A Study on Integration Opportunities of Renewable Energy Sources to District Cooling Systems

Russell Khoo Wei En[1], *Md Raisul* Islam[1*]

[1]Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117575, Singapore

Abstract. This study conducts a techno-economic evaluation of four scenarios that combine renewable energy technologies with a District Cooling Systems (DCS) to explore potential energy and cost savings. First, the cooling load and electricity consumption of buildings connected to the DCS were simulated using eQUEST. A benchmark scenario was then established using a self-developed Genetic Algorithm optimization code in MATLAB. The study further examines the effects of varying key parameters related to a Thermal Energy Storage (TES) tank, a Photovoltaic (PV) system, and a Biomass fired Combined Heat and Power (CHP) plant with an Absorption Chiller (ABC). This analysis was conducted using a combination of Helioscope software and mathematical modelling. Finally, the four scenarios were compared in terms of energy use, carbon emissions, and economic viability. Key findings indicate that incorporating a TES tank enables load shifting, resulting in a 12.64% increase in Net Present Value (NPV). The integration of PV systems within the district leads to a 4.5% reduction in overall energy consumption and a 4.47% decrease in annual carbon emissions. Implementing a 1 MWe Biomass fired CHP plant with an ABC achieves 25.9% energy savings and an 11.85% reduction in carbon emissions.

1 Introduction

Approximately 95% of Singapore's electricity is generated from natural gas, contributing to around 40% of the nation's carbon emissions [1, 2]. A significant share of this electricity is used for air-conditioning in buildings and industrial facilities. District Cooling Systems (DCS) present a more energy-efficient alternative to conventional cooling methods. For instance, Singapore's Marina Bay DCS, the world's largest underground network, achieves over 40% energy savings and avoids nearly 20,000 tonnes of carbon emissions annually [3].

To meet Singapore's target of net-zero carbon emissions by 2050 and address the growing demand for cooling, integrating renewable energy into DCS is crucial to reduce dependency on the grid. Various renewable options including biomass, geothermal, hydrogen, hydropower, solar thermal, solar photovoltaics (PV), and wind energy can be considered [4].

* Corresponding author: mpemdri@nus.edu.sg

Among these, solar energy is particularly promising due to Singapore's year-round solar irradiance [1]. Biomass-fired CHP plants generate both electricity and steam from waste, are also viable [5]. The waste heat from such plants can drive ABC, reduce electricity consumption and enhance overall system efficiency.

Recent research has emphasized improving DCS efficiency through renewable integration. Ozcan et al. [6] assessed hybrid systems combining absorption and vapor compression methods, concluding that solar-assisted vapor compression systems offer higher exergy efficiency. Huang et al. [7] conducted a techno-economic comparison of renewable-based combined cooling, heating, and power systems, identifying a configuration integrating battery, hydrogen, and thermal energy storage as the most cost-effective. M. Neri et al. [8] showed that utilizing waste heat via ABCs can shorten DCS payback periods by up to five years. A review by Inayat and Raza [4] highlighted the strong technical and economic potential of biomass, solar thermal, geothermal, surface water, solar PV, and waste heat as sustainable energy sources for DCS.

While these studies explored various energy-storage integrations with DCS, most did not analyse the effect of different storage capacities or use localized weather and irradiance data relevant to Singapore. Although renewable integration can yield significant energy and cost savings, solutions must be tailored to local conditions such as weather patterns, public holidays, and building operating schedules as there is no universal model. This study aims to address these gaps by evaluating the integration of Singapore's most viable renewable sources, namely PV and biomass, while balancing energy savings against capital and installation costs. Key system parameters are investigated to optimize both performance and cost-effectiveness.

2 Modeling and Simulations

2.1 Simulation of Cooling Load using eQUEST

In this study, the District Cooling System (DCS) network comprises a mix of building typologies, including retail, hotel, hospital, and office facilities. The principal simulation inputs are summarized in Table 1. Meteorological data specific to Singapore was utilized, with national public holidays manually incorporated to reflect realistic occupancy patterns and operational schedules. To account for the anticipated load growth stemming from the increasing adoption of DCS, a load-scaling factor of 1.2 was applied uniformly across all cooling demand profiles. The resulting simulated cooling load profile is illustrated in Fig. 1. Additionally, the hourly end-use electrical demands for lighting ($E_{Lighting}$) and plug loads/miscellaneous equipment ($E_{Equipment}$) were extracted from the simulation. The electrical energy generated by the PV system was first allocated to satisfy the internal electrical demand of the buildings; any surplus PV energy was subsequently redirected to offset the electricity consumption of the centralized DCS plant. Given that the DCS operates independently via a centralized chiller facility, the total electrical demand of the buildings is defined as follows:

$$E_{Building} = E_{Lighting} + E_{Equipment} \quad (1)$$

Table 1. Key building simulation inputs

Building Type	Quantity	Area (m^2)	Operating hours (SGT)
Retail	3	74322	11:00 to 22:00
Hotel	2	55741	00:00 to 00:00

Hospital	2	55741	00:00 to 00:00
Office	10	11612	09:00 to 19:00

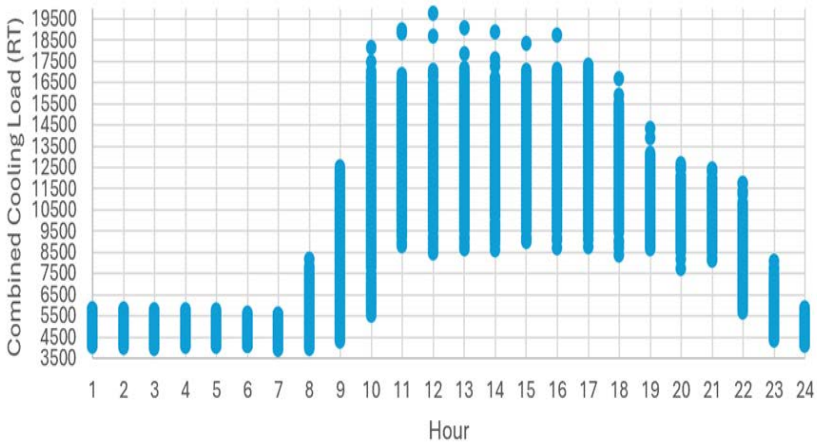

Fig. 1. Consolidated average cooling load

2.2 Positioning

The total chiller plant energy consumption in kW is calculated as:

$$E_{Chiller\ Plant} = E_{CH} + E_{CHWP} + E_{CWP} + E_{C\,T} \quad (2)$$

where the terms ECH, ECHWP, ECWP, and ECT are the energy consumed by the electric chillers, chilled water pump, condenser water pump, and cooling tower, respectively. The energy consumed by the electric chillers can be computed as:

$$E_{CH} = Q_{CH} \times PLR \times \eta_{CH} \quad (3)$$

where QCH is the chiller capacity in RT, PLR is the part load ratio at which a chiller operates, and η_{CH} is the efficiency of the chiller in kW/RT with respect to the PLR. The energy consumed by the chilled water pump, condenser water pump, and cooling tower can be computed as:

$$E_x = CL_{hourly} \times \eta_x \quad (4)$$

where CLhourly is the cooling load in RT at each hour, and x is an arbitrary term to be replaced by CHWP, CWP, and CT accordingly. A Genetic Algorithm (GA) optimization code was developed and executed using MATLAB. The objective of the GA code is to minimize the chiller plant energy consumption under different loadings. The optimization algorithm suggested the number of chillers of each type to be turned on and the corresponding PLR to achieve the best efficiency at each cooling load.

2.3 Simulation of PV System with Helioscope

The PV system output is simulated using the commercial software Helioscope. The simulation is conducted with a PV array with dimensions of 60m x 40m. The features of Longi LR5-66HPH-500M Huawei SUN2000 100KTL-M2 solar panel were used for the simulation. The results were scaled up to the total building area of the district according to the different PV coverage ratios, and the results are tabulated in Table 2.

Table 2. Results of scaled up PV system

PV coverage ratio	Installed Area (m2)	System Size (kWp)	Annual Solar Output (MWh/Year)
0.2	112412	19320	18430.71
0.3	168619	29400	28046.73
0.4	224825	39060	37262.08

2.4 Biomass CHP Plant with ABC

The performance of a biomass-fired Combined Heat and Power (CHP) plant integrated with Absorption Chillers (ABC), shown in Fig. 2, were simulated using a set of governing equations.

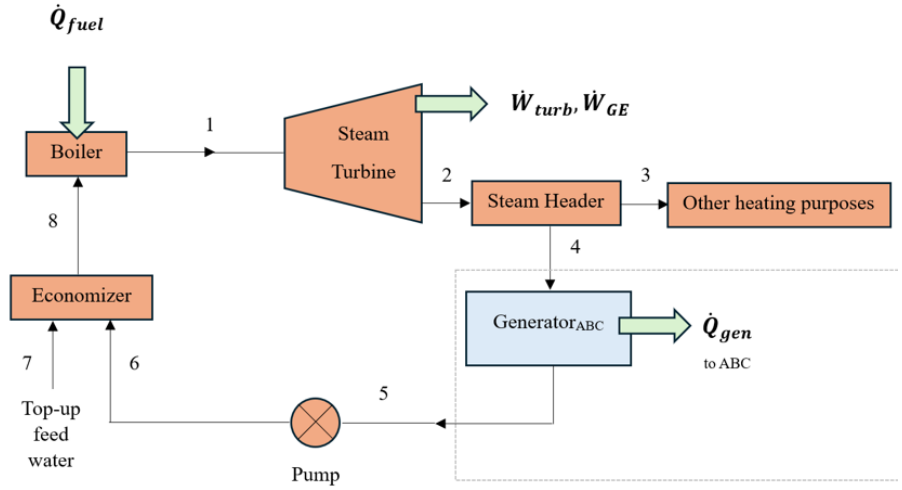

Fig. 2. Schematic diagram of Biomass CHP plant with ABC

Governing equations to simulate the performance of the biomass-fired CHP integrated with ABC:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (5)$$

$$\dot{Q}_{fuel} = \dot{m}_{fuel} \times LCV \quad (6)$$

$$\dot{m}_1 \times (h_1 - h_8) = \eta_{boiler} \times \dot{Q}_{fuel} \quad (7)$$

$$\dot{W}_{turb} = \eta_{turb} \times \dot{m}_1 \times (h_1 - h_2) \quad (8)$$

$$\dot{W}_{GE} = \eta_{gen} \times \dot{W}_{turb} \quad (9)$$

$$\dot{W}_{NE} = \dot{W}_{GE} - \dot{W}_{AE} \quad (10)$$

$$\dot{Q}_{gen} = \dot{m}_4 \times (h_4 - h_5) \quad (11)$$

$$\dot{Q}_{cooling} = COP_{ABC} \times \dot{Q}_{gen} \quad (12)$$

where Eqs. (5) and (6) denote the conservation of mass and the heat of combustion ($\dot{Q}_{fuel}$) in kW, respectively. The mass flow rate of fuel ($\dot{m}_{fuel}$) is 8000 kg/hr, and the lower calorific value (LCV) based on the assumed fuel moisture is 15.36 MJ/kg. Eqs. (7) and (8) denote the energy balance of the turbine and boiler, respectively. The boiler efficiency (η_{boiler}) is 80%, and the turbine efficiency (η_{turb}) is 40%. The enthalpy at each state (h) in kJ/kg, is determined using the steam table based on the corresponding thermo-properties. The gross electrical power ($\dot{W}_{GE}$) in kW, and the net electrical power ($\dot{W}_{NE}$) in kW are determined by

Eqs. (9) and (10), respectively. The electrical generator efficiency (η_{gen}) is 95%, and the auxiliary electrical power ($\dot{W}_{AE}$) in kW is 10% of the gross electrical power ($\dot{W}_{GE}$). Lastly, the cooling load produced by the ABC ($\dot{Q}_{cooling}$) is 8791 kW, and the coefficient of performance of the ABC (COP_{ABC}) is 1.41. The heat absorbed by the generator of the ABC ($\dot{Q}_{gen}$) in kW is determined by Eq. (11).

2.5 Carbon emissions analysis

There were two main sources of carbon emissions identified, which are carbon emitted from producing grid electricity and the carbon emitted from burning of biomass fuel for biomass-fired CHP plant. The annual carbon emissions from producing grid electricity can be computed as

$$Annual\ CO_2\ emitted\ by\ grid = \text{GEF} \times E_{annual} \quad (13)$$

where GEF = 0.412 CO_2 kg/kWh is Singapore's average grid emission factor. The term E_{annual} is final annual energy consumption of the DCS after offsetting available electricity from PV and Biomass CHP, where applicable, in kWh/year. The annual carbon emissions from burning of biomass fuel can be computed as:

$$Annual\ CO_2\ emitted\ by\ CHP = \text{CEF}_{wood} \times Annual\ gross\ electricity\ generated \times 3.6 \quad (14)$$

where CEF_{wood} = 112 CO_2 tonnes / TJ is the carbon emission factor of wood. Annual gross electricity generated is the gross electricity generated by the CHP plant in TWh/year, and 3.6 is a conversion factor from TWh to TJ.

3 Results and discussion

Table 3 presents the average daily results for all four scenarios, using the consolidated case with GA Optimization as the base case. Except for the base case, the following applies to all scenarios where relevant:

- Capacity of each electric chiller is 3000 RT
- Capacity of the ABC is 2500 RT
- DCS operates with TES Case-1 with a capacity of 40%
- PV coverage ratio is 0.4

Fig. 3 illustrates the hourly energy consumption for each scenario on an average day, while the results of the financial analyses are summarized in Table 4. The analysis reveals that the integration of the TES system facilitates effective load shifting, yielding a 12.64% improvement in the NPV of the overall system. Deployment of distributed PV systems across the district results in a 4.5% reduction in total electricity consumption and contributes to a 4.47% decrease in annual CO_2 emissions. Furthermore, the incorporation of a 1 MWe biomass-fired CHP plant equipped with the ABC system leads to a 25.9% reduction in primary energy consumption and an 11.85% decrease in carbon emissions, demonstrating the potential of multi-generation strategies to enhance energy efficiency and sustainability in district energy systems. However, financial analysis shows that while these integrations reduce energy use and emissions, they also lower overall NPV and extend the payback period. Sensitivity analysis further reveals that chilled water tariffs significantly influence the financial viability of all scenarios. Overall, while integrating renewable energy with DCS contributes to energy and emissions reductions, it involves higher initial investment costs.

Table 3. Average daily energy analysis

Scenario	Number of electric chillers	Number of ABC	Average Daily Energy Consumption (kWh/day)
Base case: GA optimized central chiller plant	12	-	168625.99
Scenario A: DCS	8	-	175162.48
Scenario B: DCS + PV	8	-	161102.11
Scenario C: DCS + Biomass CHP with ABC	6	1	124803.59
Scenario D: DCS + Biomass CHP with ABC + PV	6	1	111002.63

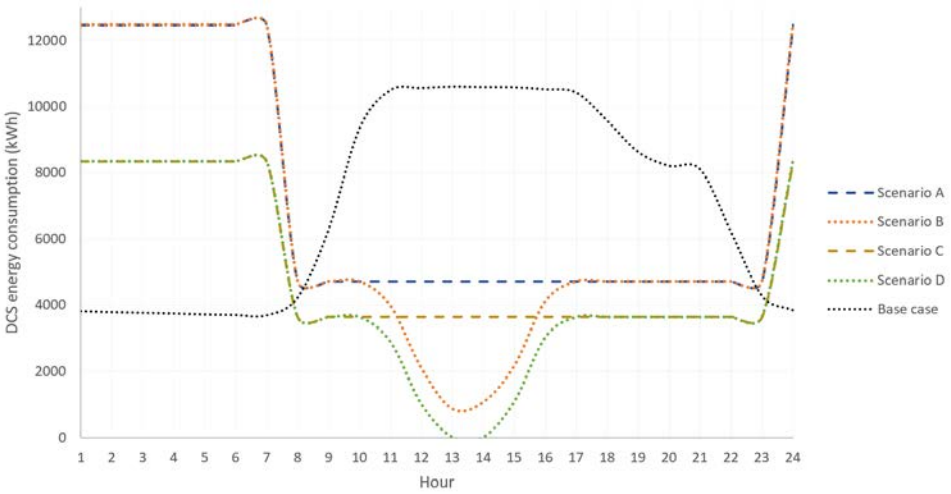

Fig. 3. Average hourly consumption for all scenarios

Table 4. Annual carbon emissions results

Scenario	Annual Carbon emission (CO_2 tonnes)	Carbon reduction compared to Base case (%)	NPV ($)	Payback period (year)	IRR (%)
Base case: GA optimized central chiller plant	25359	-	181,158,754	6	20.32
Scenario A: DCS	26340	- 3.87	204,055,484	6	20.77
Scenario B: DCS + PV	24226	4.47	185,746,565	7	14.86
Scenario C: DCS + Biomass CHP with ABC	22354	11.85	172,462,143	6	17.73
Scenario D: DCS + Biomass CHP with ABC + PV	20278	20.04	147,291,204	9	11.47

4 Conclusion

A comprehensive techno-economic analysis was conducted on four integrated scenarios combining renewable energy sources with a DCS to quantify potential energy savings, cost implications, and carbon mitigation. The scenarios varied in configurations of key subsystems, including the capacity of TES, PV system sizing, and a biomass-fired CHP unit coupled with ABC system. Results indicate that renewable integration with DCS leads to notable reductions in primary energy consumption and CO_2 emissions, albeit at the expense of increased capital expenditure. Financial modeling revealed a decline in NPV and an extension of the simple payback period, primarily driven by higher initial costs. Sensitivity analysis highlighted chilled water tariff as the most influential parameter affecting the economic feasibility across all configurations. Despite the observed economic trade-offs, the integration of renewable energy sources significantly enhances grid independence and aligns with long-term decarbonization objectives. Moreover, with ongoing advancements in technological performance and cost reductions, the negative impact on financial indicators is expected to attenuate over time.

Acknowledgment
This research is supported by the Ministry of Education, Singapore, under its Academic Research Fund Tier 1 (FY2024).

References

1. 10 Things You Should Know About Singapore's Energy Story. EMA. (2024, October 17). https://www.ema.gov.sg/news-events/news/feature-stories/2024/ten-things-you-should-know-about-sg-energy-story
2. POWER. NCCS. (n.d.). https://www.nccs.gov.sg/singapores-climate-action/mitigation-efforts/power/#:~:text=Power%20generation%20is%20one%20of,gas%20to%20power%20our%20nation.
3. SP Group Expands Marina Bay District Cooling Network With New Partnerships. (SP Group). (n.d.). https://www.spgroup.com.sg/about-us/media-resources/news-and-media-releases/SP-expands-Marina-Bay-district-cooling-network-with-new-partnerships
4. A. Inayat, M Raza, District cooling system via renewable energy sources: A review. Renewable and Sustainable Energy Reviews. 107, 360-373 (2019). https://doi.org/10.1016/j.rser.2019.03.023
5. Is Singapore considering biomass power plants? (EMA). (n.d.). https://www.ema.gov.sg/resources/faqs/energy-supply/low-carbon-alternatives/is-singapore-considering-biomass-power-plants
6. H.G. Ozcan, A. Hepbaslie, A. Abusoglu, A numerical approach to exergy-based sustainability and environmental assessments of solar energy-powered district cooling systems using actual operational data. Process Safety and Environmental Protection. 188, 1411-1422 (2024). https://doi.org/10.1016/j.psep.2024.06.043
7. Z.F. Huang, W.D. Chen, Y.D. Wan, Y.L. Shao, M.R. Islam, K.J. Chua, Techno-economic comparison of different energy storage configurations for renewable energy combined cooling heating and power system. Applied Energy. 356, 122340 (2024). https://doi.org/10.1016/j.apenergy.2023.122340

8. M. Neri, E. Guelpa, J.O. Khor, A. Romagnoli, V. Verda, Hierarchical model for design and operation optimization of district cooling networks. Applied Energy. 371, 123667 (2024). https://doi.org/10.1016/j.apenergy.2024.123667