Performance Optimization of Chiller Used for Commercial Building Air-Conditioning

Aaliya Azeem, C. Chiranjeevi, Y. Raja Sekhar, M. Natarajan, and T. Srinivas

Abstract The energy efficiency of buildings is highly affected by heating, ventilation, and air-conditioning (HVAC) systems being more energy intensive. The paper aims in providing an energy-efficient cooling solution by analyzing and modeling the cooling load requirement of a commercial building and optimizing the chiller system. Design Builder software integrated with Energy plus simulation software is used for predicting the scope of improvement by energy simulation modeling. The study also focuses on analyzing the performance improvement achieved with the optimized chiller system and by integrating it with efficient control strategies at the component level. With the energy-efficient optimization, along with the assessment of energy cost savings, the reduction in carbon emissions is also interpreted. About 50% energy savings is achieved with the water-cooled chiller retrofit, and with improved control strategies, energy consumption is reduced by 62%. An added advantage of reduced energy consumption is the reduction in carbon footprint, which is analyzed in the study. This reduction contributes to the global aim of reducing carbon dioxide emissions and controlling global warming.

Keywords Cooling load · Heating ventilation and air-conditioning (HVAC) · Chiller system · Energy simulation modeling · Energy consumption reduction · Carbon dioxide emission

---

A. Azeem (✉)
Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, Maharashtra, India
e-mail: aaliyaazeem95@gmail.com

C. Chiranjeevi · M. Natarajan
School of Mechanical Engineering, VIT, Vellore, Tamil Nadu, India

Y. R. Sekhar
Center for Disaster Mitigation and Management, VIT, Vellore, Tamil Nadu, India

T. Srinivas
Department of Mechanical Engineering, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar, Punjab, India

V. Edwin Geo and F. Aloui (eds.), *Energy and Exergy for Sustainable and Clean Environment, Volume 2*, Green Energy and Technology,
https://doi.org/10.1007/978-981-16-8274-2_34

1 Introduction

With the increase in population growth and demand for comfort needs, the energy usage has increased rapidly in the world. The energy usage of buildings is quite high, accounting to almost 40% of world's energy consumption. In buildings, more than 60% of energy consumption is by heating, ventilation, and air-conditioning (HVAC) systems followed by lighting systems and others [5]. The main aim of this paper is to lower the energy consumption of HVAC systems in a building by providing an energy-efficient cooling solution. The required cooling load for the building is modeled by cooling analysis of the building and necessary calculations. By obtaining the cooling load required, the cooling system can be designed accordingly to meet the optimum cooling requirements of the building. With the proposed chiller system, reduction in chiller energy consumption was predicted, and scope of improvement in effectiveness was analyzed using the energy simulations done through Design Builder software, which is integrated with Energy plus simulation software generated by US Department of Energy's (DOE) Building Technologies Office (BTO) [15].

By literature survey, different air cooling methods, its energy and economic analysis, etc., were studied [7], and this paper has focused on reducing the overall cost spent in chillers, by financial analysis. Studies about savings obtained through cooling equipment of different capacities in office building with its simulation analysis were also studied [8]. Also, by literature survey, the chiller effectiveness improvement through retrofit process was studied [9], and in this paper, the analysis also focuses on the monthly energy consumption reduction of the energy-efficient chiller system. Along with the retrofit of energy-efficient optimized chiller, the chiller components were also optimized by efficient mechanical control strategies. The importance of control system at the component level in improving the chiller effectiveness was also studied [3]. With these optimized efficient strategies, it means that the power consumption reduction was achieved, either by retrofit of the components or by automated controls [16]. This included replacement of pumps with variable drive pumps controlled by VFD, replacement of belt-driven blowers with efficient EC fans, etc. With the retrofit of less energy consuming EC fans with inbuilt speed controls, the energy consumption in air handling units (AHUs) is also reduced. By variable air volume (VAV) system, with advanced dampers and efficient controllers, volume of supply air can be varied, by which, demand-based cooling is achieved. For better chiller efficiency and heat transfer in the condenser side, auto-tube cleaning system (ATCS) is also implemented to remove condenser scaling. By integrating these control strategies with the energy-efficient chiller system, the energy savings and energy efficiency improvement is quantitatively validated with the real chiller plant studied here. Also, a financial analysis is done, in which scope of generating savings in total energy cost spent in chillers will also be estimated. Energy-efficient chiller system with its control measures helps in reducing the kW/TR that leads to better cooling results with high energy and cost savings.

Studies prove that the carbon emissions have a linear relationship with the electricity usage [18]. Therefore, with less chiller energy consumption and reduced electricity usage, CO_2 emissions can also be decreased. The reduction in CO_2 emissions due to less electricity usage is also calculated. Reduction in CO_2 emissions and lowering energy consumption leads to more energy-efficient sustainable buildings.

2 Methodology

2.1 Optimization of Chiller System—Cooling Load Analysis and Retrofit

In this paper, a corporate office building located in Bangalore, India, is taken as the case study here, in which the HVAC system optimization has to be done [12]. The building has six floors and two blocks, namely A-wing and B-wing. The building was already facilitated with three air-cooled chillers of 180 TR capacity (Screw compressor) in both the wings with a chilled water supply temperature of 7–9 °C. The chillers in A and B-wing support the base load and work for 12 h a day. The various zones in the office building are air-conditioned through 28 nos. of air handling units (AHUs). All the required details of existing chiller system were collected including the readings from energy meters for calculating the current chiller energy consumption. After analyzing the current load profile of the chiller and the data obtained from the existing system, we find the need to optimize the chiller. The existing system is short of many energy saving possibilities due to deterioration of chiller and lack of sophisticated technology and limitation of automated BMS system. Optimization of the chiller system and its components was highly essential. The chiller system has to be retrofitted with an energy-efficient chiller system, which can meet the present cooling load requirement [1]. For this, an efficient chiller system of capacity equivalent or more than the existing chiller capacity was preferred, meeting the cooling load requirement of the building.

Here, the cooling load requirement of the building was modeled using heat load calculations and Design Builder software, in which all the heat load factors were accounted for cooling analysis. This means that the factors contributing to heat generation in the building need to be considered. These factors include:

- Construction and orientation of the building,
- Number of people occupied in the building that contributes to sensible and latent heat load,
- U-value of the walls and windows exposed,
- Other loads, i.e., load of equipment or components like computers, etc.

For the 4054.72 m^2 floor area office building with six floors of ceiling height 4 m, the necessary considerations and factors were considered in the calculations for

Table 1 Factors for accessing the cooling load requirement

Sl. No.	Description	Values
1	Area of the building (m^2)	4054.72
2	No of people/employees occupied	1500
3	Occupancy density (people/m^2)	0.37
4	Computers power density (W/m^2)	4.72
5	Power density of other office equipment (W/m^2)	11.72
6	Window to wall (%)	40%

estimating the cooling load and for simulations in Design Builder software [14] as listed in the following Table 1.

The number of people occupied was observed to be 1500, which is needed for considering people heat load calculations. For solar heat gain through walls and windows, wall area and window area of the building in each orientation are accounted. Relative temperature difference is also accounted in heat gain for walls. The solar heat gains for walls, floor, and roof were calculated by using the formula:

$$Q = UA\Delta T \tag{1}$$

While in case of windows other than window area (A), the shading coefficient (SC) and solar heat gain factor (SHGF) of glass were also considered for calculating the solar heat gain factor (Q). The solar heat gain for windows is calculated by using the equation:

$$Q = A * SC * SHGF \tag{2}$$

For other heat load factors, U-values of walls and windows, solar heat gain coefficients, equipment power density (W/m^2), etc., were taken as according to the standard values specified in ISHRAE Data book. All the latent and sensible heat load factors were accounted, and the total effective room heat load was obtained by summing up the effective sensible heat load and effective latent heat load.

$$ERHL = E.S.H.L + E.L.H.L \tag{3}$$

By modeling the cooling load requirement for the building using heat load calculations and Design Builder software, the cooling capacity was estimated to be 320TR. The existing 3 nos. 180 TR air-cooled chillers in both the wings are replaced with 2 nos. (1 no. working and 1 no. standby) 320 TR water-cooled chillers in one of the wing and 1 no. air-cooled chiller in the other. Also, the chiller systems of both the wings are proposed to be integrated. This means that, the energy-efficient water-cooled chiller is proposed to be the main chiller system for the whole building, while the air-cooled chiller to be used as standby. The interconnection of both the wings helps in sharing of load during peak time.

2.2 Energy Simulations by Design Builder Software

The commercial building was modeled and simulated using Design Builder software which is integrated with the Energy plus simulation software, generated by US Department of Energy [4]. By energy simulations, energy consumption of the chiller system is derived for peak summer months (March, April, and May) from which, the efficient cooling system, reduction in energy consumption, etc., were determined. This software uses the built-in templates, in which simulations were done based on the COP, and all the heat load factors of the building were considered. The office building under case study is modeled in the Design Builder software as shown in Fig. 1.

By Design Builder software, the energy consumption results were generated for both the wings. After the retrofit of water-cooled chiller, the chiller effectiveness was decreasing over months. So, for proposed 320 TR water-cooled chiller (WCC) installed, the measured energy consumption was compared with the simulated results. The scope of reducing energy consumption and improving its effectiveness to the rated efficiency is studied by mitigating the cause for increase in kW/TR. By comparing energy consumption of installed water-cooled chiller during its installation and that of present condition, the condenser scaling was assumed to be a major cause for decrease in efficiency. Also, for the 300 TR air-cooled chiller to be installed as standby, the future energy consumption is simulated, and the reduction in energy consumption caused by the retrofit is predicted.

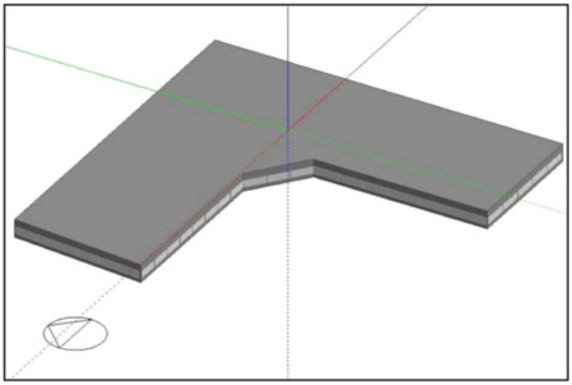

Fig. 1 Office building model generated in design builder software

2.3 *Performance Improvement with Efficient Control Strategies*

Other than the chiller replacement, the efficiency of chiller can be even more improved at the component level by optimizing the chiller components with efficient mechanical control strategies. With these optimized efficient integrated control strategies, it means that the power consumption reduction is achieved either by retrofit of the components or by automated controls [11].

This includes replacement of primary-constant and secondary-variable pumps with variable-driven primary pumps, replacement of belt-driven blowers with efficient electronically commutative fans, etc. Variable air volume (VAV) system with advanced dampers and efficient controllers automated by the building automation or building management system (BMS) helps in achieving demand-based cooling. After comparing energy consumption of water-cooled chiller during its installation and that of present condition, the condenser scaling was assumed to be a major cause for decrease in efficiency. For better chiller efficiency and heat transfer in the condenser side, auto-tube cleaning system (ATCS) is also implemented to remove condenser scaling, in order to improve chiller effectiveness.

2.3.1 Variable Primary Flow System

The initial system in both the wings had 4 nos. of primary pumps and 3 nos. secondary-variable pumps in chilled water system. The primary pumps were working with constant speed, and the secondary pumps were variable pumps in which the speed was varied according to the load. This system was proposed to be replaced with energy-efficient variable primary flow system without affecting the flow requirement. By proposed system, the secondary pumps were removed, and the constant flow primary pumps were replaced with variable primary pumps. With variable primary-driven system, the flow through the chillers can be increased slowly from zero to minimum required rate by controlling the speed at which the isolation valve opens. This helps in lowering the rate of change in chilled water flow through operating chillers. Also, the number of operating pumps need not match the number of operating chillers [17]. With variable speed drives (VSDs) provided in the primary pumps, it improves the pumping efficiency and lowers the pump energy cost due to reduced pump full load power requirement. It also contributes to huge energy savings and cost savings by eliminating the secondary pumps, its associated fittings and controls.

The inefficient primary–secondary-variable system is replaced with variable primary pumping system in both the wings, that included 4 nos. primary variable pumps, in which 2 nos. running and 2 nos. standby and 3 nos. of condenser pumps with 2 nos. working and 1 no. standby, for the main 320 TR water-cooled chiller. And for the air-cooled chiller, three primary variable pumps (in which 2 nos. running and 1 no. standby) were retrofitted.

2.3.2 Electronically Commutative Fans (EC Fans)

The existing variable frequency drive (VFD) fans are replacedwith energy-efficient electronically commutative (EC) fans with inbuilt speed controls [16]. EC fans can give 18–20% energy saving at full load operation, >30% energy saving during part load operations. EC fans are direct drive fans that are integrated into the cooling unit by replacing the centrifugal fans and motor assemblies. EC fans have permanent magnet motors with inbuilt speed controls. They are inherently more efficient than traditional centrifugal fans because of their unique design, which uses a brushless EC motor in a backward curved motorized impeller. EC fans achieve speed control by varying the DC voltage delivered to the fan. One of the main differences between VFDs and EC fans is that VFDs save energy when the fan speed can be operated below full speed. VFDs do not reduce energy consumption when the airflow demands require the fans to operate at or near peak load. Conversely, EC fans typically require less energy even when the same quantity of air is flowing [10]. With EC fans, higher energy efficiency, efficient air quality, and less maintenance are achieved.

With 27 nos. AHUs and 2 nos. EC fans per AHU, total of 54 nos. EC fans are installed. After installing EC fans, the static pressure can be measured using measuring devices behind the fans. With the measured static pressure and with high efficiency of 75%, the air flow in cfm and power consumption (kW) can be calculated.

Than the existed belt-driven blowers, more air flow (cfm) was achieved with EC fans with:

- Reduction in static pressure
- Increased efficiency and
- Less power consumption.

2.3.3 Variable Air Volume (VAV) Systems

The optimized chiller system can be operated more efficiently in terms of energy consumption if the whole system can be automated by controls and by integrating it to building automation or building management system (BMS) [13]. With advanced dampers and efficient VAV controllers, supply air volume can be varied in AHUs according to cooling demand. Normally, a variable air volume (VAV) system contains a damper, a damper actuator, controller, a digital thermostat (fixed in the room). The required temperature set in the room is achieved by thermostat and maintained; the airflow will be allowed just to maintain the set temperature. The controller and actuator works according to the feedback from the thermostat.

The main benefit of VAV controllers is that the power consumption is highly reduced and works according to the need by which more precise temperature control is achieved. Also, it helps in lowering the energy consumption of system fans. VAV units can respond to environmental changes such as increased occupancy or cooling demand and adjust air flow according to signals from a local or central control system providing good air quality. Better performance and constant temperature profile is achieved in the work place. With advanced dampers and effective controllers integrated with efficient automated control system, better cooling with improved efficiency is achieved. Implementation of VAV system with precision control actuators and BMS compatibility, i.e., completely automated, energy savings is obtained.

2.3.4 Auto-Tube Cleaning System (ATCS)

After comparing energy consumption of installed water-cooled chiller during its installation and that of present condition, the condenser scaling was assumed to be a major cause for decrease in efficiency. ATCS cleans the tubes, removing scaling, and the chiller works in full capacity. The water and balls are injected under controlled water pressure into the condenser removes accumulating residue every few minutes, before it can adhere to the tube walls. It also avoids the difficulty involved in manual cleaning. Auto-tube cleaning system (ATCS) was introduced to remove condenser scaling and to improve chiller efficiency. Energy consumption was simulated by Design Builder software for peak months with rated 0.5 kW/TR and present 0.7 kW/TR measured. On comparing the energy consumption before and after scaling, 28.57% increase in energy consumption was observed, as shown in Table.2.

From the literature studies [2], there is a linear relationship between percentage increase in chiller energy consumption and condenser scale thickness. Scale thickness of 0.76 mm was analyzed from 28.57% increase in energy consumption, as from case studies. With auto-tube cleaning system (ATCS), 20% energy savings can be achieved. Performance improvement with ATCS system was evaluated. Energy consumption reduction was realized by comparison of chiller system with and

Table 2 Increase in chiller energy consumption with condenser scaling

Sl. No.	Description	Value	Unit
Before scaling			
1	Design kW/TR	0.5	kW/TR
2	Chiller load	320	TR
3	Power consumption	160	kW
4	Operating hours	2880	h
5	Energy consumption	460,800	kWh
After scaling—present condition			
1	Measured kW/TR	0.7	kW/TR
2	Chiller load	320	TR
3	Power consumption	224	kW
4	Operating hours	2880	h
5	Energy consumption	645,120	kWh
	Percentage increase in energy consumption	28.57	%

without ATCS. Avoiding or decreasing the scale lowers the condenser approach temperature and increases COP, thereby chiller efficiency gets improved.

2.4 Financial Studies and Carbon Analysis

In HVAC chiller system optimization, with the reduction in energy consumption, energy costs can also be saved. The energy costs in INR per unit value of energy consumption kWh are 8 Rs. Therefore, energy costs are obtained by multiplying the energy consumption kWh with 8 Rs. The energy consumption of initial chiller system was calculated. With very high kW/TR, the annual energy consumption of 180 TR chiller system was 13,47,840 kWh. With energy cost of about 8 Rs. per unit kWh, annual chiller energy cost was 107.83 lakhs.

For the proposed 300 TR air-cooled chiller system with specific energy consumption of 0.7 kW/TR, the energy consumption was 210 kW. With 12 operating hours in a day, 20 operating days in a month, the annual operating hours was estimated to be 2880 h. Annual chiller energy consumption and annual chiller energy costs were estimated to be 6,04,800 kWh and 48.384 lakhs. As compared to the initial chiller system, annual energy savings and cost savings calculated were 7,43,040 kWh/annum and 59.44 lakhs (INR/annum). Therefore, with the retrofit of proposed 300 TR air-cooled chiller in A-wing, the chiller energy consumption and energy costs are expected to decrease by 55.12%.

In B-wing, for the proposed 320 TR water-cooled chiller system with specific energy consumption of 0.5 kW/TR, the energy consumption was 160 kW. With 12 operating hours in a day, 20 operating days in a month, the annual operating hours were estimated to be 2880 h. Annual chiller energy consumption and annual chiller energy costs were estimated to be 4,60,800 kWh and 36.86 lakhs. As compared to the initial chiller system, annual energy savings and cost savings calculated were 8,87,040 Kwh/annum and 70.96 lakhs (INR/annum). Therefore, with the retrofit of proposed 320 TR water-cooled chiller in B-wing, the chiller energy consumption and energy costs were expected to decrease by 65.81%.

For carbon analysis, studies proves that with carbon emissions have a linear relationship with electricity usage. Therefore, with less chiller energy consumption and reduced electricity usage, CO_2 emissions can also be decreased [6]. The reduction in CO_2 emissions due to less electricity usage is also calculated by multiplying 0.89 to energy consumption (kWh). The carbon emissions are derived with the measured chiller energy consumption values for each month and are compared [6].

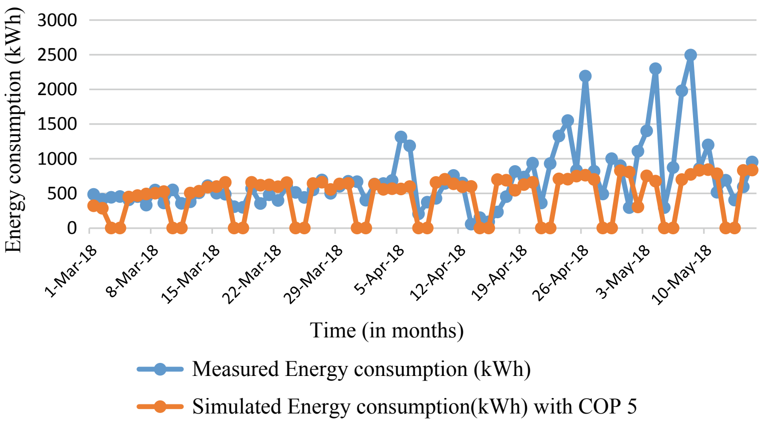

Fig. 2 Comparison of measured and simulated energy consumption of water-cooled chiller

3 Results and Discussion

3.1 Simulation Results for the Modeled Office Building

For the proposed main 320 TR water-cooled chiller (WCC) installed, the measured energy consumption was compared with the simulated results. The simulations template assumed weekends to be holidays, but practically, the chiller energy consumption on Saturdays and Sundays never went zero. Also, for the 300 TR air-cooled chiller to be installed as standby, the future energy consumption is simulated for the peak summer months, i.e., (for March, April, and May), and the reduction in energy consumption caused by the retrofit is predicted. The energy consumption is predicted to decrease by more than 70%. The graphical results as shown in Figs. 2 and 3.

3.2 Performance Improvement-Energy-Efficiency by Retrofit of Water-Cooled Chiller

By optimization of chiller and making it energy efficient, the building energy consumption decreased. The performance improvement obtained is studied, by comparing the monthly energy consumption before and after the retrofit. With the replacement of 180 TR air-cooled chillers by 320 TR energy-efficient water-cooled chillers, up to 50% energy consumption reduction is achieved, as shown in Fig. 4.

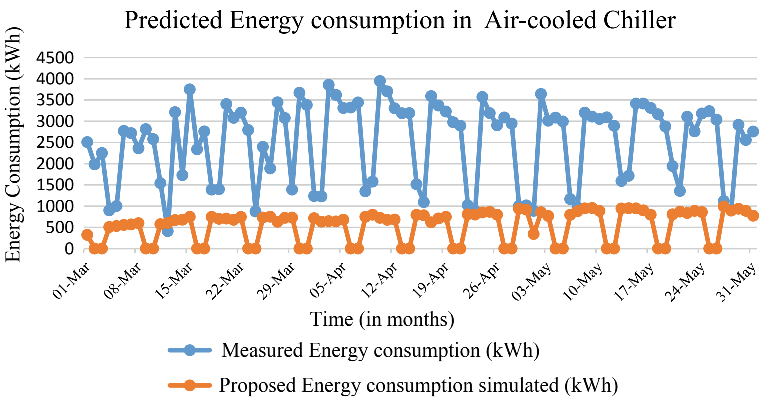

Fig. 3 Predicted chiller energy consumption reduction with proposed chiller

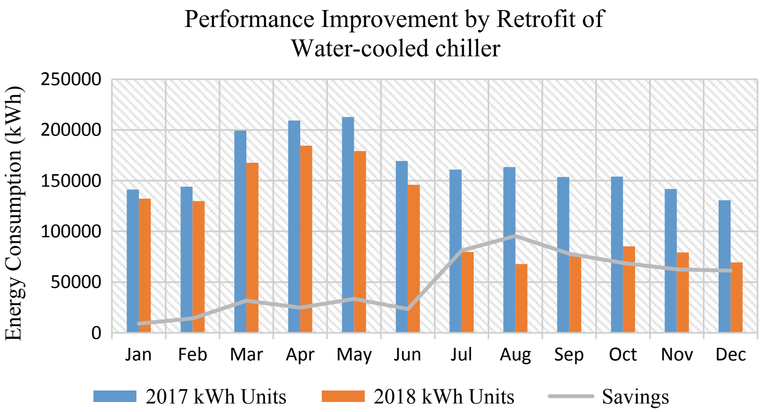

Fig. 4 Performance improvement with the retrofit

3.3 Reduction in Overall Chiller Plant Energy Consumption with Optimized Chiller and Efficient Control Strategies

Other than retrofit of energy-efficient water-cooled chiller, the chiller efficiency can be more improved by bringing energy efficiency at its component level. This is done by integrating the chiller system with efficient control strategies, i.e., by replacing its components with more efficient ones and also by automated controls. With the integration of energy-efficient control strategies at the component level, the chiller energy consumption is reduced by more than 60%. (as shown in Fig. 5).

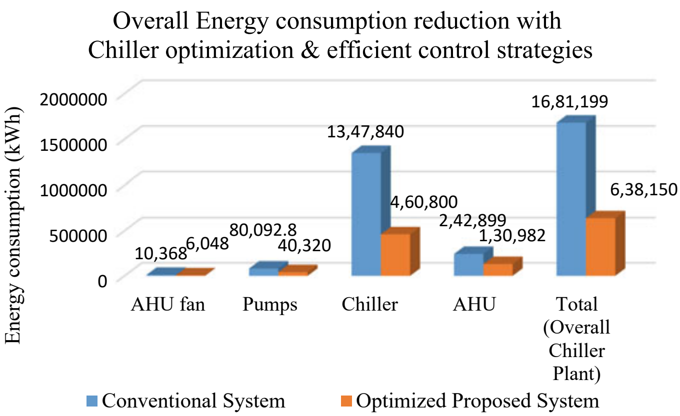

Fig. 5 Energy consumption reduction with efficient control strategies

3.4 Financial Studies: Energy Cost Savings with Energy-Efficient Chiller Retrofit

The energy cost savings achieved with both the proposed main water-cooled chiller and standby air-cooled chiller are studied, by calculating the energy costs caused due to old chiller system and that caused due to energy-efficient chiller system. With retrofit of air-cooled chiller to be used as standby, reduction in energy costs achieved is about 55%. While with the main operating energy-efficient water-cooled chiller installed which act as the main chiller for the whole building, the cost savings of more than 60% achieved, as in Fig. 6.

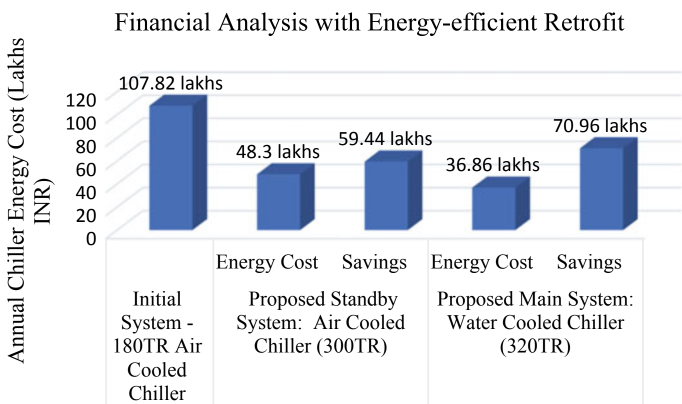

Fig. 6 Energy cost savings with the energy-efficient chiller retrofit

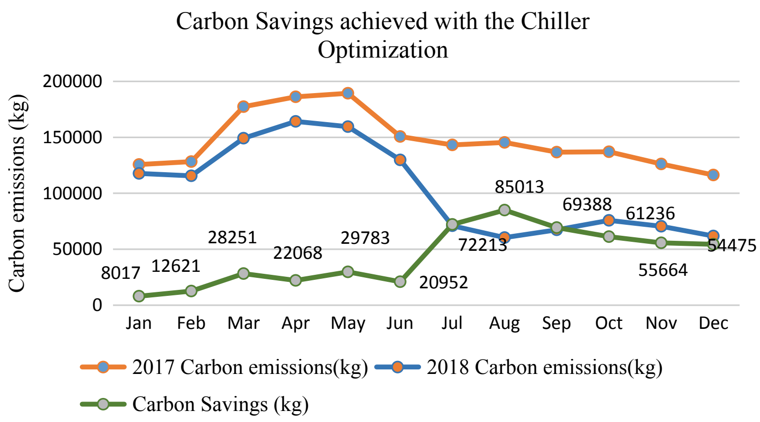

Fig. 7 Carbon emission savings with chiller optimization

3.5 Carbon Savings Analysis with Chiller Optimization

By calculating the carbon emissions from energy consumption values measured before and after the retrofit of energy-efficient water-cooled chiller, the monthly carbon savings achieved are analyzed. Since, the carbon emissions (in kg) are assumed to vary linearly with the energy consumption (kWh), as in Fig. 7, about 40–50% carbon savings are also achieved.

4 Conclusion

The air-conditioning system of the commercial building was analyzed and modeled meeting its cooling requirements. Energy savings of almost 50% are achieved by replacing the inefficient chiller system with energy-efficient water-cooled chiller. Also, with the increase in energy consumption observed for water-cooled chillers due to condenser, scaling was mitigated by auto-tube cleaning system. With the integrated control strategies at chiller component level, the chiller efficiency was improved by 62%. By financial studies, energy cost savings of about 55 and 65% were obtained with the proposed standby and main chillers, respectively. Along with decrease in chiller energy consumption (kWh), the carbon emissions also decreased by 40–50%.

Acknowledgements We are very thankful to VIT University for providing great support in completion of this project work. Also, expressing gratitude to those in office building, Bangalore, and who have helped in providing the constant support.

References

1. Arya JS, Chavda DK (2014) Design and performance analysis of water chiller—a research. Int J Eng Res Appl 4(6):19–25
2. Beitelman AD, McInerney MK (2014) Demonstration of noncorrosive, capacitance based water-treatment technology for chilled water cooling systems. US Army Corps of Engineers
3. Chen CW, Lee CW, Chen CY (2010) To enhance the energy efficiency of chiller plants with system optimization theory. Energy Environ 409–424
4. Chowdhury AA, Rasul M, Khan M (1923) Modelling and simulation of building energy consumption. A case study on an institutional building in central Queensland, Australia. Build Simul 1916–1923
5. Chua KJ, Chou SK, Yang WM (2013) Achieving better energy-efficient air conditioning—a review of technologies and strategies. Appl Energy 104:87–104
6. Congradac V, Kulic F (2009) HVAC system optimization with CO2 concentration control using genetic algorithms. Energy Build 41(5):571–577
7. Dashtebayaz MD, Najafabad PK (2018) Energy, Exergy, Economic, and Environmental analysis for various inlet air cooling methods on Shahid Hashemi-Nezhad gas turbines refinery. Energy Environ 1–18
8. Entchev E, Kangb EC, Lee EJ (2015) Future energy paradigm of microgeneration technologies for decentralized smart home and office buildings. Energy and Environ 67–81
9. Kumar CV, Marjanovic-Halburd D (2014) An investigation into retro-commissioning effectiveness in tropical climates. ASHRAE Trans 120(L1)
10. Lelkes A (2003) Electronically commutated motors. In: Proceedings of the international intelligent motion conference. INTERTEC International, Inc., pp 167–172
11. Liu Z, Song F, Jiang Z, Chen X (2014) Optimization based integrated control of building HVAC system. Build Simul 7(4):375–387
12. Lu L, Cai W, Xie L, Li S, Soh YC (2005) HVAC system optimization—in-building section. Energy Build 37:11–22
13. Ma K, Zhao T, Shen D, Liu M (2017) Web based chiller plant optimal control-a case study. Proc Eng 205:967–974
14. National Renewable Energy Laboratory (2011) Saving energy in commercial buildings-plug load assessment guidelines. Colorado:National Renewable Energy Laboratory (NREL)
15. Pan Y, Yin R, Huang Z (2008) Energy modeling of two office buildings with data center for green building design. Energy Build 40(7):1145–1152
16. Saidur R, Mekhilef S, Ali M, Safari A, Mohammed H (2012) Applications of variable speed drive (VSD) in electrical motors energy savings. Renew Sustain Energy Rev 16(1):543–550
17. Shaikh PH, Nor NB, Nallagownden P, Elamvazuthi I, Ibrahim T (2014) A review on optimized control systems for building energy and comfort management of smart sustainable buildings. Renew Sustain Energy Rev 34:409–429
18. Taylor ST, E P (2002) Primary-only versus primary-secondary variable flow systems. ASHRAE J 25–29
19. Wang X, Huang C, Zou Z (2016) The analysis of energy consumption and greenhouse gas emissions of a large-scale commercial building in Shanghai China. Adv Mech Eng 8(2):1–8