP}\, h_{OP}) \tag{13}$$

where $Q_{DCS,P}$ and $Q_{DCS,OP}$ are the hourly cooling produced by the operating chillers in RT during the peak hours h_p and the off-peak hours h_{op} respectively. When ($Q_{DCS,P} > Q_{P,i}$) or ($Q_{DCS,OP} > Q_{OP,i}$), excess chilled water production is used to charge TES. Conversely, when $Q_{DCS,P} < Q_{P,i}$, cooling demand by the consumers exceed cooling production of chillers in chiller plant. The shortfall of the cooling demand is supplied by TES. The capacity of TES $Q_{TES,Capacity}$ (RTh) is calculated as follows:

$$Q_{TES,Capacity} = \left(\left(Q_{DCS,OP}\ h_{OP}\right) - \ Q_{OP}\right) + \sum_{i=1}^{n} Q_{c,i} \qquad (14)$$

$\sum_{i=1}^{n} Q_{c,i}$ represent charging of the TES during peak hours, which is defined as:

$$Q_{c,i} = \begin{cases} 0, & if\ Q_{DCS,P} < Q_{P,i} \\ Q_{P,i} - Q_{DCS,P}, & if\ Q_{DCS,P} > Q_{P,i} \end{cases} \qquad (15)$$

$Q_{c,i}$ is the charging of TES for i^{th} peak hour when the chiller plant production $Q_{DCS,P}$ is more than consumer cooling demand $Q_{P,i}$. Charging of TES during peak hours is a strategy to improve chiller plant efficiency when $Q_{P,i}$ is low.

2.5 Simulation of photovoltaic system using Helioscope

The photovoltaic (PV) system output was simulated using the commercial software Helioscope. The analysis considered a PV array measuring 60 m × 40 m and incorporated the specifications of 630 Wp Astronergy module (model CHSM78N(DG)/F-BH-630). Based on these inputs, the simulation estimated an installed solar capacity of 3,530 kWp, corresponding to a total usable roof area of 25,200 m² and a PV coverage ratio of 0.2.

3 Results and discussion

Three different scenarios as depicted in Figure 3 are investigated in this study to evaluate energy saving potential. Each scenario incorporates a different combination of chiller optimisation strategies, demand-side management techniques, and onsite renewable energy generation, with the aim of reducing electricity imports from the grid.

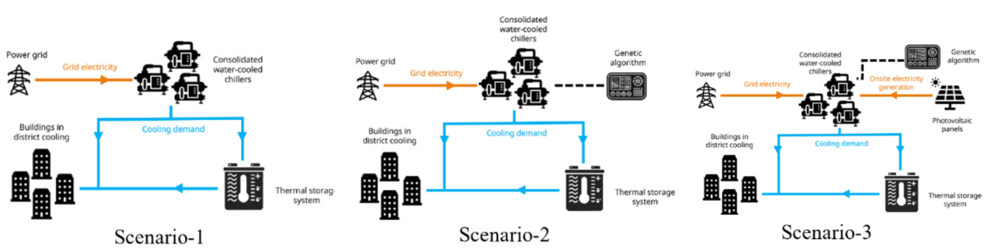

Fig. 3. Scenario-1: Simple DCS configuration, Scenario-2: DCS configuration with GA optimization, and Scenario-3: DCS configuration with GA optimization and PV system.

Figure 4 presents the hourly cooling load profile on the hottest day. The peak cooling load of the building cluster is about 24,500 RT. TES system with a capacity of 89,400 RTh is utilized to shift and balance the cooling load. The chiller plant can be operated at a constant cooling load of about 14,300 RT during the peak and the off-peak periods with the TES to support the cooling load of building cluster. Figure 5 illustrates the average hourly electricity consumption of the chiller plant under average day cooling conditions in Year-1. The red line represents the system with GA optimization (scenario-2), while the black line reflects the baseline performance from scenario-1 without GA optimization. Overall, the GA-optimized system consistently demonstrates lower electricity consumption across most operating hours.

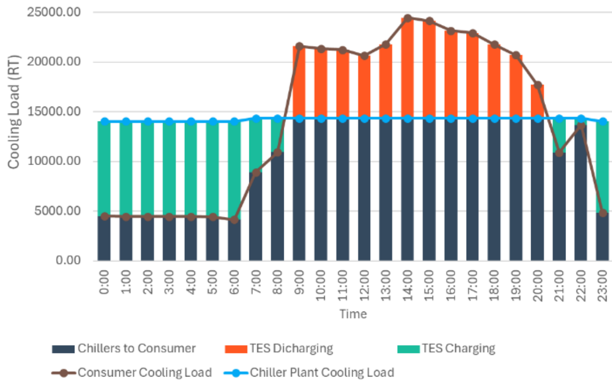

Fig. 4. Hourly cooling load profile on the hottest day for the district cooling plant without optimization.

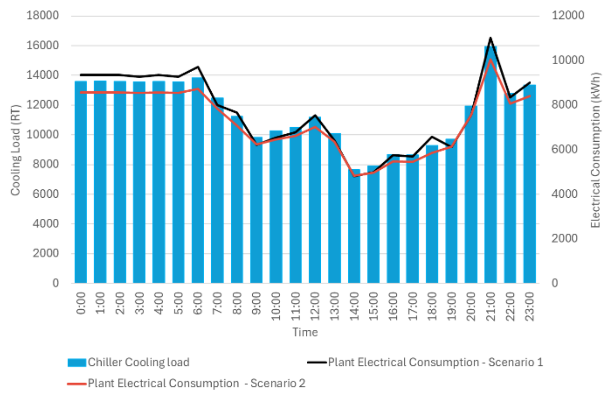

Fig. 5. Hourly average electricity consumption of chiller plant for scenarios-1 & 2.

The total grid electricity consumption for scenarios-1, 2, and 3 accumulated over the operational lifespan of 25 years are 1790,000 MWh, 1690,000 MWh and 1590,000 MWh, respectively. Based on Singapore's average grid emission factor of 0.412 kg CO_2/kWh [14], scenarios-2 and 3 achieve annual carbon emission reductions of approximately 1,648 and 3,296 tons, respectively, compared to scenario-1. Implementation of GA accounts for 5.59% decrease in energy consumption over the system's lifespan. As for photovoltaic deployment in scenario-3, the installed capacity and the solar specific yield are 3,530 kWp and 1,190 kWh/kWp/year respectively based on system modelling on photovoltaic system. The installation of the photovoltaic system results in a 5.92% reduction in electricity consumption over the lifespan when comparing scenarios-2 and 3. In the initial year, the PV system contributes to a 6.57% reduction, indicating a higher impact in the early stage of operation. The decrease from 6.57% to an average of 5.92% over time is primarily attributed to the degradation of both the chiller plant and the PV system. As the chiller system becomes less efficient with age, it requires more electricity to deliver the same cooling output.

Simultaneously, the performance degradation of the PV system leads to a reduction in electricity generation, further lowering its contribution to overall energy savings.

4 Conclusions

This paper presented an integrated framework to enhance the energy performance of DCS in the Singapore context by jointly leveraging demand-side operational optimization and onsite renewable energy integration. A baseline DCS model, developed using building-specific cooling load simulations from eQUEST, represented a conventional system comprising electric water-cooled chillers and thermal energy storage. Building on this foundation, three alternative system configurations incorporating GA-based optimization and PV generation were evaluated.

The results demonstrate that GA-based chiller load optimization is a low-cost and effective strategy, achieving a 5.59% reduction in lifetime electricity consumption through improved load allocation among heterogeneous chiller types. Further efficiency gains were realized through PV integration. With an installed capacity of 3,530 kWp and a solar specific yield of 1,190 kWh/kWp/year, the PV system contributed to an average 5.92% reduction in electricity consumption over the system lifespan, with a higher impact of 6.57% observed in the initial year of operation. The gradual reduction in benefits over time is mainly attributed to the performance degradation of both the chiller plant and the PV system. The implementation of GA-based chiller load optimization together with PV system installation results in annual carbon emission reductions of about 3,296 tons.

Overall, the findings highlight the effectiveness of coordinated operational optimization and renewable energy integration in improving the energy and economic sustainability of district cooling systems. The proposed hybrid configurations offer a viable pathway to meeting Singapore's growing cooling demand while supporting long-term decarbonization efforts and national net-zero emissions targets by 2050.

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