SUSTAINABILITY MANAGEMENT IN ENERGY CONSUMPTION THROUGH OPTIMISED OPERATION OF HVAC SYSTEMS IN COMMERCIAL BUILDINGS

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Declaration

This research project is submitted in fulfilment of the requirements of the degree of Master of Research, in Macquarie Graduate School of Management, Macquarie University. This represents the original work and contribution of the author.

I hereby certify that this has not been submitted for a higher degree to any other university or institution.

Signed:

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October 2018

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Abstract

Sustainability is a multifaceted concept that is being discussed and considered in almost every aspect of our society today. One of the significant business sections where sustainable development could be considered is in buildings. As most activities in buildings are significant contributors in energy considering their size and operating hours, reducing energy demand plays an important role in a building's sustainability. Most of the energy in buildings is used by heating, ventilation and air conditioning (HVAC) systems; so high-level performance of an HVAC system is a critical factor in a building's sustainability.

Building management systems (BMS), through using computer hardware and software, manage various functions of a building including but not limited to HVAC systems, which enables monitoring, controlling and optimising the operation of these systems that results in improving energy efficiency (Smiciklas et al. 2012).

The aim of this research is to demonstrate the effects of an integrated and comprehensive HVAC operation in the reduction of energy consumption and CO_2 emissions and to establish the potential for achieving a sustainable environment. In this regard, the performance of six chillers and three pumps, as most demanding components of a given HVAC system in terms of energy consumption, have been compared before and of after optimisation.

Results show that through appropriate operational management not only the equipment life increase but a significant decrease in the greenhouse gas emissions also will be achieved.

LIST OF ABBREVIATIONS

˚C	degrees Celsius
bhp	brake horsepower
c	cent
c/kWh	cent per kilowatt hour
CH_4	Methane
CO_2	carbon dioxide
CO_2-e	carbon dioxide equivalent
$GtCO_2$	gigatons of carbon dioxide
Gtoe	gigatons of Oil Equivalent
kg	Kilogramme
kW	Kilowatt
kWh	kilowatt hour
L/s	litres per second
m	Metre
m^2	square metre
m^3/s	cubic metre per second
M-tonnes	Megatonnes
N_2O	nitrous oxide
NH_3	Ammonia
NOx	Nitrogen oxides
P	Power
Pa	Pascal
ppm	parts per million
Q	the quantity of electricity purchased

V	Water volume flow rate
Y	Emissions measured in CO_2-e tonnes
ΔP	Pump total (static + dynamic) pressure drop across the pump
η	Pump efficiency × motor efficiency × drive (belt and pulleys) efficiency × VSD efficiency
ACE	Automated commissioning for energy
ACT	Australian Capital Territory
AHU	air handling unit
AIRAH	Australian Institute of Refrigeration, Air Conditioning and Heating
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCS	Building control system
BEES	Building for Environmental and Economic Sustainability
BEP	Best efficiency point
BMCS	Building monitoring and control system
BMS	Building management systems
BREEAM	Building Research Establishment Environmental Assessment Method
CBD	Central business district
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of performance
DC	direct current
DDC	direct digital control
EER	Energy efficiency ratio
EF	emission factor
EU	European Union
GBCA	Green Building Council of Australia
GHG	Greenhouse gases

HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
IPLV	Integrated part-load value
LEED	Leadership in Energy and Environmental Design
MEPS	Minimum energy performance standards
NABERS	National Australian Built Environment Rating System
NBI	New Buildings Institute
NPLV	Non-standard part-load value
OED	Orthogonal experimental design
PC	Personal computer
PV	Photovoltaic
TPES	Total primary energy supply
USGBC	US Green Building Council
VAV	Variable air volume
VFD	Variable-frequency drive
VSD	Variable-speed drive
WBCSD	World Business Council for Sustainable Development
WC	Western countries

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1 Introduction

The concept of sustainable development started in the early 1980s based on which standards and measures were set to prevent market failures, confirm the regenerative capacity of renewable resources, avoid growing pollution and manage production processes towards greater eco-efficiency (Turner 2006).

In sustainability studies, energy savings and protection of the environment are great points of concern. Energy economy is considered in its totality, i.e. production as well as consumption. Given the close relationship between energy consumption and economic development, the necessity of a comprehensive understanding and continuous monitoring of energy consumption requires ever-increasing attention (Allouhi et al. 2015).

Since the industrial revolution, the growing levels of consumption of fossil fuels has led to a rapid enhancement in CO_2 emissions, Figure 1 exhibits a growth of 62% from 1990 to 2016, disrupting the global carbon cycle and resulting in a planetary warming impact. Global warming and climate change have a range of potential physical, ecological and health impacts, such as extreme weather events (including droughts, floods, storms, and heatwaves); sea-level rise; crop growth alteration; and water systems disruption (Ritchie & Roser 2018). The global average temperature growth can be seen in Figure 2. The red line shows the average annual temperature trend within time, which over the last few decades has risen sharply at the global level to approximately 0.8°C. The grey lines show the upper and lower confidence intervals (the possible upper and lower range).

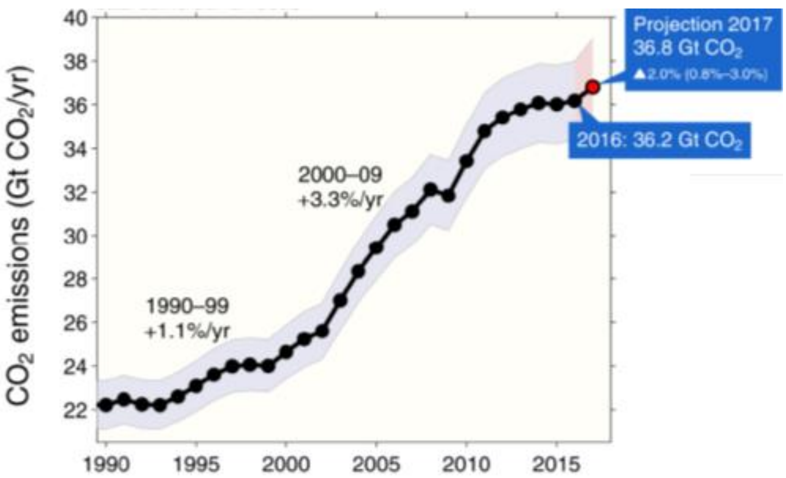


Figure 1: Global emissions from fossil fuel and industry:36.2 ± 2 $GtCO_2$ in 2016, 62% over 1990. (Le Quéré et al. 2017, p. 9)

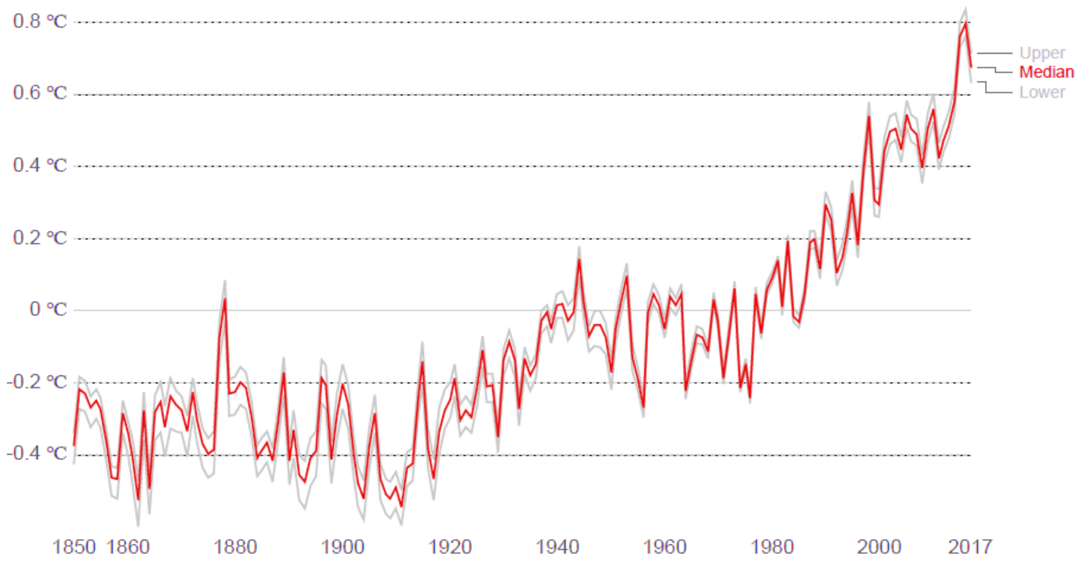


Figure 2: Temperature anomaly (Ritchie & Roser 2018, p. 2)

A significant amount of energy used in the world today is consumed in the buildings sector. The International Energy Agency (IEA) has identified the building sector as one of the most cost-effective sectors for reducing energy consumption. It consumes approximately 32% of global final energy use, making it responsible for almost 15% of total direct energy-related CO_2 emissions from final energy consumers. By considering indirect upstream emissions attributable to electricity and heat consumption, the building sector contributes 26% of all CO_2 emissions (IEA 2012).

CO_2 emissions of buildings grew 1.9% per year between 1971 and 2009. Direct CO_2 emissions from fossil fuels accounted for 36% of the buildings sector's emissions in 2009, 2.9 gigatons of CO_2 ($GtCO_2$), with indirect emissions considered for the remaining 64% (IEA 2012).

Buildings are complicated structures, with intertwined uses of energy. In most countries, the most potential for upgrading energy efficiency and minimising CO_2 emissions relates to space heating, ventilation, and air conditioning. As can be seen in Figure 3, about 40% of energy consumption in an office building in Australia is accounted for heating, ventilation and air conditioning (HVAC) systems (Lecamwasam, Wilson & Chokolich 2012).

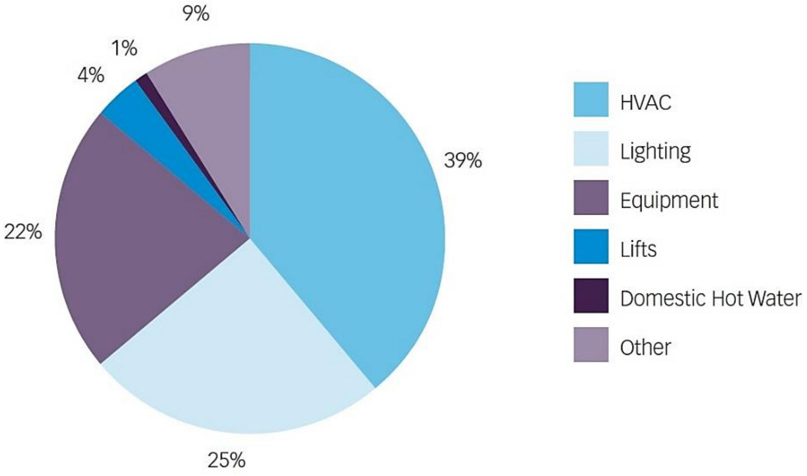


Figure 3: Typical energy consumption breakdown in an office building in Australia
(Lecamwasam, Wilson & Chokolich 2012, p. 36)

HVAC systems are targets for sustainability improvements in many facilities due to the high costs of their installation, operation, and maintenance. Changing an HVAC system demand is more easily done than other energy users in an office. An appropriately adjusted HVAC system can provide years of comfort for occupants with lower energy bills (Williamson 2014a).

The building control system (BCS) or building management system (BMS), is a computer-based control system to monitor and evaluate a building's mechanical and electrical equipment systems. A BMS consists of centralised software and hardware networks, which connect the different pieces of building equipment so that they operate as one perfect integrated system to control the indoor climatic conditions in building facilities. The operational performance of buildings can be examined with these control systems (Shaikh et al. 2014).

Adjusting the operations of HVAC equipment results in substantial reductions in energy consumption. Arranging only static set-point temperatures for the heating and cooling equipment regardless of external conditions cannot achieve adequate benefits (Rocha, Siddiqui & Stadler 2015).

In this research, the importance of optimised HVAC operation in reducing energy demand in commercial buildings and resulting in a sustainable environment have been demonstrated. In this regard, operational data for HVAC systems is gathered from CIM Enviro, which is an environmental group that offers optimisation solutions for building owners to reduce their energy footprint and, consequently, energy expenditures. Their automated commissioning for energy (ACE) platform implements fault detection and rectification algorithms to detect and pinpoint faults in building systems. Reducing energy wastage due to faulty systems or off-design control strategies represents a low-cost, high-impact approach to energy conservation.

2 Background

2.1 Sustainability in buildings

Sustainable development benefits a wide range of sectors and generations. Our actions today can have a remarkable impact on future generations. Reducing energy consumption and emissions of greenhouse gases is a social goal concerning everyone (Gohardani 2014).

The idea of sustainability ultimately aims to improve the quality of life and provide a healthy environment for people to live, with improved social, economic, and environmental conditions (Ortiz, Castells & Sonnemann 2009). Sustainability is a complex and broad area and has become one of the crucial issues in the building industry, as buildings have a great potential to contribute to sustainable development. A sustainable project is designed, built, operated, and reused in an efficient manner (Ortiz, Pasqualino & Castells 2010). In this regard, it should meet several aspects such as resource and energy efficiency; CO_2 and GHG (greenhouse gases) emissions reduction; pollution prevention; improved indoor air quality (John, Clements-Croome & Jeronimidis 2005). Controlling and correcting the environmental damage of the building industry has attracted the attention of building industry practitioners. Engineers, architects, and others involved in the building process try to reduce environmental impact by implementing sustainability objectives through the design and operation stages of a building project.

New standards such as the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED) and Building for Environmental and Economic Sustainability (BEES) are being developed to improve sustainable structures. They aim to decrease the overall impact of the built environment on human life and the natural environment (Olomolaiye, Chinyio & Akadiri 2012).

2.2 Energy use and greenhouse gases

Greenhouses gas (GHG) emissions made by human activities change the radiative energy balance of the Earth’s atmosphere system. These emissions intensify the natural greenhouse effect, causing temperature variations and other consequences for the Earth's climate. Climate change is a concerning issue, as it affects ecosystems (biodiversity), human settlements, agriculture, and the frequency and scale of weather events. Thus, it would have significant outcomes for human wellbeing and socioeconomic activities, which could in turn influence global economic output (OECD 2014).

Climate scientists' observations show that carbon dioxide (CO_2) concentrations in the atmosphere have increased significantly over the past century, in contrast to the pre-industrial era level which was about 280 parts per million (ppm), in 2016 it reached 403 ppm, about 40% more than in the mid-1800s, with an average growth of 2 ppm/year in the last 10 years.

The fifth appraisal research of the intergovernmental panel on climate change emphasises human activities, as using energy is by far the largest source for emissions. Smaller shares relate to agriculture, producing mainly methane (CH_4) and nitrous oxide (N2O) from domestic livestock, industrial processes not related to energy, producing mainly fluorinated gases, N_2O, and etc.[1] (Figure 4).

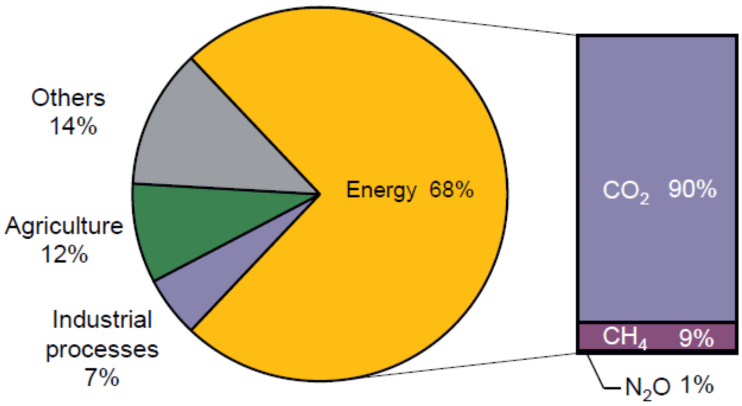


Figure 4: Estimated shares of global anthropogenic GHG in 2014 (IEA 2017, p. xi)

CO_2 emissions from the oxidation of carbon in fuels during combustion account for the majority contribution of global anthropogenic GHG emissions (IEA 2017).

Worldwide economic growth and development have raised energy consumption. According to Figure 5, which shows world primary energy supply in gigatons of oil equivalent (Gtoe) in years 1971 and 2015, global energy demand as measured by total primary energy supply

[1] Others include large-scale biomass burning, post-burn decay, peat decay, indirect N_2O emissions from non-agricultural emissions of NO_x and NH_3, waste, and solvent use.

(TPES) has increased about 150% between 1971 and 2015, while it is still mainly relying on fossil fuels.

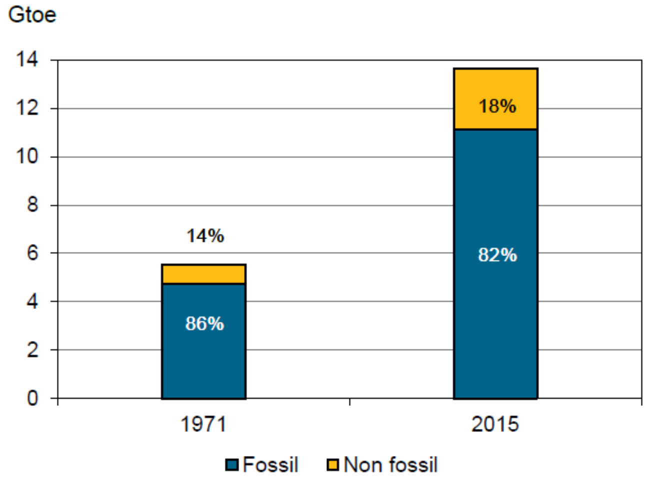


Figure 5: World primary energy supply (IEA 2017, p. xii)

Although the non-fossil energy industry (considered as non-emitting) has developed during the last decades (including nuclear, hydropower and other renewable sources), the contribution of fossil fuels is relatively constant (IEA 2017). Rapid growth in energy consumption from fossil fuels has played a key role in the upward trend of CO_2 emissions. Thus, the urgency of decreasing energy demand is an essential issue in the world. For this goal, a particular notice should be given to the characteristics of the building sector due to its significant amount of energy usage and the associated CO_2 emissions (Allouhi et al. 2015).

2.3 Commercial buildings are one of the large energy sectors

Most of the energy used by commercial buildings is in the form of electricity, which is the most greenhouse-intensive energy source (Saltman 2000). They are one of the most considerable contributions of energy consumption. For example, commercial buildings in Australia account for almost a quarter of the electricity consumed (Figure 6).

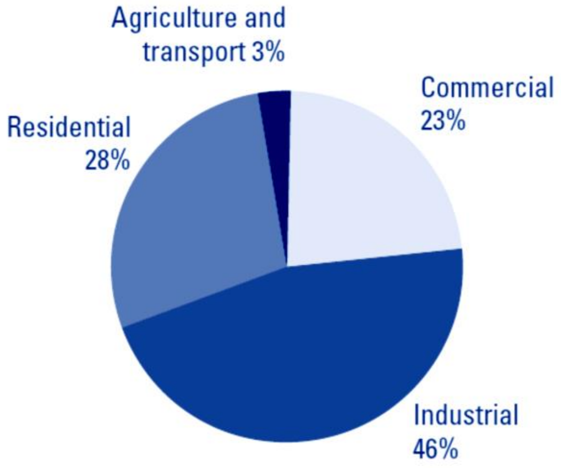


Figure 6: Electricity use in Australia by sector (Saltman 2000, p. 8)

The quality of operational phase in buildings has a significant impact on the total CO_2 emissions. For instance, between 70% and 90% of a commercial building's total greenhouse gas emissions are produced during the operational phase. Also, a considerable proportion of total commercial buildings are old (older than 15 years); thus, improving the environmental performance of existing buildings during their life-cycle requires significant attention (Hes et al. 2009).

Improving energy efficiency will (Saltman 2000):

- reduce energy bills
- reduce greenhouse gas emissions
- reduce maintenance costs
- increase product output
- extend the useful working life of the equipment

One of the large segments in consuming energy in commercial buildings belongs to the HVAC system. The use of HVAC technologies is an essential element of contemporary life. These systems contribute to greenhouse gas releases directly and indirectly through energy-related effects and directly through the effect of refrigerant losses. (ASHRAE 2006)

2.4 HVAC and maintenance

It is undeniable that having frequent maintenance would affect a building's performance positively. HVAC systems impact a building's efficiency in various ways. Comprehensive control and maintenance results in better operating performance and efficiency, which lengthens the lifespan of equipment. A well-maintained system is less likely to break down and results in a safer and more comfortable environment. It improves the system productivity, energy and water use, and a systems' sustainability over its 'whole life'.

System performance and benchmarking are critical issues when considering the sustainability of HVAC systems. What can't be measured can't be managed, so monitoring, metering, recording and reporting practices are all fundamental to sustainability claims. (AIRAH 2014). However, sometimes energy savings opportunities are missed through maintenance.

There are three basic modes of maintenance of HVAC systems in buildings as follows (IBE 2012):

1. *Reactive maintenance.* Through this management practice, HVAC systems work until a problem or failure occurs. In this procedure, repair cost will be at its maximum level, and there will be interruptions in service during the repairs. (This strategy also called run-to-fail maintenance.)
2. *Preventative (or scheduled) maintenance.* In this practice, used by 31% of properties, the number of checking times is based on manufacturers' prescriptions.
3. *Predictive maintenance.* This is practised by 12% of buildings, and the strategy differs from preventative maintenance, as maintenance is based on the actual condition of the machine, rather than on a pre-set schedule. This type can be the most cost-effective in the long term, but it requires technology infrastructure enterprises up front.

Planned predictive maintenance is vital for an HVAC system in accordance with the task detail and standards required. Effective management of HVAC operation and maintenance can be improved with an advanced computerised maintenance building management system (BMS). The BMS is cost-effective and can raise tailored instructions and minimise faults. It can also be used to maintain records for electricity meters, water meters and equipment working-hour (Lecamwasam, Wilson & Chokolich 2012).

2.5 How BMS works

Building management systems (BMS) is a solution for measuring and managing energy consumption. It can control and monitor energy consumption in large systems within a building, such as HVAC system, lighting, fire, and security systems. The main goal of a BMS is to maintain occupant comfort and safety while delivering energy efficiency at lower operating costs. Optimum operation via a BMS system is essential for every building to be cost-effective and achieve better performance by reducing energy consumption.

An HVAC system is made up of several equipment such as chillers for cooling, boilers for heating, air handling units for air conditioning, pumps, fans, and other auxiliary components controlled by a central system. The BMS can monitor and control the operation of these elements by receiving information from different sensors. These sensors measure key parameters including temperature, system pressure, flow, relative humidity, and carbon dioxide levels (as a measure of indoor air quality), etc. These parameters should be monitored and changed based on various outside conditions (HVAC HESS 2013a).

2.5.1 Some BMS basics

In most buildings, the BMS has various direct digital control (DDC) systems which are located separately with HVAC equipment or in a plant room. All these systems can be linked together via a local area network and are connected to a head station to provide a user interface for monitoring control settings and altering them in different situations. BMS uses communication protocols, which are rules that electronic components or microprocessors use when communicating with one another. There are various types of communication protocols (HVAC HESS 2013a).

3 Literature review

3.1 Building approach to sustainability

The concept of sustainable development became more acceptable after Brundtland's commission report, 'Our Common Future', in 1987, which was at the request of the United Nations and became an ethical principle: 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (United Nations 1987, p. 16). This report aimed to combine technology, economics and sustainable development based on justice in the world (Gohardani 2014).

In 1994, John Elkington used the term 'triple bottom line' to define sustainability as the association of social, economic and environmental value (Hosey 2017). Since then, thousands of initiatives have been taken to address various aspects of environmental challenges.

In the 1990s a key technology introduced that was building energy management systems, which at first used expensive minicomputers as central stations, but as PCs were introduced the system became more economical and intelligent, and the energy consultancy market became more popular (Fawkes 2001).

However, as the impact of shaping 'Our Common Future' couldn't be compared with the enormity of the global environmental challenges, many national and international policies appeared (Mebratu 1998).

Many countries set building codes as minimum requirements for energy efficiency, and some have developed optional standards to encourage building owners to achieve higher-energy-efficiency buildings. These standards contain energy assessment tools and calculation methods to label building energy performance while having more forward-looking requirements that contain environmental aspects as well (Allouhi et al. 2015).

One of these first attempts is the US Green Building Council (USGBC), which was created in 1993 to promote sustainability in the buildings and construction industry. The USGBC created Leadership in Energy and Environmental Design (LEED) to rate a building's sustainability based on design, construction, operation and maintenance (Williamson 2014b). Today, LEED has become the most widely used building rating system in the world as is used in over 165 countries and territories (LEED 2018). After the verification of project acknowledgment with

LEED requirements, the certification is decided particularly by the GBC Institute. However, verification of energy assessment in buildings with LEED certification is a subject of scientific argument. For instance, in 2008 the New Buildings Institute (NBI) published a report about energy reduction of about 25–30% by LEED certification (Turner & Frankel 2008), although the results and the methodology adopted have been criticised by many researchers. In this regard, many studies investigated the energy savings of LEED-certified buildings and calculation methodology (Allouhi et al. 2015).

At the beginning of the 21st century, due to concerns over changing climatic conditions (global warming, depletion of ozone layer, etc.), the European Union (EU) described some rules for energy consumption as below (EU 2011, p. 2):

- The EU GHG emissions reduction should be at least 20% below the levels of 1990.
- Renewable energy contribution should be a minimum of 20% in energy consumption.
- Primary energy usage should be reduced to 20% in comparison to anticipated levels through energy efficiency measures.

The Green Building Council of Australia (GBCA) was established in 2002 to improve sustainability in Australia. Buildings were soon subsequently evaluated in a range of categories including energy, management, GHG emissions, indoor air quality, water, materials, transport, land use and site selection (Allouhi et al. 2015).

Another standard in Australia is NABERS (National Australian Built Environment Rating System), which the environmental performance of a building is measured and compared against its market. It evaluates the energy efficiency, waste management, water usage and indoor environment condition of a building or tenancy and its impact on the environment. The rating system is on a 6-star scale, with 3 stars representing average performance. A 6-star rating demonstrates market-leading performance, and a 1-star rating means the building is performing below average market and has considerable scope for improvement (AIRAH 2013).

As well as these organisations setting minimum energy performance standards (MEPS) is another successful effort. MEPS specify the minimum energy performance that appliances and electrical equipment (products) must meet before they can be used for commercial purposes. The first minimum energy performance standards were introduced for residential refrigerators, industrial motors and commercial fluorescent lamp appliances and equipment between 1999 and 2003. Since then many other appliances and equipment have been subject to MEPS (Saddler 2013).

In a research by Allouhi et al. (2015) an overview of measures and policies adopted by different countries has been reported and discussed in detail. It contains critical aspects of these policies based on the feedback of the early adopters.

Generally, the growing energy demand in buildings has become a challenging issue, as buildings consume more than one-third of the total primary energy supply. Figure 7 shows the building energy consumption percentage in some countries in 2008 (Shaikh et al. 2014).

In this context, the World Business Council for Sustainable Development (WBCSD) in 2009 in a research study found that the energy usage in buildings could be cut dramatically as much as the entire transport sector uses (WBCSD 2009).

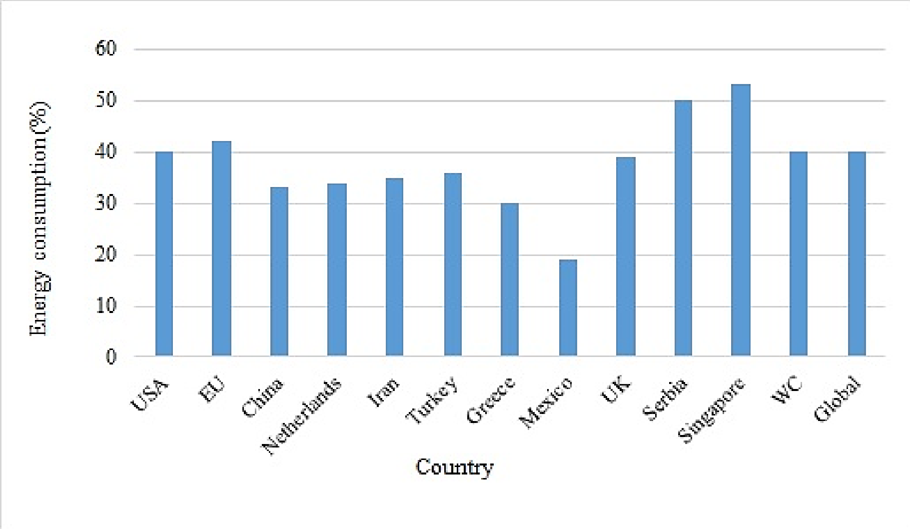


Figure 7: Building energy consumption in selected countries (Shaikh et al. 2014, p. 410)

Many studies have aimed at implementing sustainability principles in the building industry and putting forward strategies and methods to mitigate the environmental impacts, thereby facilitating the sustainability of building projects. This research contains a review of these studies.

3.2 Low-carbon strategies

A comprehensive approach to achieving low-carbon sustainability incorporating both energy and carbon-reduction strategies in large commercial buildings in China has been discussed by Jiang & Tovey (2009). They look at effective energy management systems, incorporation of appropriate advanced energy-saving technologies and policies to encourage a more environmentally friendly behaviour.

Regarding sustainable cooling technologies in buildings, Hughes, Chaudhry & Ghani (2011) reviewed basic descriptions along with the features and limitations of different techniques and evaluated the common practice of implementing passive and active cooling technologies in buildings. The study revealed that wind towers[1] could be an excellent source to decrease external electricity loads in buildings, as they consume minimal or no external power for their operation.

Zhu et al. (2013) developed a new optimisation method for building envelope design to achieve the lowest carbon emissions of building operational energy consumption using OED (orthogonal experimental design), which includes a simplified algorithm based on steady-state heat transfer theory, and dynamic simulation based on the unsteady heat transfer theory.

Ardente et al. (2011) showed that energy consumption and environmental impact are concentrated in the operational phase of a building. Production and transportation of building materials and the construction of the building only account for 2.2% of the primary energy consumption over the lifetime of the building. Through the 75-year lifetime of a building, the operational phase consumes about 97.6% of the total primary energy consumption. This amount includes the HVAC system, lighting, appliances, general services (94.4%), and water services (3.2%). About 0.2% of the primary energy consumption over the lifetime of the building relates to demolition and transportation of waste. Thus, the predominance of HVAC systems as a high energy consumption application especially in commercial buildings is conspicuous (Pérez-Lombard, Ortiz & Pout 2008).

However, most building owners don't have detailed knowledge of their electricity bills. A survey in the United Kingdom shows of 2.5 million small businesses suggests that 52% have no grasp of how much their electricity and heat bills account for (*Half of small business owners don't know what they spend on energy*, 2014).

Existing facilities constitute a large share of the building stock in industrialised countries due to the lack of new construction. Thus, making retrofits and having operational management in existing equipment is of paramount importance (Groissböck et al. 2013).

It should be noted that using renewable resources in buildings has several limitations (Shaikh et al. 2014). Therefore, efficient energy management through HVAC systems in buildings would be noticeable, since they account for most of the electricity consumption in the lifetime

[1] A wind tower (wind catcher) is a traditional Persian architectural element to create natural ventilation in buildings (Bahadori & Dehghani-Sanij 2014).

of a building and have a broad potential to improve. The consequence is that they would help to preserve fossil resources, reduce the energy cost for consumers and business, and lead to a significant reduction in GHG emissions that would allow building sustainability.

3.3 A survey on HVAC system optimisation

The most significant portion of energy inside buildings is used by HVAC systems. A small increase in operating efficiency can result in striking energy savings. However, due to the complexity of HVAC systems – thousands of rooms and hundreds of cooling coils in a large-scale – achieving optimal operation is not an easy task (Lu et al. 2005).

There has been much research about energy saving in HVAC systems both for individual component efficiencies or part-of-system efficiencies. The energy saving via the variable-speed drive (VSD) pumps in the chilled water loop is an interesting topic that has attracted many researchers' interest. The efficiencies of pumps and fans were studied by Braun et al. (1989). In pumps or fans equipped with VSD, the total pump/fan efficiencies may vary between 80% and 40%. House and Smith (1996) studied optimisation on variable air volume (VAV). Braun et al. (1989) and Ahn & Mitchell (2001), described indoor air loops and chilled water loops.

For whole-system optimisation, various energy-saving strategies have been compared for HVAC systems by Rahman, Rasul & Khan (2010) in a building in sub-tropical (hot and humid climate) area in Queensland, Australia and could achieve 41.87% energy conservation without disturbing thermal comfort.

A simulation–optimisation approach in response to the problem of effective energy management in HVAC systems has been developed in recent years. In this regard, various functions have been developed, like the year-round energy consumption, life-cycle cost, thermal comfort, design parameters, as reflected from the studies of Wright (1986), Kintner-Meyer (1994), Huh (1995) and Taylor (1996) respectively.

The number of applications of the plant simulation models for decision-making purposes are increasing. For instance, Wright, Loosemore & Farmani (2002) investigated a multi-criterion optimisation approach and several possible scenarios for decision-making rather than just one solution (Fong, Hanby & Chow 2006).

Cutillas, Ramírez & Miralles (2017) have modelled an air conditioning system in which the main elements are a cooling tower and a water-cooled chiller in a reference building. The model has been validated using experimental data. They implemented an optimising control strategy to reduce both energy and water consumption and could reach up to 10.8% energy savings and a reduction of 4.8% in water consumption.

In the 1980s, energy performance before and after retrofit programs for 100 residential buildings in the US and Canada have been studied at Lawrence Berkeley Laboratory. First, they derived up to 20–30% reduction in average space-heating energy use (Goldman 1984), while follow-up research showed an average annual electricity savings of 16% (Cohen, Goldman & Harris 1991).

Later, energy and environmental benefits due to retrofit of six public buildings were checked by Ardente et al. (2011) who obtained significant energy benefits in the renovation of HVAC plants and lighting systems.

In another residential retrofit program in 2012 in Blacksburg, Virginia, Pitt et al. (2012) presented a methodology to estimate potential energy and GHG savings, which could reduce energy consumption as much as 36% up to the year 2050.

These findings demonstrate the potential for energy-efficiency retrofits to reduce energy demand in buildings considerably. The results (Pitt et al. 2012) show that even a basic upgrade could reduce predicted space-heating demand by 17%, while a premier retrofit with the best available technologies could reduce that demand by more than 80%.

3.4 A survey on HVAC system operation

Regarding the strategic facilities management of HVAC systems, one of the major areas of interest is effective and efficient energy management. It is essential to recognise the suitable energy management opportunities among a variety of measures to achieve energy-saving targets. These measures may have no significant expenses.

For example, in Australia, a survey has shown that by raising indoor air temperature set-points just up to 1°C in summer in 33 office buildings, a reduction of 6% was achieved in energy use (Roussac, Steinfeld & De Dear 2011).

Rocha, Siddiqui & Stadler (2015) in a research in an Austrian and a Spanish buildings, have compared BMS with policy measures to a smart BMS with dynamic temperature set-points.

An integrated optimisation model was presented, which combined decisions on HVAC systems operations with decisions on energy sourcing. They concluded that smart BMS results in a greater reduction in energy consumption than a conventional one with policy measures.

Tovey & Turner (2006) have made a comprehensive analysis of consumption data in newly built low-energy buildings at the University of East Anglia in the UK. Through effective adaptive energy management strategies over the first two years of occupation using techniques of data analysis, they could reduce electricity consumption up to 50%.

Fresner et al. (2017) demonstrated energy-saving potential up to 20% by smart energy management strategies through 280 companies across Europe.

In typical HVAC installations, the automatic control requirements and the computerised building management systems would be provided for both full- and part-load operations, while control commissioning mostly covers full-load settings, not necessarily part-load situations. As the operating capacities of the major equipment would be over-provided on many occasions, energy management would not be achieved effectively (Fong, Hanby & Chow 2006).

Implementing temperature reset programme based on different seasons would be effective; however, more effectiveness could be achieved through appropriate control of peak loads and the trial and error approach for each season; and even on a more detailed basis.

The potential for energy efficiency and demand management strategies in office buildings to reduce peak loads has been determined for 25 office buildings in Sydney, Australia. The results represent that peak loads in buildings with best practice energy performance are 26% lower than buildings with average energy performance, while the annual electricity reduction is 57% lower (Steinfeld, Bruce & Watt 2011).

In a survey by Airaksinen & Vuolle (2013) peak-power demand was compared in a standard and low-energy buildings, and it was shown that the difference of space-heating energy consumption between them was about 55–62%. However, the difference in peak energy demands was only 28–34%, which indicates the importance of paying attention to peak demands.

In a US study (Sadineni & Boehm 2011) the total reduction of electrical consumption during the peak period due to energy efficiency and PV (Photovoltaic) generation was 46%. Meanwhile, the average demand during the peak period grew by a further 69% when the indoor temperature was increased by 2.2°C.

Optimising energy use in Reef HQ Aquarium by Thyer et al. (2018) resulted in achieving 13% energy saving in the first year by increasing indoor air temperature set-points up to 1.5°C. Peak demand was decreased by 46% by upgrading the computerised building management system (BMS) and by installing a 206 kW photovoltaic (PV) solar power system.

Groissböck et al. (2013) pointed out that the energy required for heating in buildings can be reduced by over 10% by adjusting the system in a way that is more responsive to external conditions.

Having a suitable predictive method that can provide optimum information on related parameters to HVAC systems such as outside temperature, room size, etc. can be implemented as a primary energy management opportunity for useful facilities management in HVAC systems (Fong, Hanby & Chow 2006).

3.5 Control systems

Control systems of HVAC components have improved during the years. However, these systems were complicated in earlier years. Austin (1993), as cited by Lu et al. (2005), summarised some general ideas, which was difficult to extend to other systems for precise optimal control. Hartman (1995) showed that integrated DDC (direct digital controls) provide new approaches to improve energy efficiencies and comfort of typical facilities significantly, but they are incapable of dealing with mixed-integer non-linear optimisation.

Computational models of HVAC components successfully validated by Salsbury and Diamond (1999) by comparing a real system with simulations. They used simulation predictions as performance targets to compare monitored system outputs for performance validation with energy analysis. These attempts resulted in numerous tools and plug-ins for model development in demonstrating building energy simulation. Crawley et al. (2008) presented features of 20 major applications which are commonly used for building energy simulation, including BLAST, HEED, BSim, DeST, ECOTECT, Erwin, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r, DOE-2.1E, Tas, IDA ICE, IES/VES, HAP, PowerDomus, SUNREL, TRACE and TRNSYS.

Since then, hundreds of programs have been developed containing many methods for estimating energy performance, such as whole building energy simulation, model input calibration, energy conservation measures, building energy auditing, life-cycle analysis and cost analysis (Tam et al. 2018).

Pfeiffer, Skeie & Perera (2014) reviewed current control systems used for temperature and energy consumption in buildings. They have provided a complete understanding of several control techniques in the field of HVAC applications as well as information regarding the design of various controllers.

Tam et al. (2018) conducted an experimental study in Australia on contemporary computational programs for a building's life-cycle energy consumption and greenhouse gas emissions assessment. They have reviewed all considerable researches up to 2016 about the biologically inspired algorithms on different fields of sustainable building designs.

3.6 Barriers to have sustainability in building

Häkkinen & Belloni (2011) in a research based on previous studies, interviews and case studies addressed various aspects of obstacles in achieving sustainability in buildings. They reached the conclusion that the most important actions to promote sustainable building are increasing of the awareness of clients about the advantages of sustainable building, the expansion and adoption of methods for sustainable building requirement management, the mobilisation of sustainable building tools, the progress of designers' qualification and team working, and the development of new concepts and services.

Pitt et al. (2009) through different interviews in the UK found eight various topics as drivers and barriers for sustainable building. Table 1 summarises their findings:

Table 1: Drivers and barriers to sustainable building (Pitt et al. 2009, p. 211)

Item	Drivers	Barriers
1	Financial incentives	Affordability
2	Building regulations	Lack of client demand
3	Client awareness	Lack of client awareness
4	Client demand	Lack of proven alternative technologies
5	Planning policy	Lack of business case understanding
6	Taxes/levies	Building regulations
7	Investment	Planning policy
8	Labelling/ measurement	Lack of labelling/ measurement standard

The results represent that financial implications are consistent with 'affordability' due to the risk of unforeseen cost and the fear of investment.

Although concerns about using new technologies because of risks is a hindrance, this may also reflect the actual deficiency of well-developed and tested technologies to reach sustainability in buildings. It is difficult to evaluate with accuracy the real economic, social or environmental impact of an energy policy, especially when there are several limitations and uncertainties as of the rebound effect, hidden costs and hidden impacts (Boza-Kiss, Moles-Grueso & Urge-Vorsatz 2013).

To encourage investment in this field, building owners or managers should rely on the positive outcomes, as some aspects like energy efficiency and low environmental impacts are not directly visible.

One of the most important obstacles is the difficulty of describing the requirements (Häkkinen & Belloni 2011). Targets should be expressed clearly and explicitly, and methods used must enable comparisons, quality control, and monitoring to achieve the required performance with the minimum of environmental impact and at the same time encouraging economic, social and cultural improvement at a local, regional, and global level, which is a huge challenge. As Sodagar and Fieldson (2008) have explained, insufficient knowledge to develop a project with clear goals and mitigating strategies prevents sustainability.

This research aims to clarify some major aspects of sustainability in buildings by showing several comparisons in commercial buildings throughout the HVAC systems.

4 Aims and objectives

4.1 Research targets

As mentioned previously, an optimised HVAC system plays a critical role in the reduction of energy consumption in buildings facilitating reaching a more sustainable ecosystem in buildings.

Many old buildings, or even recently constructed but poorly looked-after, lack appropriate BMS technology (installed) as one would expect, so refurbishment of HVAC systems is critical in these buildings regarding energy efficiency. Nonetheless, even new buildings with the latest BMS technology may not achieve desired savings due to inappropriate operation. Many of these systems are scheduled to work only based on some specific set-points in different seasons; in this procedure, the system is not running as efficient as it can be. While by having optimised operation plans, the system would be operating based on outside conditions which is monitored regularly; which results in the system to operate at optimum performance levels and save more (if not maximum possible) energy.

Although the immediate impact of building optimisation on the cost of utilities is usually the main incentive for building owners, there are additional longer-term benefits as well. In optimised systems, equipment loads are moderated and used more efficiently compared to non-optimised systems. This results in the extension of the effective life of individual equipment and reduces the life-cycle costs of the system.

This study aims to find out how much energy, raw material, and CO_2 emissions can be saved by having an optimised operation through HVAC systems in commercial buildings.

The research indicates that having appropriate energy management results in an increase in the service life of equipment, which preserves raw material, fossil resources, and CO_2 emissions during manufacturing and transportation of new equipment. On the other hand, as the equipment works under better conditions, it doesn't use as much electricity as it did while working under full-load, a fact which reduces energy demand and consequently CO_2 emissions. Furthermore, energy bills and operating costs decrease dramatically for customers who are certainly welcomed.

If this optimisation takes place in all commercial buildings, a noticeable amount of energy and CO_2 emissions would be saved, which could be constituted as a step towards a low-carbon sustainable economy.

4.2 Research questions

This study examines the efficacy of the methods used for comprehensive energy efficiency in various buildings. Specifically, the study aims to answer the following questions:

(1) What is the quantitative effect of HVAC system optimisation via BMS controlling on electricity consumption saving?

(2) What are the financial and environmental savings?

(3) What is the impact of optimising an HVAC system on the system's service life?

(4) What is the impact of increasing system life on the environment?

(5) What is the impact of changing different temperature and pressure set-points?

This study shows the energy efficiency achieved by technical steps taken in the operation of HVAC systems for four different types of buildings, in a real-world.

4.3 Limitations

Due to the nature of the problem being studied and considering the fact that not much data is recorded or is available, data sources are considerably limited. In this regard, to show how optimised HVAC operation would result in a sustainable built environment, operational data in HVAC system were gathered from a company that is active in optimising the operation of HVAC systems in commercial buildings. This research focuses on the most important components in HVAC systems namely the chiller, in four different cases and the pump, as one of the most common equipment in the industry, in two different cases. For other components, reliable data was not accessible and obtaining pre- and post- optimisation stages data through data collection practices which could take a number of years was out of the scope of this study.

5 Methodology

5.1 Energy users in HVAC systems

HVAC systems consume around 70% of a typical building's energy usage (Lecamwasam, Wilson & Chokolich 2012). Within an HVAC system, there are several key end users including:

- Cooling: most of the time chillers produce cooling via chilled water, and sometimes it is provided via direct expansion cooling systems such as packaged air conditioners
- Heating: frequently boilers are used to produce hot water for heating; also it can be electric heaters for zonal reheat
- Pumps: they are used for the circulation of hot water or chilled water as well as condenser water
- Cooling towers: they are used for heat rejection.
- Fans: they are for air circulation and ventilation

Figure 8 illustrates a typical commercial building's consumption for these items.

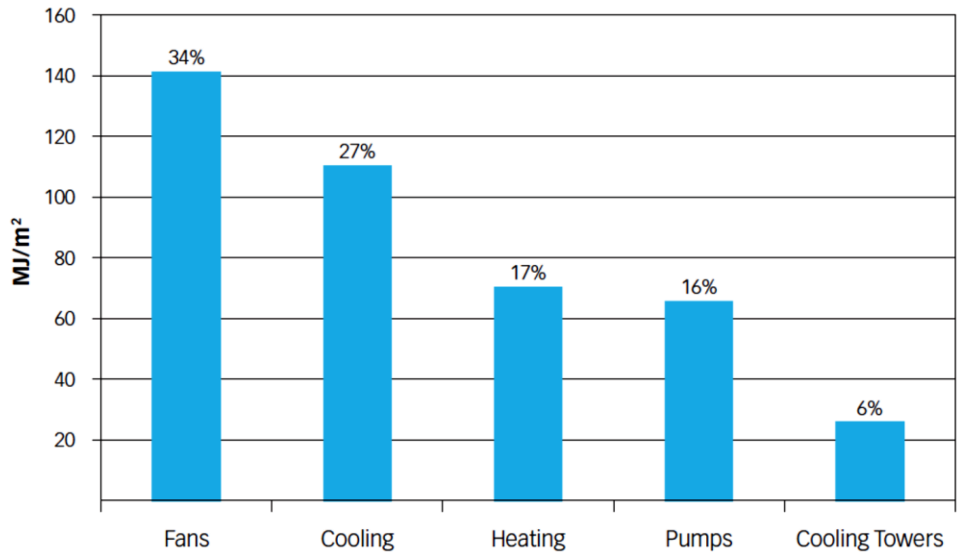


Figure 8: Typical energy consumption breakdown in an HVAC system (Lecamwasam, Wilson & Chokolich 2012, p. 37)

From building to building, energy consumption may significantly be different, due to differences in efficiency, building loads, HVAC system type and climate. About 25–35% of energy is consumed by chillers to produce chilled water for air conditioning. Thus, the efficiency and optimisation of chillers' performance within HVAC systems require significant attention (Lecamwasam, Wilson & Chokolich 2012).

Chillers are complicated systems with various controllers. These machines can be regulated according to outside conditions to work efficiently.

Based on this great potential in energy savings for HVAC systems, chillers and pumps are selected for investigation in this project.

5.1.1 Chillers

A chiller is used to produce chilled water for air conditioning in buildings. Chillers are comparatively expensive items that consume significant amounts of energy in commercial buildings. Therefore, to achieve the optimum cost (financial and environmental) efficiency of an HVAC system proper maintenance and operation is a critical issue.

Most chillers work on a vapour compression cycle, with a compressor circulating refrigerant in heat exchangers to return chilled water, and a condenser where heat is rejected. Chillers can be air- or water-cooled, depending on how the heat is rejected. Water-cooled chillers are more energy efficient than air-cooled chillers; also, they are less noisy and have longer operating lives (Lecamwasam, Wilson & Chokolich 2012).

Chiller efficiency

Chiller efficiency is expressed as its coefficient of performance (COP) or energy efficiency ratio (EER). It is the refrigeration capacity at full-load (in watts)/electrical input power (in watts).

Chillers rarely operate under full-load conditions. To achieve a better assessment for chiller efficiency, another index can be used as the integrated part-load value (IPLV). The IPLV is calculated from the COPs under load ratios and cooling-water temperatures to suit the current operational conditions. This makes evaluation of the actual performance of the chiller throughout the year. The formula used to calculate the IPLV is (Wajima et al. 2008):

$$IPLV = 0.01\,A + 0.42\,B + 0.45\,C + 0.12\,D \qquad (5\text{-}1)$$

Where:

A = COP at 100% load with a cooling-water inlet temperature of 29.4°C

B = COP at 75% load with a cooling-water inlet temperature of 23.9°C

C = COP at 50% load with a cooling-water inlet temperature of 18.3°C

D = COP at 25% load with a cooling-water inlet temperature of 18.3°C

Efficiency characteristics of compressors vary in different types, and centrifugal compressors are one of the most efficient ones. The efficiency of chillers has increased significantly over the past 10–15 years mainly due to advances in compressor technology and better control strategies (Lecamwasam, Wilson & Chokolich 2012).

Efficiency regulations

From December 2012, Chillers with capacities greater than 350kW sold in Australia must comply with the minimum energy performance standards (MEPS) regulations. Table 2 shows the efficiency ratings that chillers must achieve. The National Construction Code (formerly known as the Building Code of Australia) covers chillers with capacities less than 350kW. For water-cooled chillers, the minimum value of COP is 4.2, and the minimum value of IPLV is 5.2; for air-cooled chillers, the minimum value of COP is 2.5, and the minimum IPLV is 3.4

Table 2: MEPS ratings (HVAC HESS 2013b, p. 2)

Capacity (kW)	**Minimum COP**		**Minimum IPLV**	
	Air-cooled	Water-cooled	Air-cooled	Water-cooled
350–499	2.70	5.00	3.70	5.50
500–699	2.70	5.10	3.70	6.00
700–999	2.70	5.50	4.10	6.20
1,000–1,499	2.70	5.80	4.10	6.50
>1,500	2.70	6.00	4.10	6.50

Yu et al. (2014) reviewed national standards and guidelines for the energy performance of chiller systems in nine locations: Australia, California, Canada, China, Chinese Taipei, the EU, Hong Kong, New Zealand, and the USA. Under standard rating conditions at full-load operation, the minimum required COP differs from 2.40 to 3.06 for air-cooled chillers, and from 3.80 to 6.39 for water-cooled chillers. Some standards also state the COP requirements at part-load operation. However, the minimum energy performance standard only applies while commissioning a system, and there is no standard for the operation afterwards, so most old buildings using chillers do not require to comply with the standard.

5.1.2 Pumps

Pumps are used in HVAC systems to circulate water. They are used for heat transfer between chillers, boilers, air handling units, and other heat exchangers. The correct selection of a pump is important for energy efficiency.

Energy consumption

Pumps consume energy to direct water against the resistance of the system, such as pipework, heat exchangers, valves, strainers, and other components.

In most HVAC applications the centrifugal type of pumps is used. It is important to select the pump to operate within its optimum band and minimise water flow and system pressure drop (resistance to water flow), to reduce pump energy consumption and achieve high efficiency.

The relationship between water flow rate of a pump, pressure drop, and power consumption are (Lecamwasam, Wilson & Chokolich 2012, p. 50):

$$P = (V \times \Delta P)/\eta \tag{5-2}$$

P = power (watt).

V = water volume flow rate (m^3/s).

ΔP = pump total (static + dynamic) pressure drop across the pump (Pa).

η = [pump efficiency × motor efficiency × drive (belt and pulleys) efficiency × VSD efficiency].

Existing pumping systems can offer an excellent opportunity for efficiency improvements. Energy and maintenance costs could account for over 50–95% of pump ownership costs (Figure 9). Additionally, there might have been changes to requirements for systems operating for years as parameters for which they were designed for may have undergone changes. Pumping system efficiency enhancements of this type may have simple payback timeframes of a few weeks to a few years (Sustainability Victoria 2009).

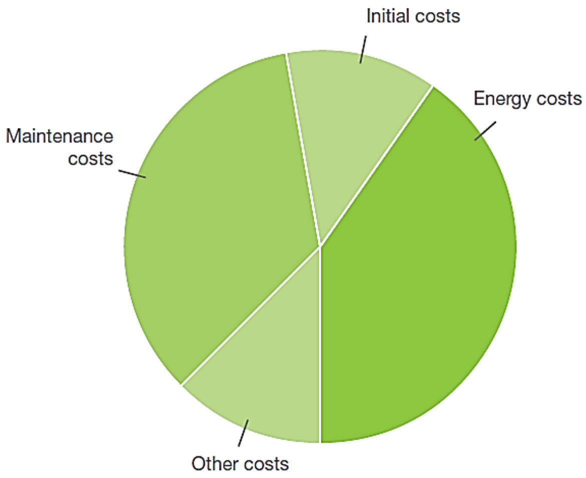


Figure 9: Life-cycle cost analysis for a medium-sized industrial pump
(Sustainability Victoria 2009, p. 5)

5.2 Life expectancy and performance curve

By having optimised operation, the number of times the equipment is working would decrease, and it would work in part-load for most of the time, which results in higher efficiency, longer life, and less energy consumption, which means saving in fossil sources and reducing CO_2 emissions in manufacturing, transportation, and operation of equipment.

5.2.1 Bathtub curve

The ‘bathtub’ curve in Figure 10 is frequently used as a model to describe the reliability and likelihood of failure of products. Failure means when the equipment can no longer provide the required performance. It is an empirical curve, applied for composite products, systems or subsystems with components that are subject to wear, such as rotating machinery. Failure may increase as the equipment gets old. With building services, the bathtub curve can be applied to entire systems, such as chillers, air handling units, packaged air conditioning systems, boilers, etc. Maintenance and replacement of damaged parts may reduce the impact of wear. There are typically three separate phases of failure in the life of equipment:

1. Decreasing failure rate: when the system is new, teething problems due to design and installation errors and manufacturing faults.
2. Constant failure rate: in some maintained systems, after the first period, the system will be in a settled state; some random faults and failures may happen, and parts that wear will need repair or replacement casually as part of preventative maintenance. These

include bearings, seals, control components, motors, heat exchanger components and compressors on packaged heat pumps/air conditioners or multiple compressor chillers.

3. Increasing failure rate: in this phase, major components begin to fail, and random failures increase with time. Also, the cost of repair of the asset begins to exceed the cost of replacement.

The most useful stage of equipment life is Phase 2, before there is any significant increase in the risk of failure rate. However, by having planned preventative maintenance or inspections, useful life can be extended (CIBSE 2014).

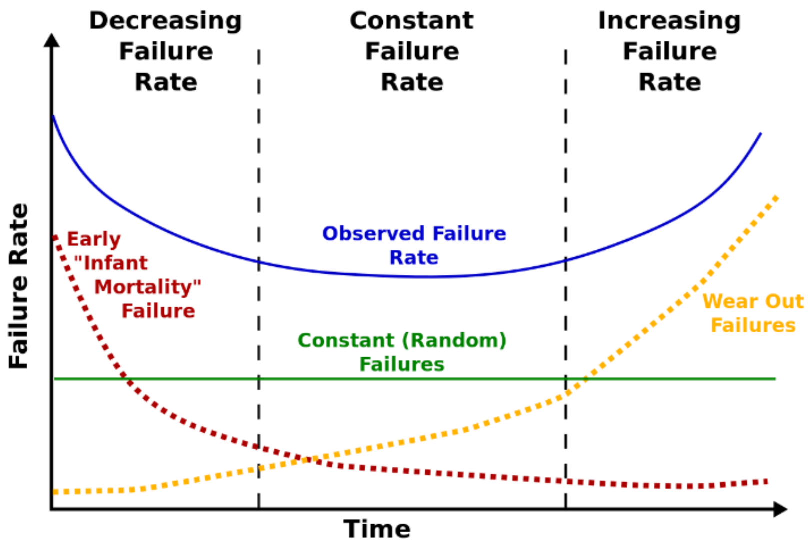


Figure 10: Bathtub curve (Suhir 2015, p. 6634)

There are several standards that can predict economic the life of HVAC equipment consisting of several factors. For example, AIRAH (Australian Institute of Refrigeration, Air Conditioning and Heating) provides a listing of likely service (economic) lives for HVAC equipment:

Table 3: Estimated economic life for some HVAC equipment (AIRAH 2014, p. 20)

Equipment	Economic life (years)
Refrigeration chillers – centrifugal	20–25
Refrigeration chillers – screw/scroll	20–25
Pumps	20–25
Fans	15–20
Cooling towers	10–25

In Table 3 a range of years is given for each item due to a possible variation of a range of factors that will impact on the service life. The service life factors that need to be considered in the variation of plant economic life include (AIRAH 2014):

- External environment: Weather, pollution, coastal, etc.
- Internal environment: Temperature, humidity, moisture, corrosive etc.
- Technology: New technology can improve reliability and performance.
- Design and specification: Departure from the original design assumptions.
- Maintenance: Level or lack of maintenance applied.
- Operation: Actual operating hours may be higher or lower than standard.
- Installation: Standard of installation and commissioning applied.
- Access: Sufficient access provided for maintenance and service to be carried out.
- Period of use: Where the plant has been unused for a period.
- Misuse: Where the plant has been operated incorrectly.

Through the above conditions, the quality of operation and maintenance affects the life of the equipment. There are other standards which have provided the same table with a range of years, such as the CIBSE guide in maintenance engineering and management (CIBSE 2014) and ASHRAE (ASHRAE 2013). They all indicate that the lack of optimised operation would decrease economic life, but there is some research that shows how much it would affect it. In this research, by comparing the performance of equipment before and after optimisation, an appropriate comparison can be achieved.

5.2.2 Performance curve

Most equipment has the best efficiency while working at part-load rather than full-load which results in less energy demand and longer existence. A few examples of components that can operate efficiently at part-load include fans and pumps with variable-speed drives, cooling towers and chillers (Graham 2016).

Chiller performance

Figure 11 shows the chiller performance curve. As can be seen (with variable speed), it has the most efficiency in the range of 30–70%, which varies based on the manufacturer’s datasheet.

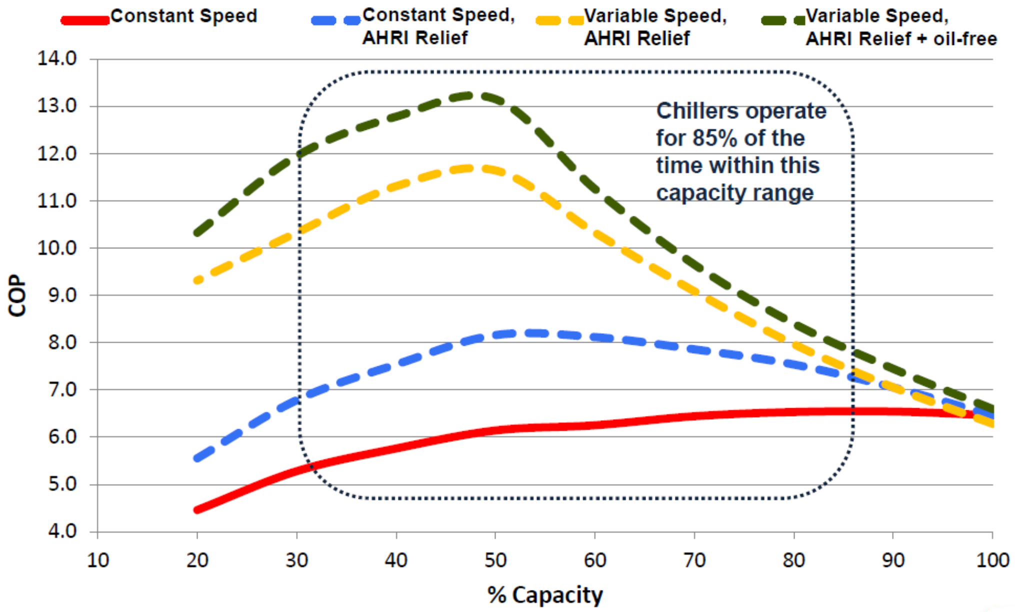


Figure 11: Chiller performance curve (York 2016, p. 7)

In a typical water-cooled chiller plant, the chiller itself accounts for most of the energy consumption. This is why improving chiller efficiency is critical to controlling operating costs.

Chillers rarely operate at their full-load efficiency rating because of various conditions. Thus, installing VSDs on centrifugal chillers is highly recommended, as it allows them to run at lower speeds under part-load conditions, resulting in higher efficiency.

Using chillers with VSDs is a proven way to optimise energy utilisation at full-load and part-load. They are also known as variable-frequency drives (VFDs) or DC inverters and can cut chillers' annual energy costs by 30% or more.

As the name indicates, VSDs can vary compressor motor speed to match capacity. Consequently, whenever a VSD can be slowed to match lower capacity requirements, energy consumption can also be lowered. In many installations, the VSD has a payback of less than a year; also, the operating savings are likely to continue for decades.

Beyond the energy-saving part, variable-speed also drives drastically decrease the electrical inrush when chiller's motors start up. Without having VSD, a normal chiller may experience an inrush as much as 650% of full-load amps, which results in massive heat build-up and flexing in motor windings. If the situation remains for a while, heat would damage the winding insulation and would cause motor failure. With a VSD, a chiller starts more slowly and never draws more than 100% of full-load amps, and mostly far less. Additionally, less heat and less wear and tear on the motor, which enhances life-long of equipment and diminishes electrical shorts and motor burnouts to minimise maintenance costs and potential downtime (*Chiller Best Practices VSD*, 2017).

Pump performance

Pumps have a similar characteristic and will save more energy while working at their best efficiency point (BEP). Figure 12, shows a centrifugal pump performance curve.

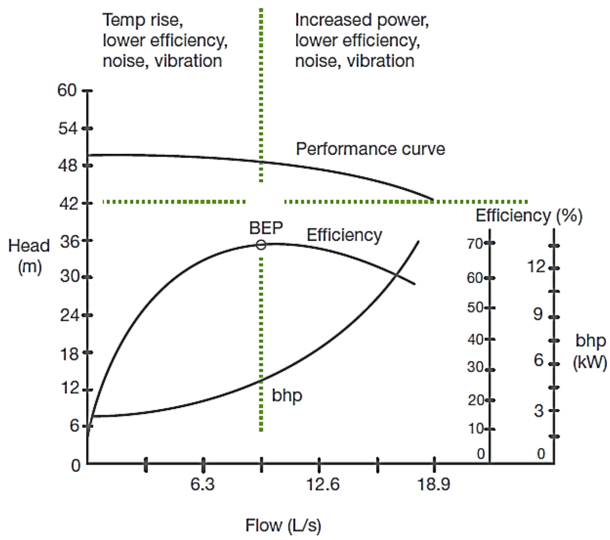


Figure 12: Centrifugal pump performance curve (Sustainability Victoria 2009, p. 16)

A centrifugal pump would operate efficiently at BEP as radial bearing loads are lowest and it would be most cost-effectively in terms of both energy efficiency and maintenance. As pumping systems have various flow rate and multiple head requirements and demands, operating a pump continuously at its BEP cannot happen.

As shown in Figure 12, the pump performance curve demonstrates the pump’s efficiency and power. The efficiency of a pump is the ratio of the pump’s fluid power to its shaft power (motor power). While the pump is working at flow rates lower or higher than the BEP, it experiences low efficiency, higher power, noise and vibration which decrease pump life service. As increase in radial loads on bearings would rise temperature due to dissipated energy generated by low efficiency (Sustainability Victoria 2009).

5.3 GHG emissions reduction potential

As shown by performance curves, through optimised operation, the equipment works efficiently; not only it would save more energy, it would also last longer.

In this regard, emissions reduction would happen firstly in saving electricity, which is due to burning different types of fuel; and secondly, as there is no need to replace new parts and equipment, a significant saving would happen through the absence of manufacturing and transportation.

5.3.1 CO_2-e emissions reduction through energy saving

The electricity supplied to a building from the national grid is generated from various energy sources, which each release diverse amounts of greenhouse gas per unit of electricity generated. CO_2-e (carbon dioxide equivalent) consist emissions of CO_2, CH_4, and N_2O.

Different amounts of greenhouse gases would be emitted from different types and amounts of fuels. So annual emission factors are used to determine the kgCO_2-e released for each kWh of grid electricity consumed at the final point (Clark 2013).

For instance, in NSW, producing electricity from coal generates about 0.92 kilograms of greenhouse gas per kilowatt hour, while getting the same amount of energy from burning natural gas directly generates only 0.23 kilograms of greenhouse gas. In this regard, the electricity which has gotten from coal is more ‘greenhouse-intensive’ than natural gas (Saltman 2000).

Greenhouse gas emissions from electricity differ between countries and different years, due to the variety of the proportion of fossil fuels consumed to get the electricity, and the losses in the distribution network. The factors are typically based on a 5-year rolling average. Figure 13 shows emissions from a typical black-coal-fired power station.

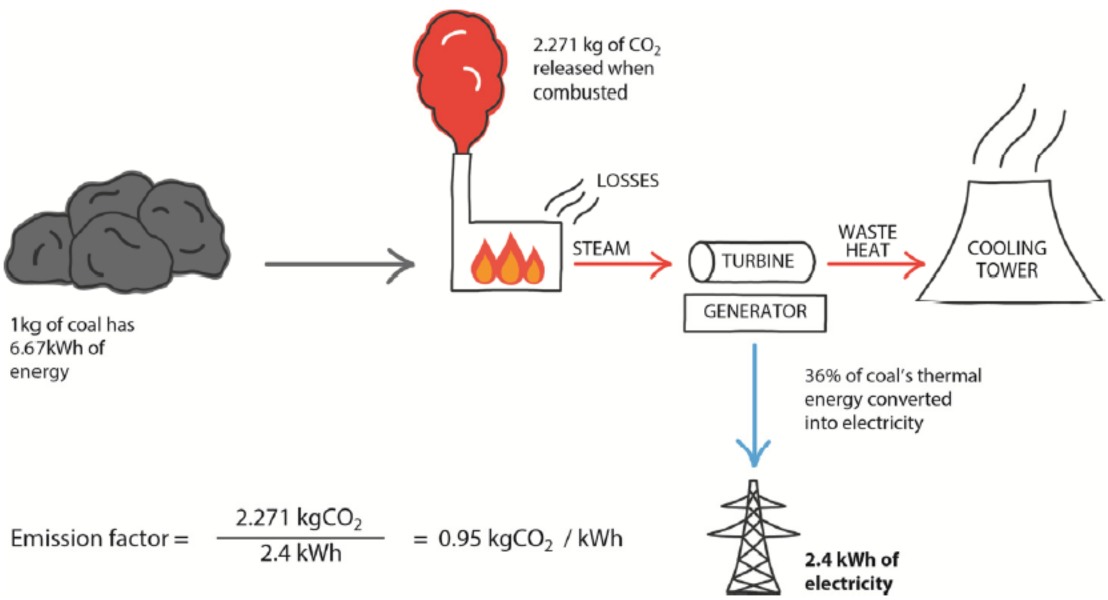


Figure 13: Simplified calculation of emission factors during generating electricity from a typical black-coal-fired power station (Clark 2013, p. 4)

The total CO_2-e emissions of grid electricity contain the following three components (Clark 2013):

- Generated emissions: These are the emissions because of the release of CO_2, CH_4, and N_2O from the combustion of fuel used in the generation of electricity (Figure 13).
- Emissions from losses: This demonstrates the emissions associated with the losses in the transmission and distribution grid between the power station and the building. These losses are about 8% in the UK, whereas it is about 30% in India.
- Embodied emissions: These are the emissions produced during the extraction and transport of primary fuels, which involves the refining, distribution, storage, and retail of finished fuels used in the generation of electricity (e.g., coal, oil).

The following table shows CO_2-e emission factors for grid electricity in various places:

Table 4: CO_2-e emission factors for grid electricity in various places (Clark 2013, p. 5)

Item	**Emission factors for 2009 (kg CO_2-e/kWh)**			
	Total	Generated	Losses	Embodied
United Kingdom	0.60	0.49	0.04	0.07
European Union - 27	0.44	0.36	0.03	0.05
Australia	1.09	0.88	0.08	0.12
United States	0.66	0.54	0.04	0.07
Middle-East	0.91	0.69	0.13	0.09

The greenhouse gas emissions in CO_2-e tonnes imputable to the amount of electricity (kWh) used in Australia would be calculated with the following (Department of the environment and energy 2017, p. 20) equation:

$$Y = Q \times \frac{EF}{1{,}000} \tag{5-3}$$

Y = the emissions measured in CO_2-e tonnes.

Q = the quantity of electricity purchased (kilowatt hours).

EF = the indirect emission factor, for the state or territory in which the consumption occurs (kg CO_2-e per kilowatt hour).

Table 5, indicates various emission factors for the consumption of purchased electricity in different states and territories of Australia.

Table 5: Indirect emission factors for the consumption of purchased electricity (Department of the environment and energy 2017, p. 20)

State or territory	**Emission factor kg CO_2-e/kWh**
New South Wales and Australian Capital Territory	0.83
Victoria	1.08
Queensland	0.79
South Australia	0.49
Tasmania	0.14
Northern Territory	0.64

5.3.2 CO_2-e emissions reduction through the manufacturing process of equipment

Manufacturing of new equipment requires extraction and transport of different raw material as well as various machine processing. To calculate GHG emissions in this phase, raw material and machine processing have been estimated through manufacturers' catalogues, then CO_2-e footprint has been assessed by OpenLCA.

OpenLCA Nexus is a free software which is developed by GreenDelta GmbH to develop a footprint model with a huge library of free and purchased databases. (Rodríguez, Ciroth & Duyan 2013).

6 Results

This section presents the results of the studies for energy consumption and greenhouse emissions for four buildings each explained in a separate case. Please note that for confidentiality arrangement, building's information, e.g. names and addresses cannot be disclosed.

6.1 Case 1

A building in Sydney CBD with 16 floors and the average area of each floor is nearly 577 m^2. Building services had a refurbishment in 2011 and had been designed to achieve a NABERS energy rating of 5 stars with a target at completion of 4.5 stars. It had rated just 1.5 stars before optimisation, and after 24 months it increased to 5.5 stars in 2018, which is a full 1 star above the design of 4.5 stars and demonstrates the impact of tuning and optimisation on the sustainability of the HVAC industry.

The building is equipped with a computerised building monitoring and control system (BMCS) to automatically control, monitor and provide alarms for the nominated building services.

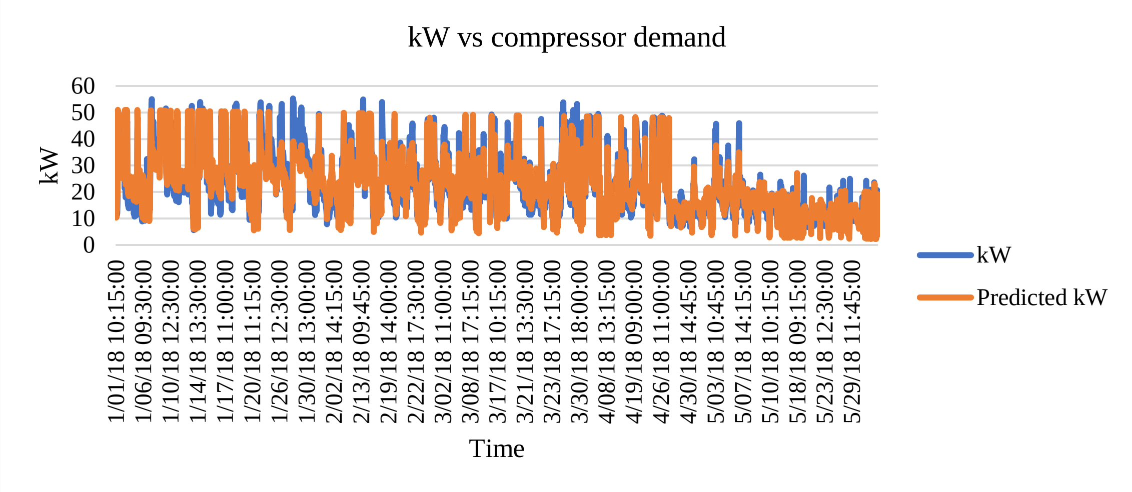
For air conditioning of the whole building, chilled water is generated by two water-cooled chillers. The chillers are sized to maximise efficiency at full- and part-load operation. Chiller-1 is the main chiller with coefficient of performance (COP) = 5.09 at full-load and IPLV = 8.82. This chiller works all the time, and chiller-2 runs in high-load demands only. As there is no data available before optimisation for chiller-2, chiller-1 is going to be discussed.

Chiller-1 works from 2011 with a centrifugal, oil-free compressor (TT300).

6.1.1 Analysing chiller-1

Chiller-1 works from 8 a.m. to 6 p.m. Chiller COP and number of times the system is working have been compared before and after optimisation. CIM Enviro has started monitoring from 22/12/2015.

As there is no data regarding compressor energy consumption, compressor demand is used to approximate COP. To show the accuracy of the estimation, a regression has been explored with Excel. Graph 1 shows the regression between compressor demand and energy consumption for the first five months in 2018 and results can be seen in Table 6. R-squared measures how well the model is fitted to the data (Frost 2017), and in this regression is about 0.84, which is reasonably good and accurate for about 2,714 observations.

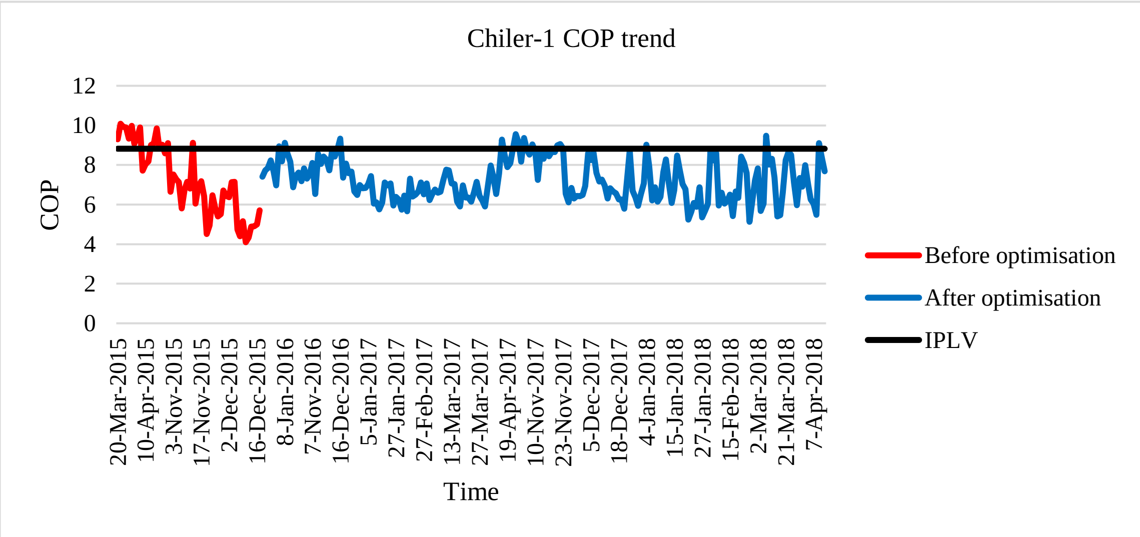


Graph 1: Regression between kW and compressor demand in 2018

Table 6: Summary of the output regression between energy consumption and compressor demand in 2018

Summary output	
Regression statistics	
Multiple R	0.92
R-squared	0.84
Adjusted R-squared	0.84
Standard error	4.55
Observations	2714

With this assumption, chiller COP can be calculated from 20 March 2015. Graph 2 shows chiller efficiency daily before and after optimisation.

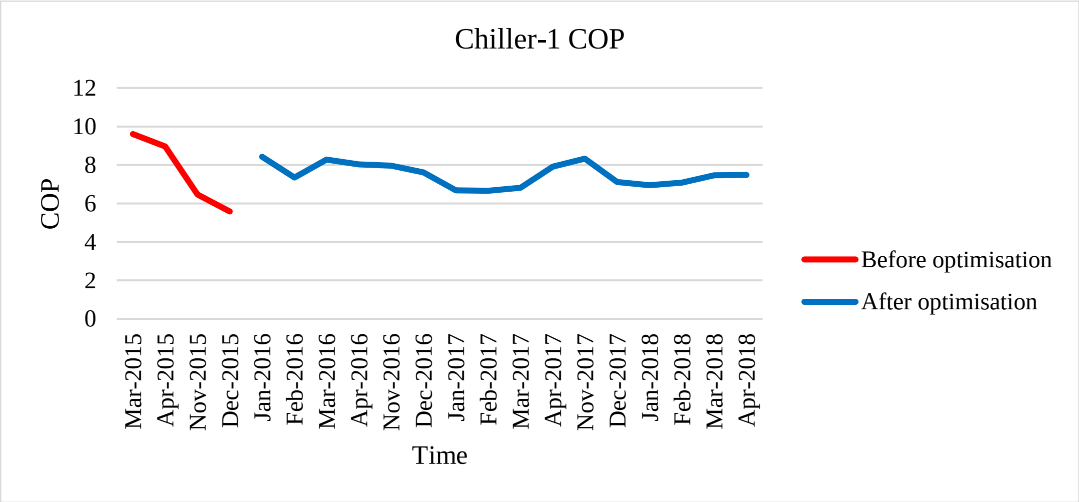


Graph 2: Chiller-1 efficiency

Chiller optimisation includes:

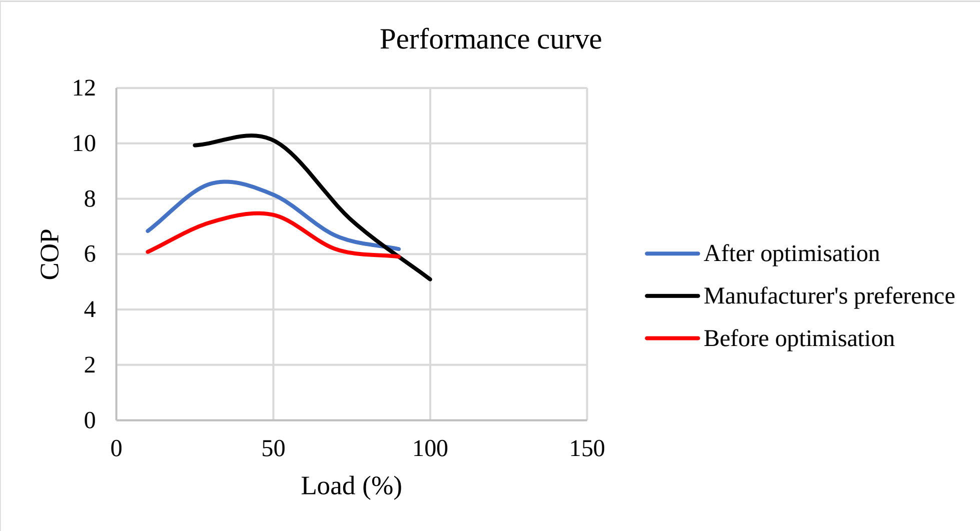
- Changing differential pressure and temperature set-points
- Resetting chilled water temperature during low-load periods
- Reducing chilled water flow and condenser water flow to its minimum in partial load
- Correcting bypass valve operation
- Correcting staging parameters point for chillers
- Locking out the chiller when outside weather gets cold
- Modifying the VSD minimum set-point setting

During winter, i.e. June to August, in Sydney, chiller mostly doesn't work or works in low demand, so to have a better sense about changes in COP, Graph 3 shows the monthly trend of efficiency without winter.

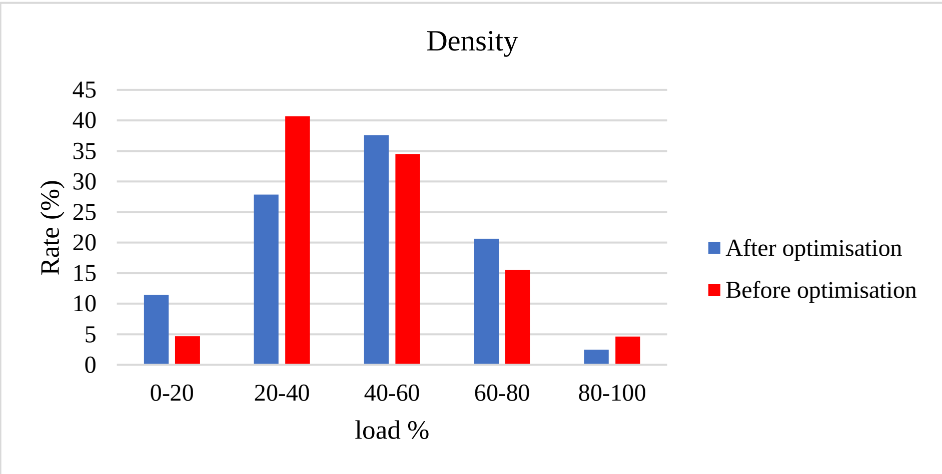


Graph 3: Monthly trend of chiller efficiency without considering winter

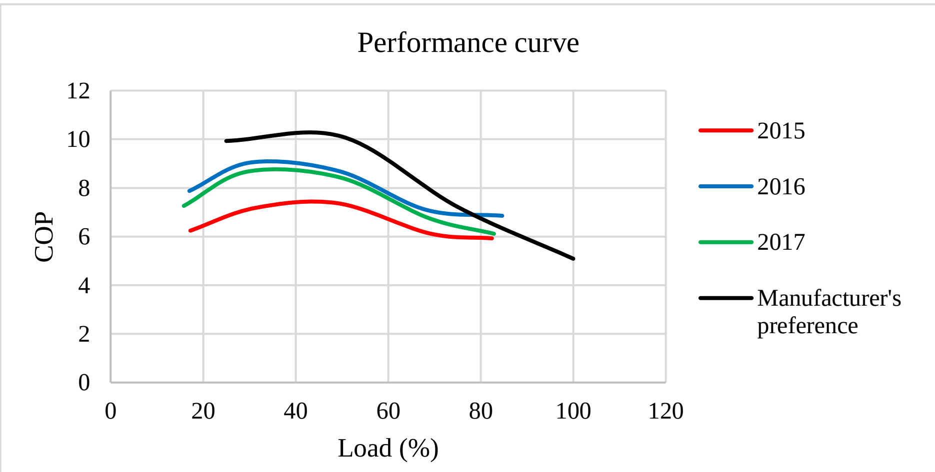
As discussed before, according to Figure 11, chillers have a performance curve, which shows the variation of efficiency for different loads. In this case, it has been shown in Graph 4. The black line is based on the manufacturer's data; the blue line is the performance after optimisation, which is higher than the red line, which relates to chiller performance before monitoring. The manufacturer's data demonstrates that the optimum performance is in loads of 40–60%. In this regard, the percentage of times the machine is working on different loads have been shown in Graph 5. The number of times the chiller is working in part-loads is higher after optimisation, but this evaluation is not accurate as the comparison is in various months. Thus, to have a better assessment, data has been evaluated from 20 March to 22 December in 2015, 2016 and 2017. In this period, data is available before optimisation, and covers most of the year; 2015 contains data before optimisation, while 2016 and 2017 are after optimisation and have been compared in Graph 6 and Graph 7.



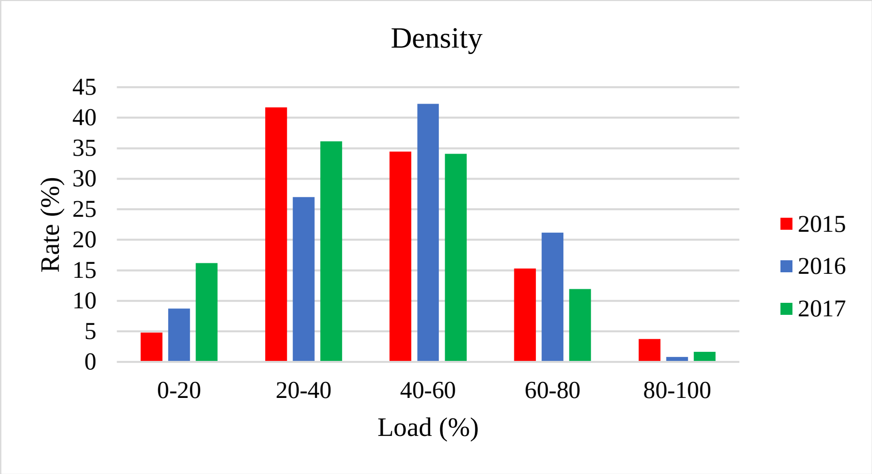
Graph 4: Chiller-1 performance curve before and after optimisation



Graph 5: Percentage of times the chiller is working in various loads



Graph 6: Chiller-1 performance curve in three different years



Graph 7: Percentage of times the chiller is working in various loads

Studying Graph 6 and Graph 7, the following results could be achieved:

- Average energy consumption per hour is 23.06 kW in 2015 and 20.5 kW in 2016 and 18.3 kW in 2017, which means a reduction of 11% in 2016 and 21% in 2017 compared to 2015.
- Total consumption was 54,404 kWh in 2015, 11717 kWh in 2016 and 19,322 kWh in 2017, which shows a reduction of 42,687 kWh in 2016 and 35,082 kWh in 2017 in comparison to 2015.
- Also, the number of times the chiller worked in 2015 is 9,219, in 2016 is 2,283 and in 2017 is 4,223.

Financial and environmental savings due to the difference of energy consumption in 2016 versus 2015 could be calculated as below (each kWh costs about 0.3 dollar[1] (O'Neill 2018) and emission factor is 0.83 kg CO_2-e/kWh in NSW):

- In terms of dollar = (42,687 kWh × \$0.3) = \$12,806
- In terms of CO_2-e: $Y = Q \times EF/1{,}000 = (42{,}687)$ kWh × (0.83/1,000) kg CO_2-e/kWh = 35.4 CO_2-e tonnes

Financial and environmental saving due to difference of energy consumption in 2017 versus 2015 could be represented as below:

- In terms of dollar = (35,082 kWh × \$ 0.3) = \$10,524 for whole month,

[1] Electricity usage rates can vary in different state and even within different areas of the same state. For example, the average electricity usage rate in NSW is 33.1118 c/kWh, while it is about 27.6246 c/kWh in Queensland.

- In terms of CO_2-e: Y = Q × EF/1,000 = (35,082) kWh × (0.83/1,000) kg CO_2-e/kWh = 29.11 CO_2-e tonnes

These results are summarised in Table 7.

Table 7: Comparing chiller performance for three years from March to December

Item	2015	2016	2017
Mean energy consumption per hour (kW)	23.60	20.53	18.30
Total energy consumption (kWh)	54,404	11,717	19,322
Reduction in mean energy consumption per hour (%)		11	21
Total energy reduction (%)		78.46	64.45
Financial saving ($)		12,806	10,524
CO_2-e tonnes		35.43	29.15
Running times (every 15 minutes)	9,219	2,283	4,223
Reduction of running times (%)		75.24	54.19

According to Table 7, the number of running times in every fifteen minutes is 9,219 in 2015, 2,283 in 2016 and 4,223 times in 2017, which shows a reduction of about 75% in 2016 in comparison with 2015, and a decrease of more than a half in 2017 versus 2015. On the other hand, Graph 6 indicates that the system is working with a higher COP in 2016 and 2017 in contrast to 2015. Decreasing running times and improving efficiency cause longer life for equipment. As the most important part of a chiller is the compressor, which is the rotary part and is highly affected by maintenance, it can be the first item that fails in lack of scheduled observation. In this situation, replacing a new compressor, beyond the financial part, would release a notable amount of CO_2 footprint through extracting material, machine processing, and transportation. Table 8 is an estimation of CO_2 emission for producing a compressor, which in this case is a TT300, an oil-free compressor.

Table 8: Amount of CO_2 emissions for making a new TT300 compressor

Phase	CO_2 emission (kg)	Contribution (%)
Material	1256.09	91.60
Manufacture	88.93	6.50
Transport	21.878	1.60
Disposal	4.76	0.30
Total	1371.66	100
End of life potential	-985.62	

The compressor weighs 120kg, and most of the weight relates to the case, manufactured of cast aluminium. In addition, electronic enclosures are made of high-strength thermoplastic materials. As these sections would constitute the maximum portion of the unit's weight which are also common for every unit, i.e. not subject to customisation, just these two parts have been considered. Since the unit is manufactured in the US, the transport mode is considered to be ocean freight.

Even though not all parts have been measured, the amount of 1,370 kg CO_2 footprint is significant. However, this amount can decrease significantly in recycling process. For example, by assuming that 100% of these materials would be recycled about 986 kg, CO_2 would save, which emphasises on the importance of recycling.

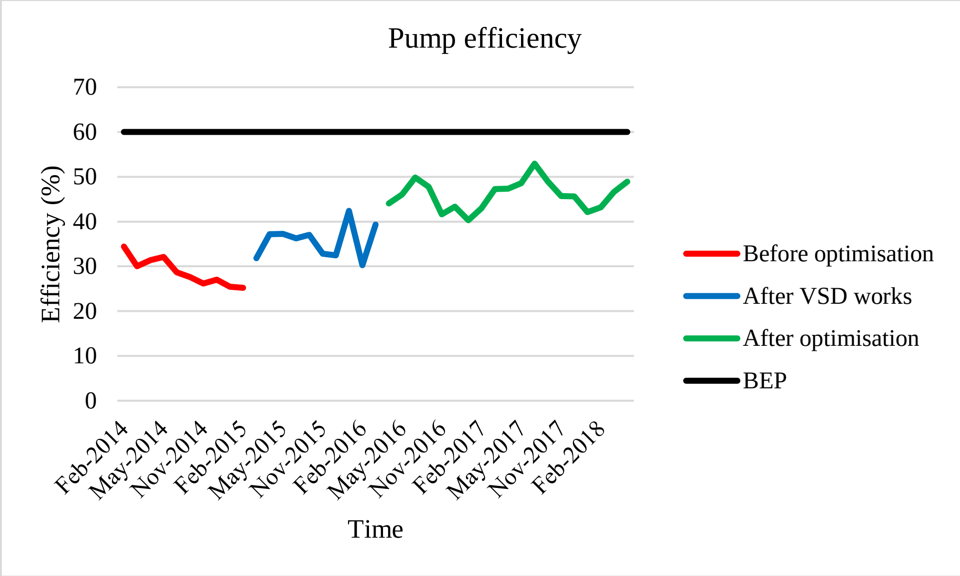
6.1.2 Analysing the chilled water pump

This chilled water pump is a centrifugal pump equipped with VSD; however, VSD wasn't operating before monitoring started. From 20/2/2015, VSD connected to pump, which resulted in a significant increase in efficiency.

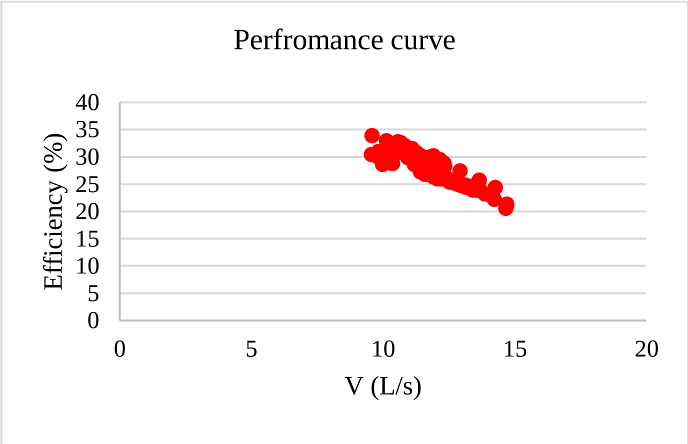
There have been many changes in speed, differential pressure, and other set-points until 11/4/2016. After April 2016 it has been mostly working with high efficiency. Graph 8, shows pump's monthly efficiency (due to low demands in winter, this season is not included). The graph contains three parts: before maintenance; after VSD is connected, and after optimisation. As mentioned before, at or near BEP, a pump operates most cost-effectively in terms of energy efficiency and maintenance. The BEP point of this pump is around 9 L/s, with 60% efficiency.

Performance curve for pump previously discussed in Figure 12, and it has been investigated in this case before and after monitoring in Graph 9 and Graph 10, which show efficiency of pump versus flow. As flow changes, pump efficiency varies and has the best performance around 9 L/s (BEP).

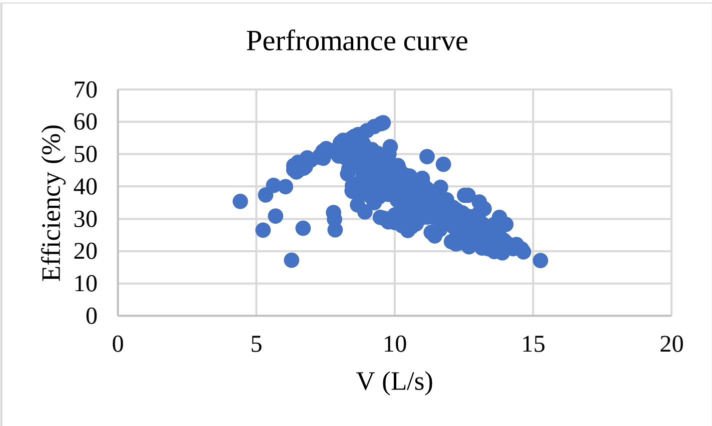
Percentage of times pump is working in different ranges of efficiency has been shown in Graph 11, which clearly displays how performance has improved after optimising. Before monitoring pump was mostly working in range of 20–40%, while after that, it is mostly operating in the range of 40–60%.



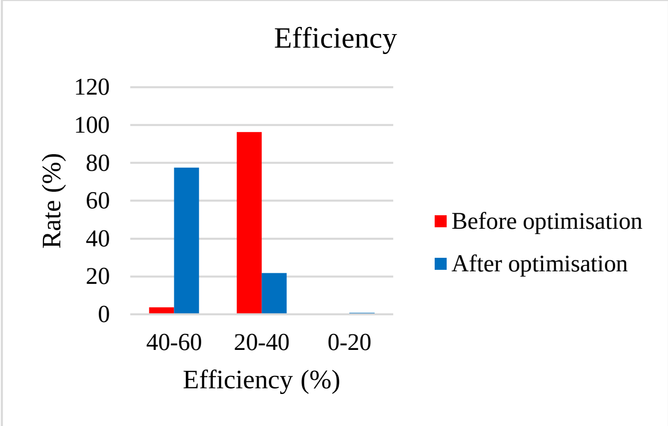
Graph 8: Pump monthly efficiency trend, without considering winter



Graph 9: Pump performance curve before optimisation

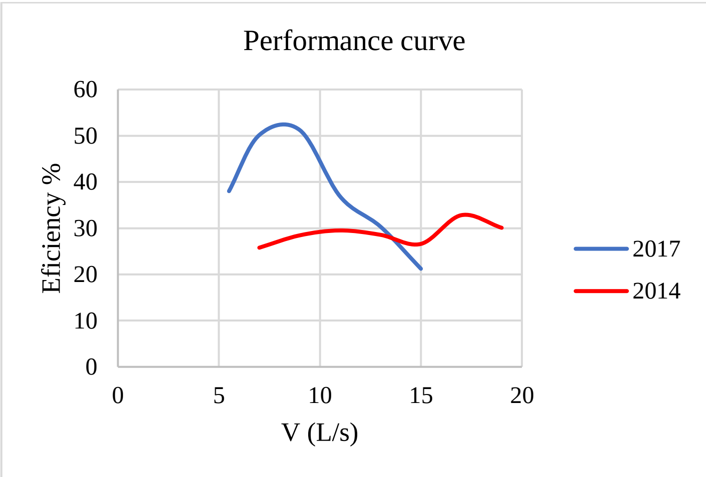


Graph 10: Pump performance curve after optimisation

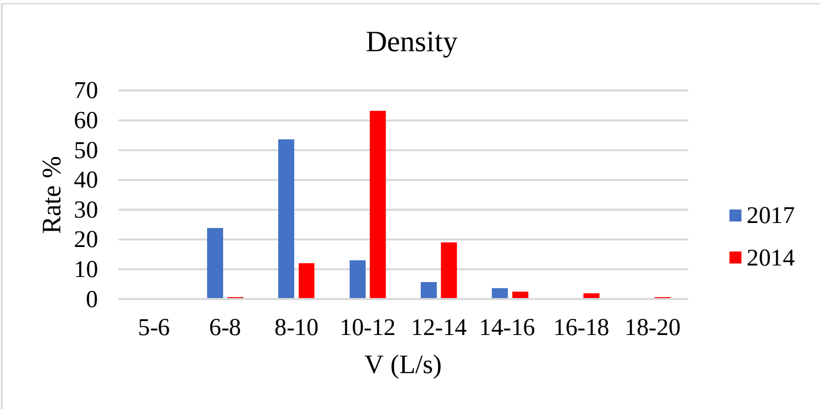


Graph 11: Percentage of times pump is working in various efficiency

To have a better evaluation the performance of pump for the whole year 2014 and 2017 have been compared, which 2014 refers to pump performance before monitoring and 2017 after that. Graph 12 and Graph 13 show pump performance curve and percentage of times pump has worked in various flow rates respectively, to show how much it has been worked near BEP.



Graph 12: Pump performance curve



Graph 13: Percentage of times pump is working in various flow rate

By analysing these two charts, the following results can be achieved.

Table 9: Performance of pump in two different years

Item	2014	2017
Mean energy consumption per hour (kW)	5.30	3.18
Total energy consumption (kWh)	32,172.87	14,761.20
Reduction in mean energy consumption per hour (%)		39.89
Total energy reduction (%)		54.12
Financial saving ($)		4,428.36
CO_2-e tonnes		12.25
Running times (every 15 min)	24,275	18,527
Reduction of running times (%)		23.68
Percentage of times working around BEP (8-10 L/s)	12%	53.16%

Average energy usage per hour has reduced about 40%, number of running times has decreased by 23%, and total energy reduction is about 54%. This results in $4,428 and 12.25 CO_2-e tonnes saving. Reducing machine working hours and increasing productivity by working close to BEP, affects equipment life-long and could prolong pump life several years more. While, in lack of comprehensive operation, it should be exchanged more often.

Replacing a new pump requires material extraction, manufacturing process, and transportation. This procedure results in extra CO_2 emissions, which have been estimated in Table 10.

Table 10: Amount of CO_2 emissions for making a new pump

Phase	CO_2 emission (kg)	Contribution (%)
Material	247.90	78.40
Manufacture	63.94	20.20
Transport	0.51	0.20
Disposal	3.97	1.30
Total	316.33	100
End of life potential	-184.30	

Weight of this pump is 101 kg, and more than 50% of that relates to bearing housing element, made from cast iron. Impeller is from bronze and is about 22.4 kg. Shaft is stainless steel and weighs 2.6 kg. The other elements have unknown weights. Also, as various parts of pump could be manufactured in different parts of the world, it has been estimated that transportation is just from pump agency in Sydney, which is about 40 km from this building. Although not all parts have been considered and transportation is limited to Sydney, the amount of 316 kg CO_2 footprint requires attention. However, if all these metals are going to be recycled a considerable amount of 184.3 kg CO_2 would be saved.

6.2 Case 2

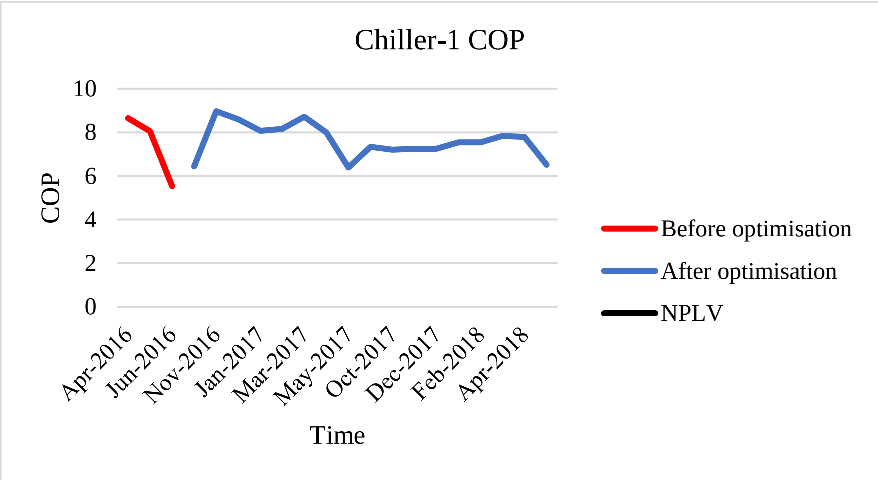
This building is a shopping centre in NSW; the installation of mechanical services completed in 2014. This construction consists of approximately 18,000 m^2.

There are two water-cooled rotary screw chillers of equal capacity manufactured by Carrier. The two chillers each have the capacity to handle 60% of the load. All AHUs[1] (Air handling units) are connected to these chillers.

In both chillers COP in full-load is 5.95 and NPLV[2] = 10.14 and each is working half of the year. From 28/9/2016 chiller staging strategy has changed and caused a better performance in chiller COP. This modification has been shown in Graph 14 to Graph 16, which compare the efficiency before and after 28/9/2016.

6.2.1 Analysing chiller-1

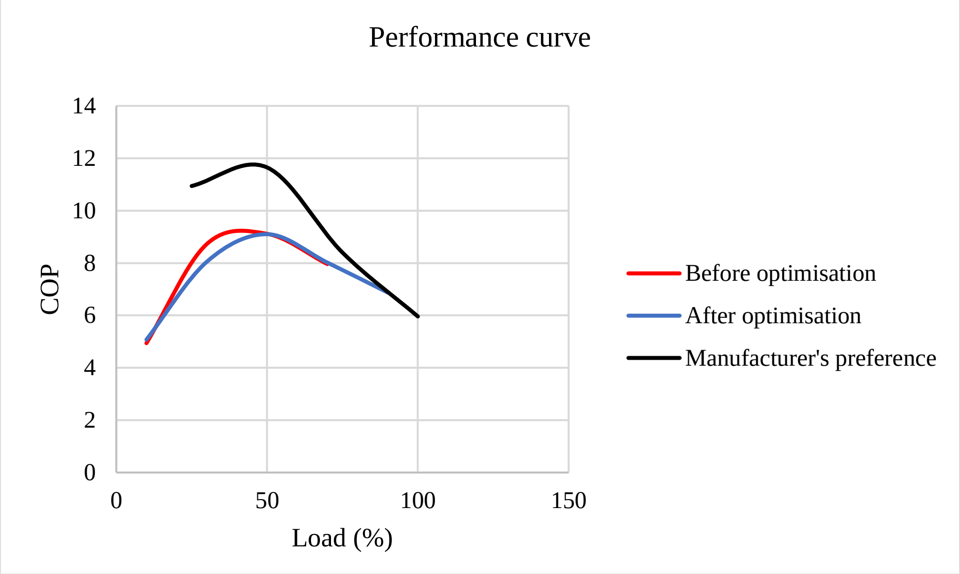
Graph 14 shows monthly trend of chiller-1 efficiency before and after monitoring starts. In Graph 15 and Graph 16, performance curve and percentage of times chiller is working in various loads have been shown. However, before monitoring, data is only available from the middle of April to the end of August and it doesn't contain summer. To have a better comparison, performance of chiller is evaluated in winter 2016 and 2017.



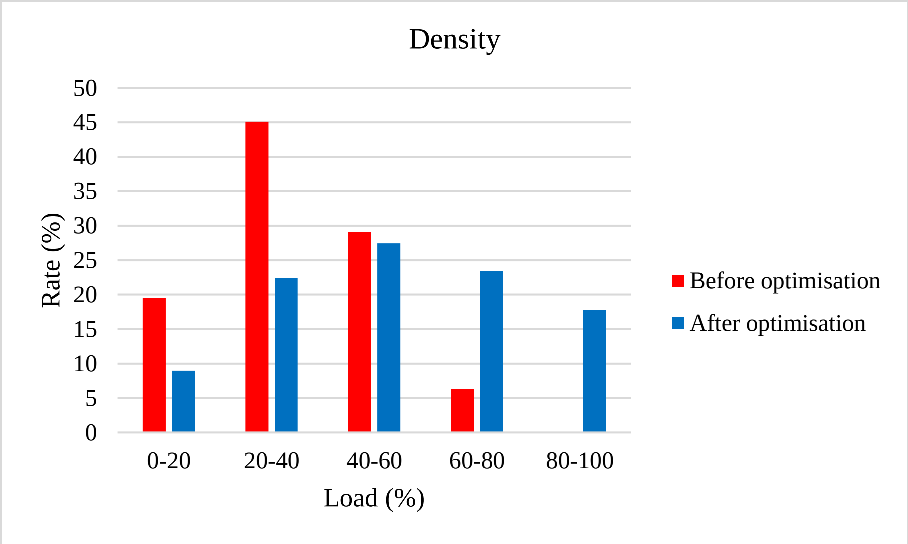
Graph 14: Monthly efficiency trend of chiller-1

[1] Air handling units (AHUs) are used to condition and circulate air in buildings. AHUs usually contain air filters, a circulating fan, cooling and heating coils (Lecamwasam, Wilson & Chokolich 2012).

[2] If a chiller is designed to operate at different conditions than specified in Table 3 of AHRI (Air-Conditioning, Heating and Refrigeration Institute) standard 550/590-2003, including lower water temperature or different flow rate, the efficiency is called NPLV (non-standard part-load value) rather than IPLV. Both ratings are calculated using the same equation (Fabian 2015).

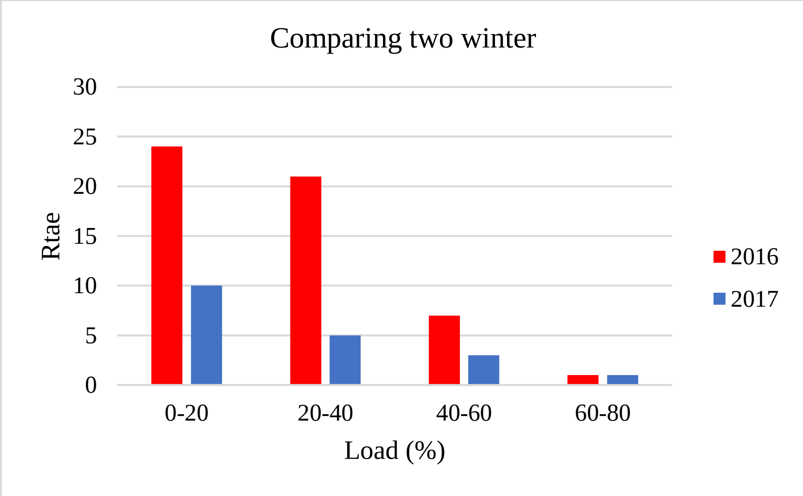


Graph 15: Performance curve of chiller before and after optimisation



Graph 16: Percentage of times chiller is working in various loads

As there is no data for summer before optimisation, comparison has been done between winters. Due to few numbers of data recorded in winter, the average COP is not valid, and the performance curve hasn't been shown. But number of times chiller is working varies significantly after optimisation. Graph 17 compares running times in winter 2016 versus winter 2017. This indicates that in 2016 chiller is mostly working in loads that are too low (less than 20%). Before optimising the chiller was scheduled to supply chilled water of 7˚C even in winter; the consequence was system operation in loads less than 20%, which is a waste of energy. After optimisation, this set-point has changed and decreased running times.



Graph 17: Number of times chiller is working in various loads

Number of times chiller is working has decreased from 53 to 19 and energy consumption has declined from 903 kWh to 391 kWh (56% decrease). This amount of energy reduction results in financial and environmental saving in winter 2017 versus winter 2016, which have been summarised in Table 11.

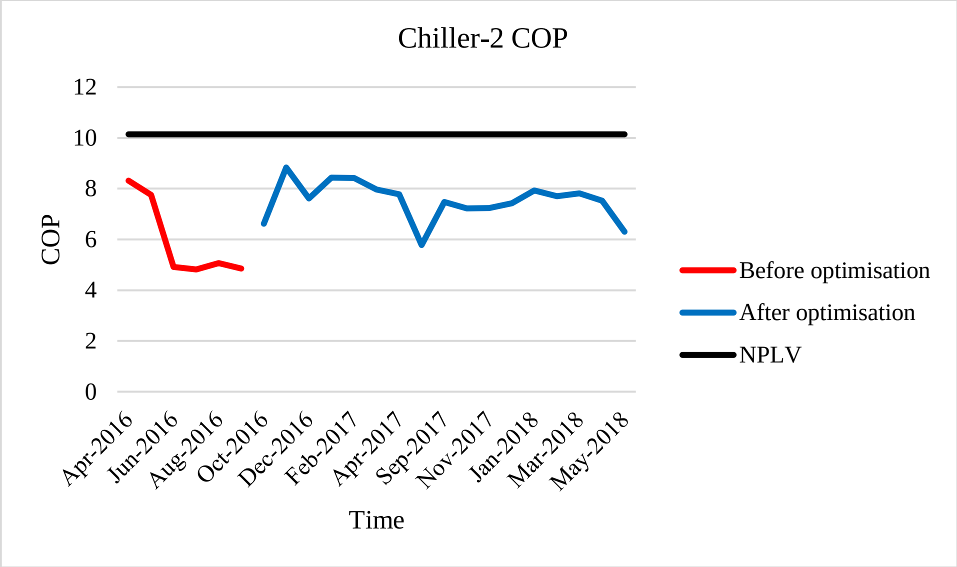
Table 11: Chiller performance in winter 2016 and winter 2017

Item	**2016**	**2017**
Total energy consumption (kWh)	903.03	391.35
Total energy reduction (%)		56.66
Financial saving ($)		153.50
CO_2-e tonnes		0.43
Running times (every 15 minutes)	53	19
Reduction of running times (%)		64%

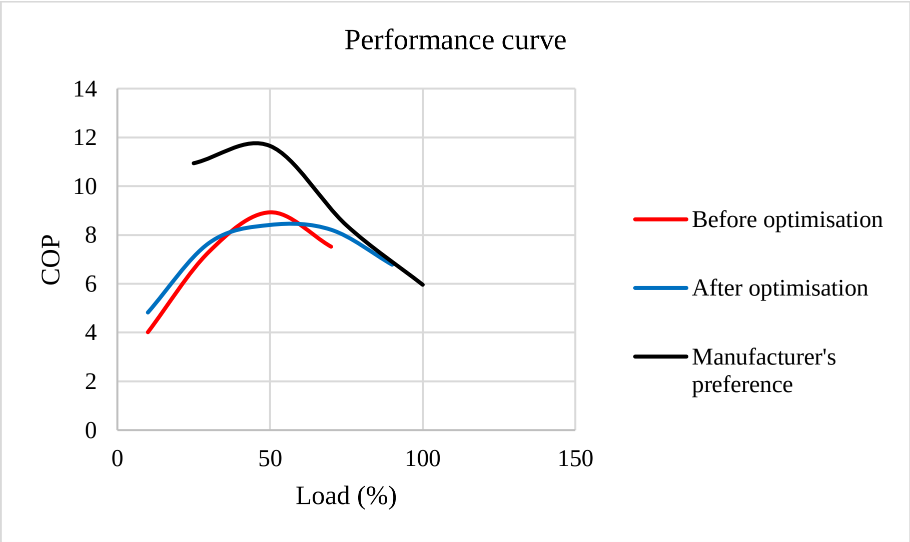
Thus, through optimised scheduling, machine running times would drop significantly in unnecessary situations like in winter period that demands are excessively low.

6.2.2 Analysing chiller-2:

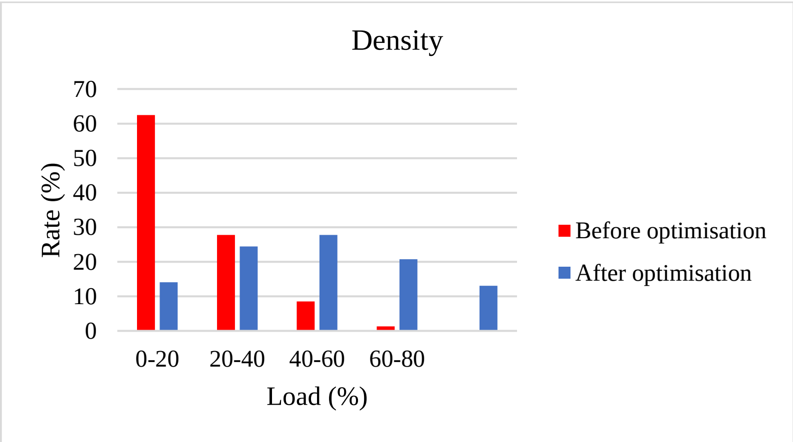
This chiller is a water-cooled rotary screw one the same as chiller-1 with the same COP at full-load and NPLV. Graph 18,Graph 19 and Graph 20 illustrate chiller COP trend before and after optimisation, performance curve and percentage of times chiller is working in different loads respectively. COP has increased, and the chiller is mostly working within 40–60% of load, while, before optimisation, it was mostly working with loads less than 20%.



Graph 18: Chiller-2 COP, monthly trend

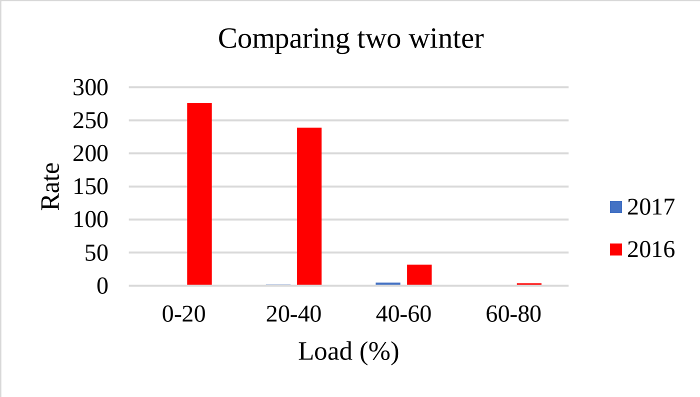


Graph 19: Chiller-2 performance curve



Graph 20: Percentage of times chiller-2 is working in various loads

To have a better observation, same as chiller-1, winter is evaluated in two years and then the period of April to September is compared. Graph 21 displays number of times system is working in winter 2016 and 2017.



Graph 21: Number of times chiller-2 is working in various loads in winter

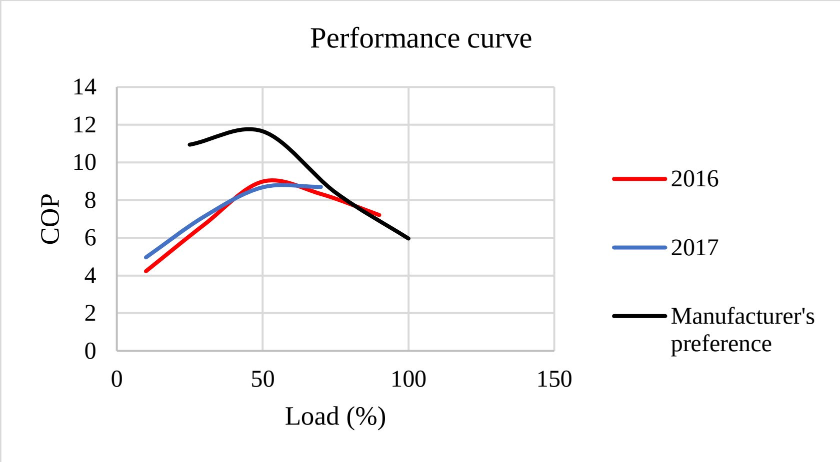
According to Graph 21, the system has worked 551 times in 2016 and just eight times in 2017. In 2016, about 50% of times, it worked in loads less than 20%, and consumed about 1,910 kWh for this period, while it hasn't worked in 2017 in loads less than 20. In this chiller, similar to chiller-1, before optimisation system had to provide chilled water with temperature of 7˚C even in cold days of winter, however, this set-point has changed after monitoring and resulted in considerable amount of energy reduction. This amount of energy reduction can result in the following financial and environmental saving:

In terms of dollar: (1,910 kWh × $0.3) = $573

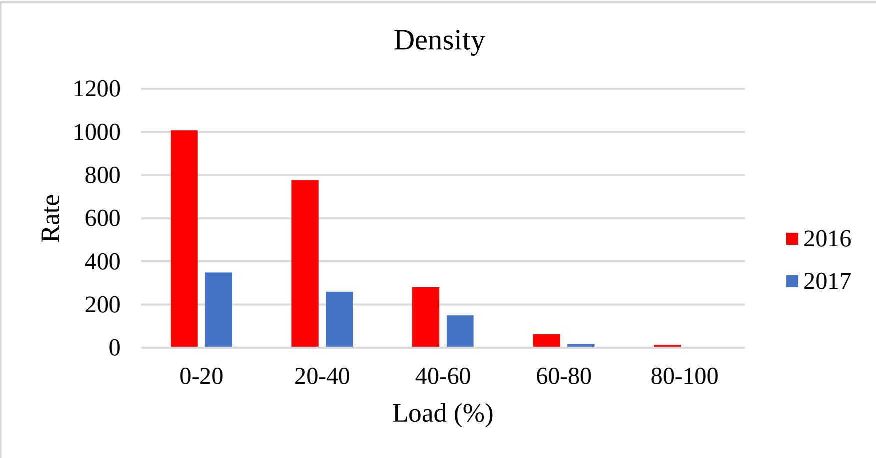
In terms of CO_2-e: (1,910 kWh × (0.83/1000) kg CO_2-e/kWh = 1.58 CO_2-e tonnes

Thus, managing operation of the system while considering outside temperature prevents unnecessary running times of the system and can result in striking savings.

Another evaluation has been done for about half of the year (April to September). Graph 22 and Graph 23 demonstrate performance curve and rate of times the machine is working for this period.



Graph 22: Chiller-2 performance curve during April to September



Graph 23: Number of times chiller-2 is working in various loads during April to September

The results have been summarised in Table 12, which illustrates 65% saving in kWh and reduction of running times by 63%, which has made about $7,591 and 21 CO_2-e tonnes financial and environmental savings.

Table 12: Comparison of chiller performance in 2016 and 2017 during April to September

Item	**2016**	**2017**
Mean energy consumption per hour (kW)	71.89	67.90
Total energy consumption (kWh)	38,459.35	13,155.19
Reduction in mean energy consumption (%)		5.55
Total energy reduction (%)		65.80
Financial saving ($)		7591.25
CO_2-e tonnes		21
Running times (every 15 min)	2,140	775
Reduction of running times (%)		63.78

The number of running times has decreased by 60% for both chillers, and they are working in better condition. Although it results in energy-saving, it would increase the life of equipment.

Table 13 estimates CO_2 footprints to replace a new compressor with the same features in lack of optimised operation, as compressor is the first item in chiller that requires substitution.

Table 13: Amount of CO_2 emissions for making a new compressor

Phase	CO_2 emission (kg)	Contribution (%)
Material	1,365.36	73.30
Manufacture	462.08	24.80
Transport	5.90	0.30
Disposal	29.59	1.60
Total	1,862.94	100
End of life potential	–1014.67	

In this case compressor weight is 2,207 kg. Casing is from cast iron and is the heaviest part, which has been estimated as 500 kg, and rotor is about 104 kg and is made of carbon steel. The mass of other parts is unknown. It has been assumed that compressor is going to be transported from Carrier branch in NSW so that transportation would be about 90.5 km.

Although the real CO_2 footprint is much more than the estimation in Table 13, the amount of 1.86 CO_2e-tonnes is remarkable. By recycling process, about 1 CO_2e-tonne would be saved.

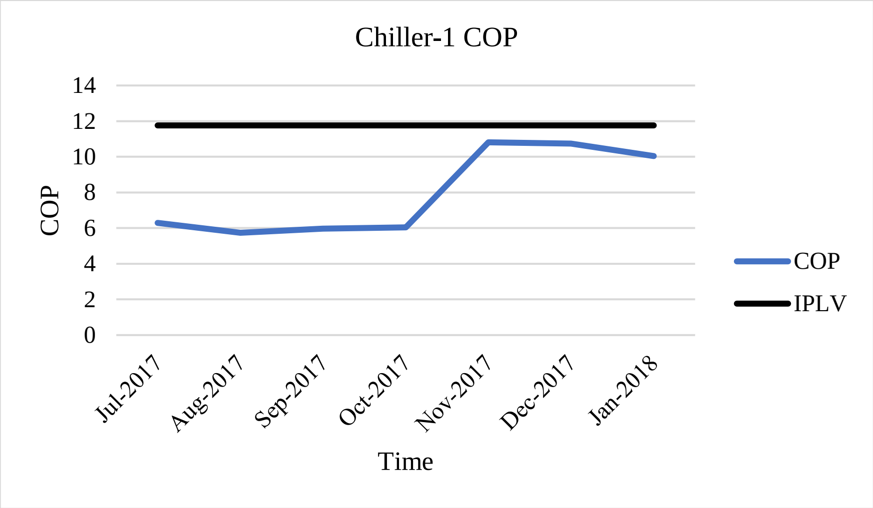
6.3 Case 3

This site comprises two, five-level commercial office buildings, located in NSW. The average floor area varies from 2,000 m^2 to 1,000 m^2 at different levels.

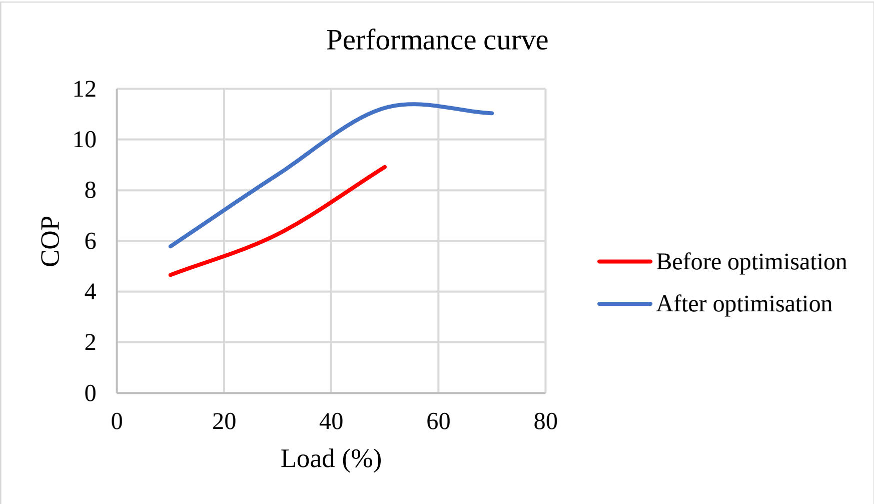
The HVAC system consists of two Carrier screw water-cooled chillers with full-load COP of 6.6 and IPLV = 11.76. The system works from 2007, but available data starts from July 2017.

6.3.1 Analysing chiller-1:

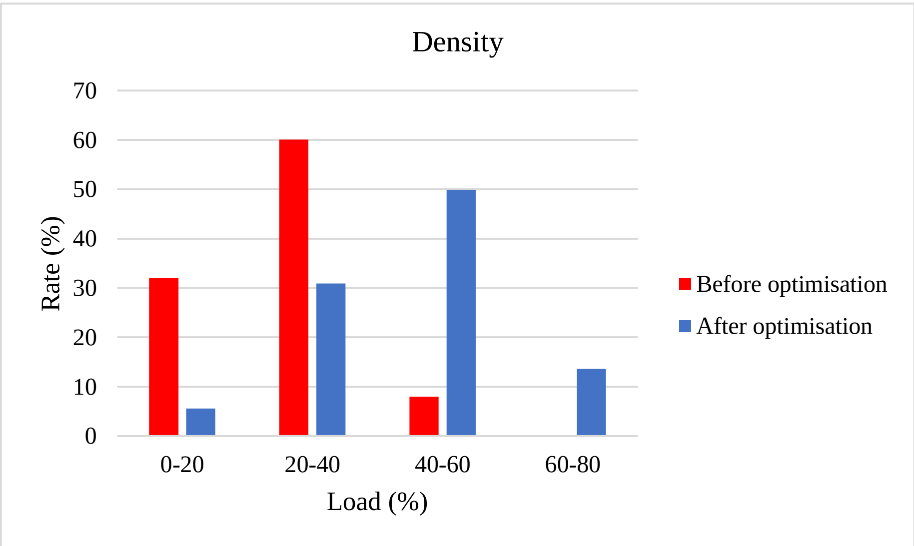
Decreasing chiller differential pressure set-point in the middle of October 2017 has caused significant changes in COP. Graph 24 to Graph 26 show monthly trend of chiller efficiency, chiller performance curve and chiller running times in different loads respectively. Both Graph 24 and Graph 25 express a remarkable increase in COP, as in November it has reached to 10, very close to IPLV = 11.76, which is a noticeable upgrade in contrast to 6, which was before October 2017.



Graph 24: Monthly COP trend of chiller-1

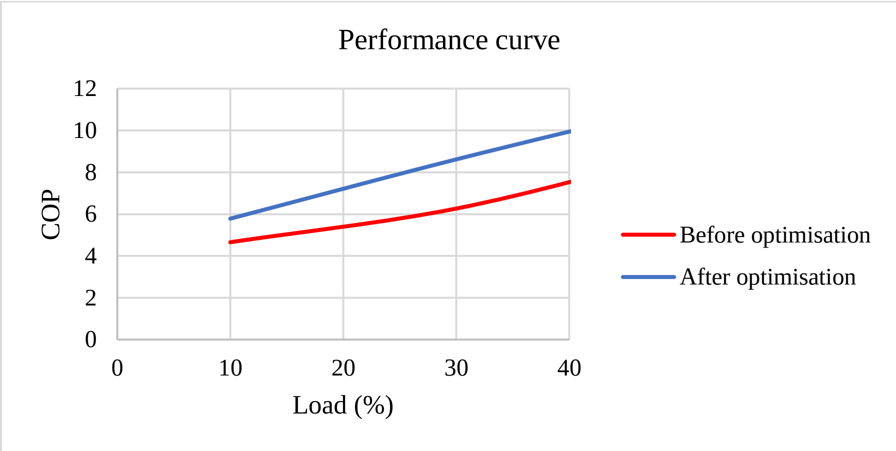


Graph 25: Performance curve of chiller-1

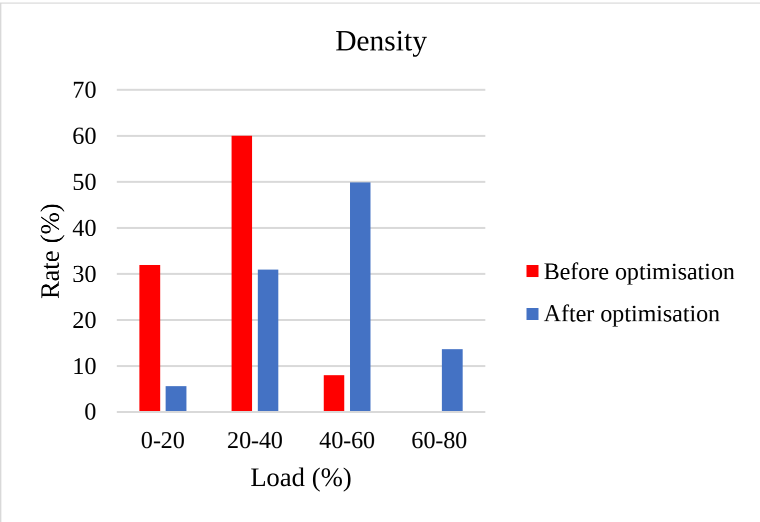


Graph 26: Percentage of times chiller-1 is working in various loads

As before optimisation, data is recorded in winter and spring, which are seasons with low demand, and after that, data is recorded in summer, season with high demand, comparison is limited to loads less than 40%, which contains both periods before and after optimisation. Graph 27 and Graph 28 show performance curve and percentage of times chiller is working for loads less than 40%.



Graph 27: Chiller-1 performance curve for loads less than 40%



Graph 28: Percentage of times chiller-1 is working in loads less than 40%

In loads less than 40%, average energy consumption before monitoring is 61.04 kW per hour, while after that, is about 52.8 kW per hour, which means 8.23 kW difference per hour that results in 13.48% reduction in energy usage. During a month this amount of energy would be:

8.23 kW × 10 hours × 30 days = 2,469.28 kWh

Reducing this amount of energy in a month would cause the following savings:

- In terms of dollar: (2,469 kWh × $0.3) = $740.7
- In terms of CO_2-e: (2,469 kWh × (0.83/1,000) kg CO_2-e/kWh = 2.05 CO_2-e tonnes

These results have been summarised in Table 14.

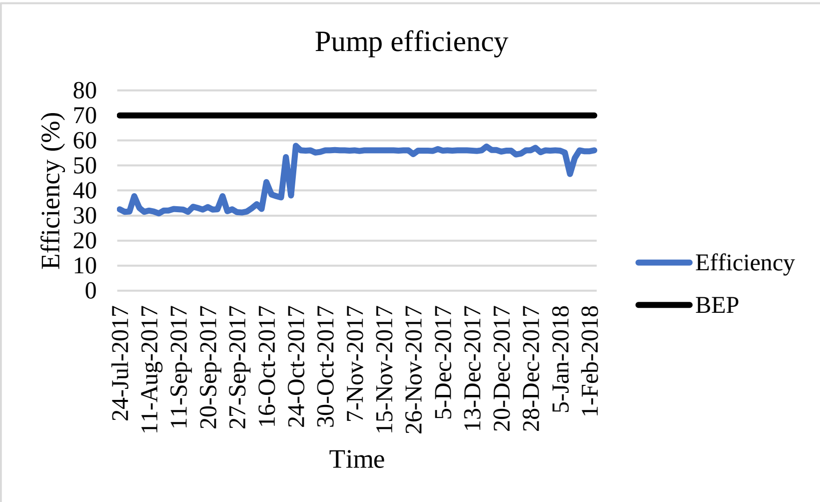
Table 14: Chiller performance in loads less than 40% within a month

Item	Before	After
Mean energy consumption per hour (kW)	61.04	52.81
reduction in energy consumption per hour (%)		13.48
Total energy reduction in a month (kWh)		2,469.28
Financial saving during a month ($)		740.70
CO_2-e tonnes produced during a month		2.05

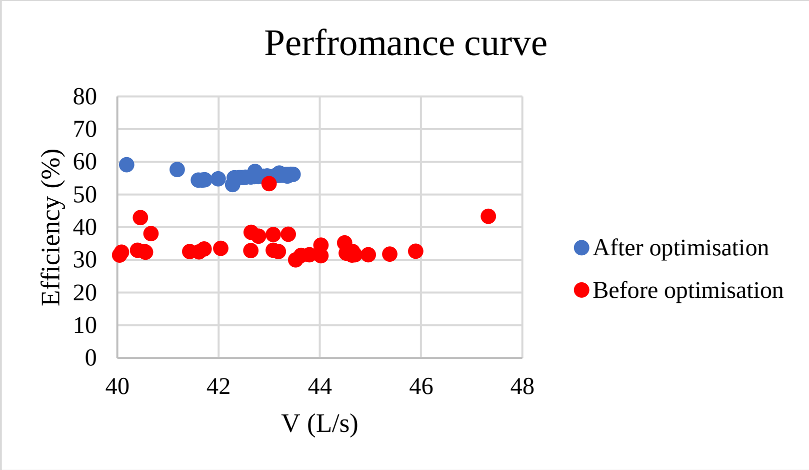
Absence of this amount of energy in a month would result in $740.7 and 2.05 CO_2-e tonnes financial and environmental saving, which is a considerable amount only for one month, and for specific period of loads.

6.3.2 Analysing pump-1

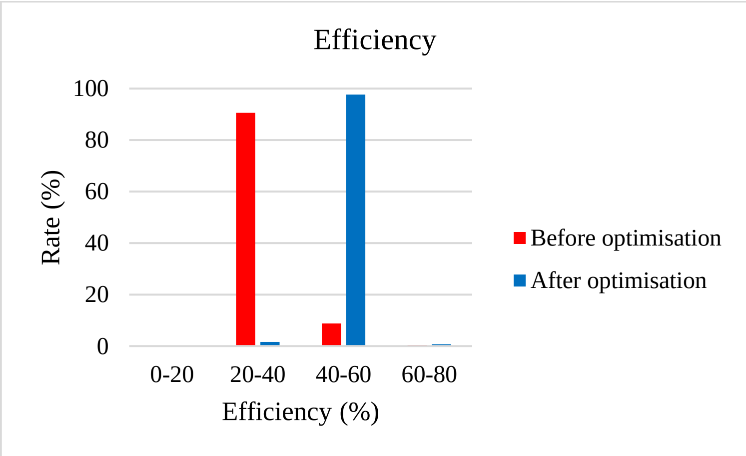
Decreasing evaporator temperature setpoint would decrease flow required by pump. This change has shifted pump flow to the best efficiency point. In this system, the pump is a centrifugal one equipped with VSD and BEP is around 43.4 L/s with an efficiency of 70%. Graph 29 investigates pump daily efficiency trend. Pump efficiency was about 30% and increased to 58% after October 2017. Graph 30 shows pump performance curve; before optimisation pump flow varies from 40 L/s to 46 L/s and after optimisation it is mostly concentrated between 42-44 L/s. Percentage of times pump is working in different range of efficiency is shown in Graph 31. Before monitoring it is mostly working in a range of 20-40% and after that, it has changed to 40-60%.



Graph 29: Pump-1 daily efficiency trend



Graph 30: Pump-1 performance curve



Graph 31: Percentage of times pump-1 is working in various efficiency range

This improvement has saved significant amount of energy. Average of energy consumption per hour has decreased from 20.46 kW to 12.10 kW which is about 41% reduction. As observation before and after monitoring is in different months, total energy consumption cannot be compared, and financial and environment saving is calculated in Table 15 based on average energy consumption for one month. Percentage of times pump is working around BEP, which is in range of 42-44 L/s, has increased from 35% to 91%.

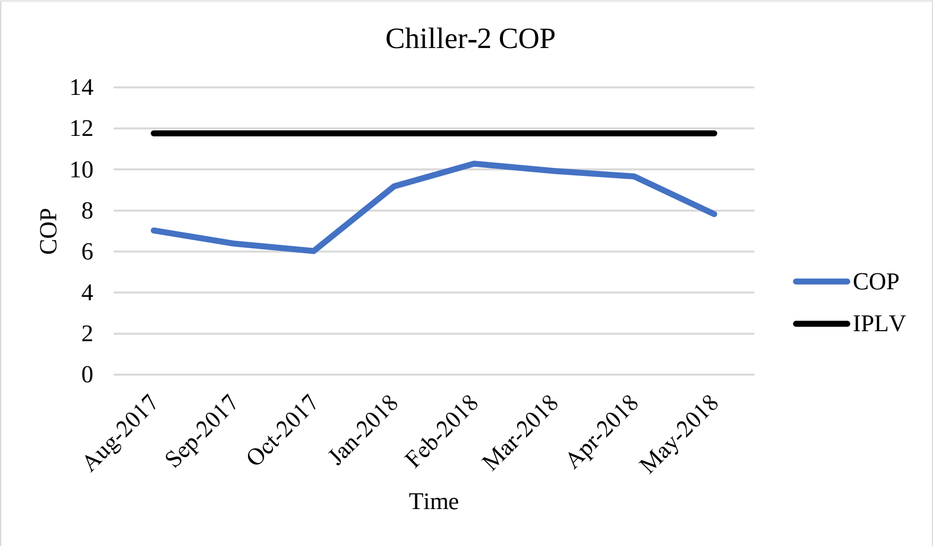
Table 15: Pump-1 performance within a month

Item	Before	After
Mean energy consumption per hour (kW)	20.46	12.10
Reduction in mean energy consumption per hour (%)		40.85
Financial saving during a month ($)		752.11
CO2-e tonnes produced during a month		2.08
Percentage of times working around BEP	35.04	91.13

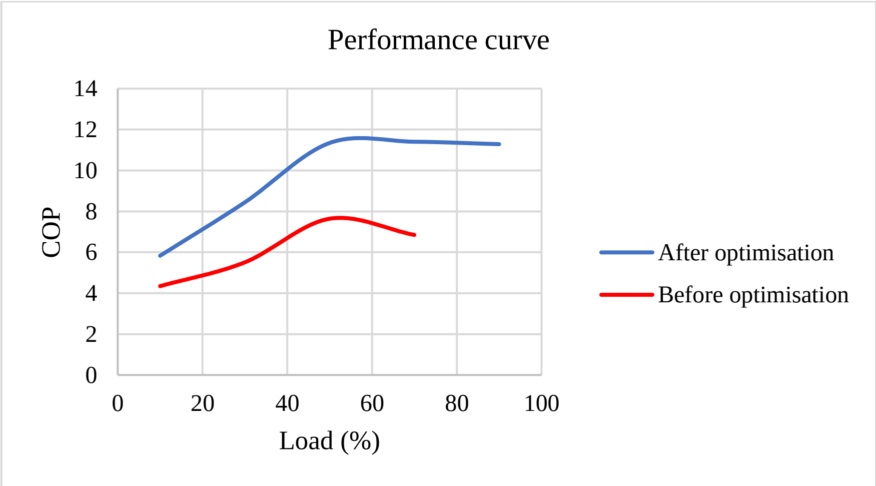
6.3.3 Analysing chiller-2

This chiller is Carrier screw with the same specification as chiller-1 as well as COP in full-load and IPLV. Data exists after August 2017, and differential pressure set-point altering has happened in the middle of October 2017.

Graph 32 and Graph 33 show chiller monthly efficiency trend and chiller performance curve, which demonstrate a huge difference in chiller efficiency. According to Graph 33 in 50% of load, COP was 7.6 before optimising and has increased to 11.3 after that.

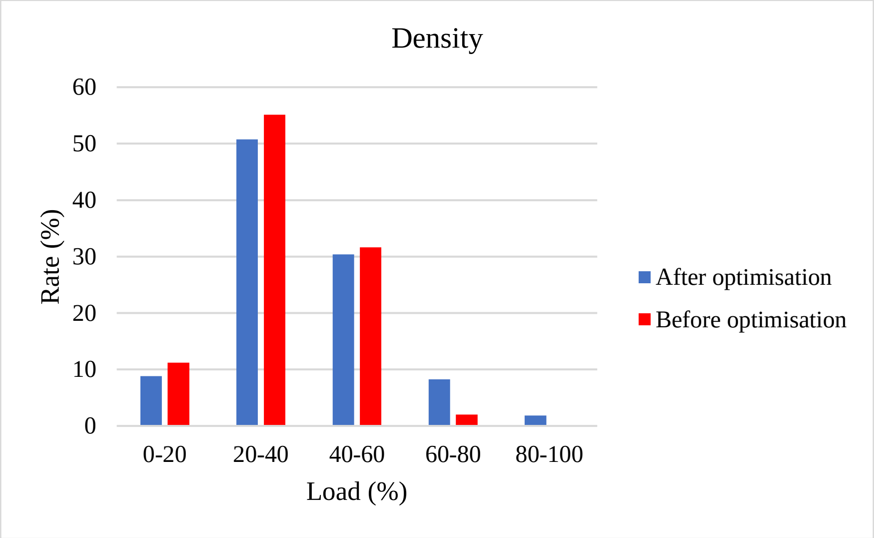


Graph 32: Monthly COP trend of chiller-2



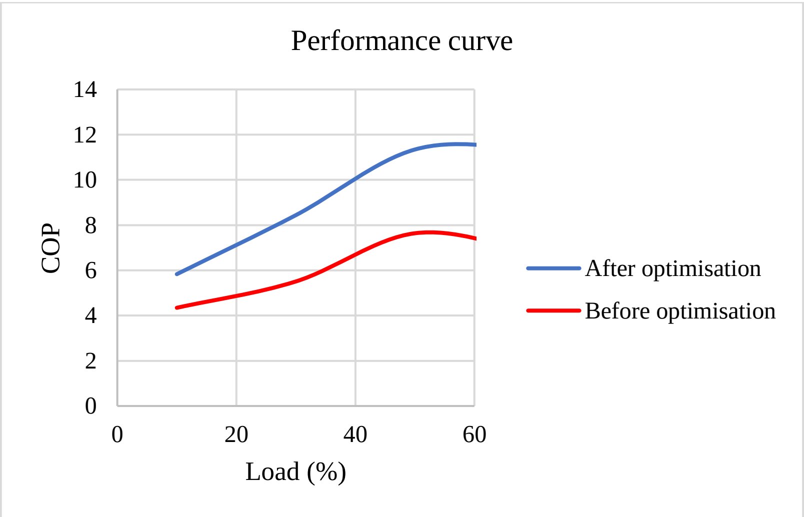
Graph 33: Performance curve of chiller-2

Graph 34 expresses the percentage of times chiller-2 is working in various loads in percentage. However, as seasons are not the same before and after monitoring, the comparison is limited to loads less than 60%, as in this range data is available in both periods.

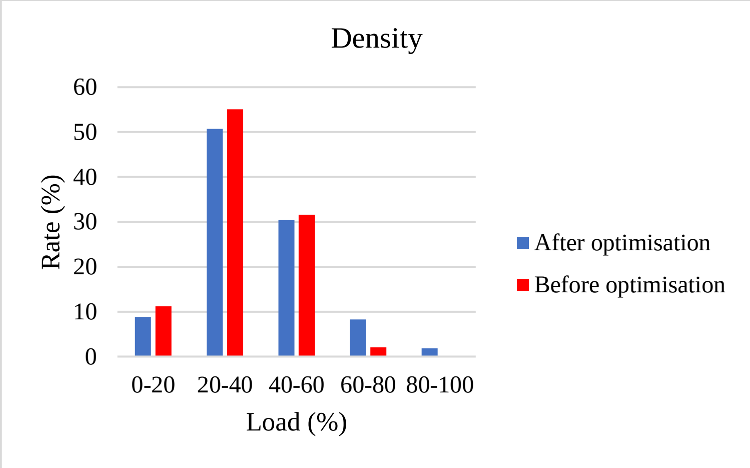


Graph 34: Percentage of times chiller-2 is working in various loads

Graph 35 and Graph 36 show chiller performance curve and rate of running times for loads less than 60%. In this period, average energy consumption before optimising is about 72.13 kW per hour, while it has decreased to 47.99 kW per hour after monitoring. This is about 24.14 kW difference per hour, resulting in 33.47% reduction.



Graph 35: Chiller-2 performance curve for loads less than 60%



Graph 36: Percentage of times chiller-2 is working in loads less than 60%

This amount in a month would cause (24.14 kW ×10 hours × 30 days = 7,242.77 kWh) further energy consumption. The absence of this amount through operational management results in financial and environmental savings. These results have been summarised in Table 16 for loads less than 60% within a month.

Table 16: Chiller performance in loads less than 60% within a month

Item	Before	After
Mean energy consumption per hour (kW)	72.13	47.99
Mean energy consumption reduction (%)		33.47
Total energy reduction in a month (kWh)		7,242.77
Financial saving within a month ($)		2,172.82
CO_2-e tonnes produced within a month		6.01

In this case, as observation is in different seasons, the comparison is limited for a specific range of loads, and it couldn't be discussed for a specific period of time, so the number of running times for a special period of time couldn't be compared. However, both Graph 25 in chiller-1 and Graph 33 in chiller-2 explicitly indicate better performance after optimisation. As chiller works in higher efficiency not only it would save more energy, it prolongs equipment life-long. In lack of operational management, compressor, the first component which damages in most of the time, should be replaced earlier. CO_2 emission to produce a new compressor for this case has been estimated in Table 17.

Table 17: CO_2 footprint to replace a compressor

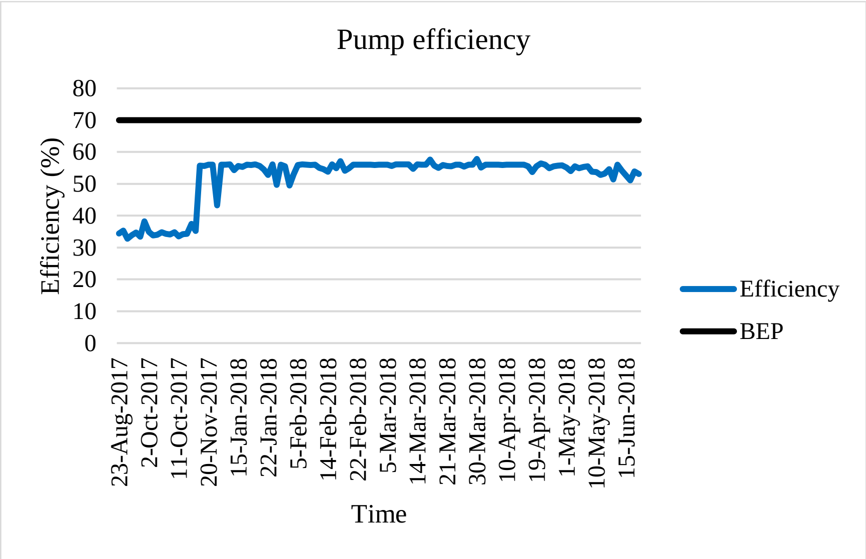
Phase	CO_2 emission (kg)	Contribution (%)
Material	1,365.36	73.30
Manufacture	462.08	24.80
Transport	0	0
Disposal	29.60	1.60

Total	1,857.04	99.70
End of life potential	–1014.67	

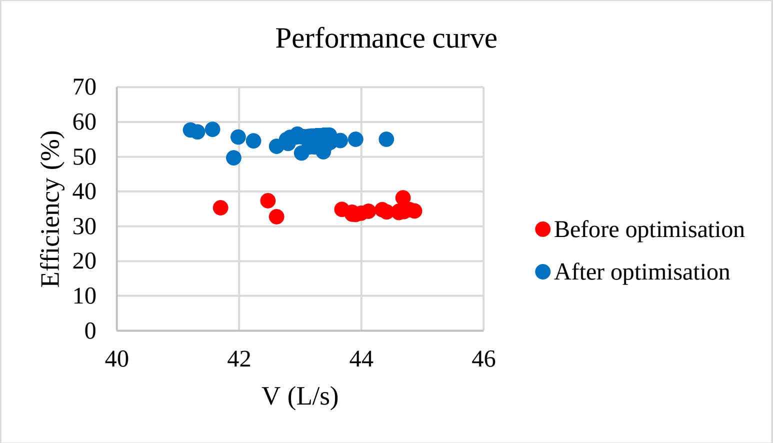
Compressor model is the same as one discussed in Case 2 with the same material. The distance of the Carrier branch in NSW to the building can be ignored, as they are so close. Total CO_2 footprint, in this case, would be about 1.85 CO_2-e tonnes, which 1CO_2-e tonnes can be saved by recycling 100% of the material.

6.3.4 Analysing pump-2

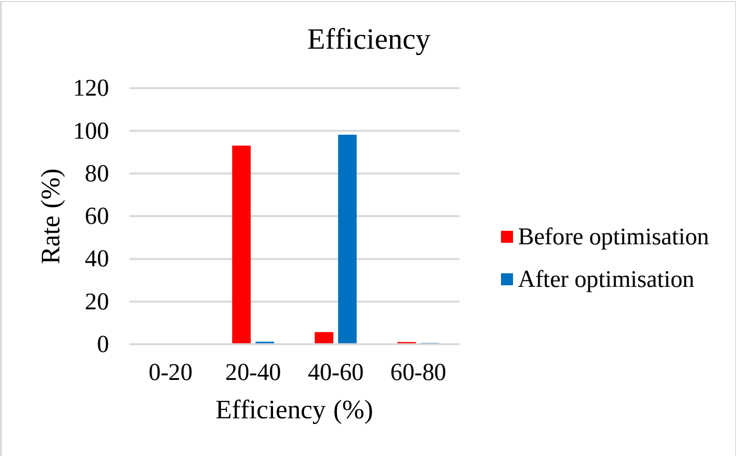
Pump-2 model is the same model as pump-1 with BEP around 43L/s and 70% efficiency. Pump daily efficiency trend and pump performance curve have been shown in Graph 37 and Graph 38 respectively. Pump efficiency has increased from 35% to 56% after October 2017. Also, before optimisation, it used to work mostly inflow greater than 44 L/s, higher than BEP. While after monitoring it is more concentrated in the range of 42-44 L/s, which resulted in working in higher efficiency for most of the time (Graph 39).



Graph 37: Pump-2 daily efficiency trend



Graph 38: Pump-2 performance curve



Graph 39: Percentage of times pump-2 is working in various efficiency range

Average of energy consumption per hour has decreased from 19.75 to 12.16, which is about 38% reduction. Due to different observation period before and after monitoring, financial and environmental saving is calculated within a month in Table 18. Working around the best efficiency point has increased from 30% to 93%.

Table 18: Pump-2 performance within a month

Item	**Before**	**After**
Mean energy consumption per hour (kW)	19.75	12.16
Reduction in mean energy consumption per hour (%)		38.41
Financial saving during a month ($)		682.74
CO2-e tonnes produced during a month		1.89
Percentage of times working around BEP	30.57	93.21

Improving pump performance would increase pump life and reduces pump vibration, noise, and wear. Table 19 shows an estimation of CO_2 emission which would be produced during the manufacturing process of a new pump. Pump net weight is 175 kg and bearing housing contains the most contribution with 97 kg made from cast iron, the shaft is stainless steel and about 5 kg. The impeller is made from bronze with 22 kg, other parts have unknown weight. With these assumptions, about 460.59 kg of CO_2 emissions would be released to produce one pump in this case. Through 100% recycling of material about 263 kg, CO_2 emission would be saved.

Table 19: Amount of CO_2 emissions for making a new pump

Phase	CO_2 emission (kg)	Contribution (%)
Material	353.32	76.70
Manufacture	100.28	21.80
Transport	0.89	0.20
Disposal	6.10	1.30
Total	460.59	100
End of life potential	-263.44	

6.4 Case 4

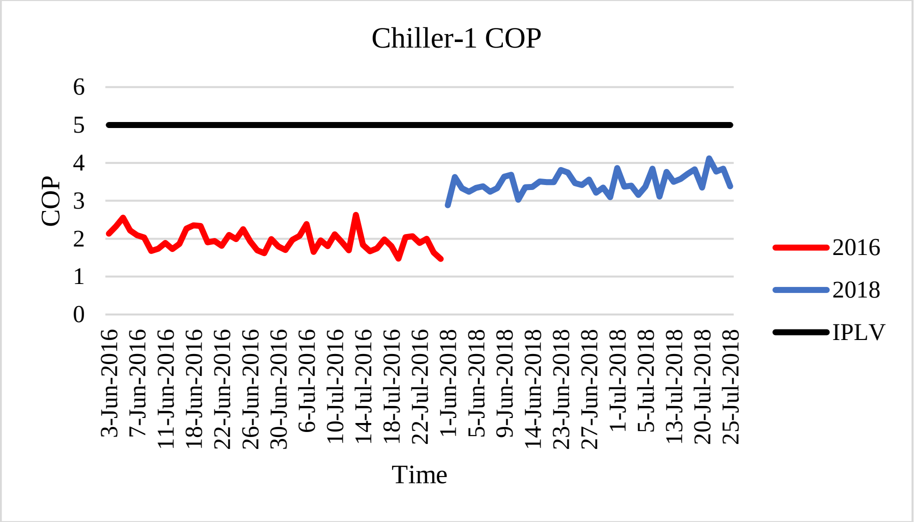
This building is a 5-star deluxe hotel located in Canberra. In addition to the hotel accommodation, it includes restaurants and a series of commercial spaces associated with the building.

The HVAC system contains two air-cooled screw chillers. Chiller-1 is smaller and is working most of the time. COP in full-load operation is 3 and IPLV is around 5. As it is air-cooled, it is not as efficient as previous ones. The system works from 2008.

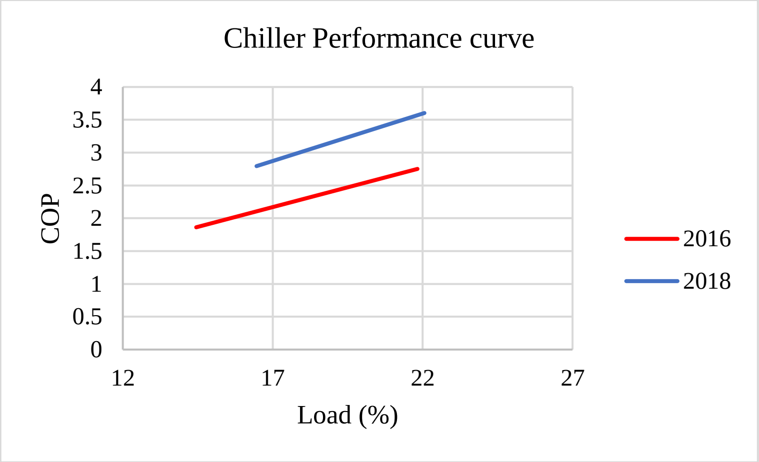
6.4.1 Analysing chiller-1

The chilled water leaving temperature set-point has been changed from August 2016. Before this time, data is recorded only for June and July, so these two months have been compared in 2016 and 2018.

Graph 40 and Graph 41 show the daily trend of chiller COP and chiller performance curve within June and July in 2016 and 2018. Both graphs illustrate COP growth as it has increased from about 2 to 3.5. However, still it hasn’t reached IPLV = 5, which can be due to chiller age, as it is about 10 years old.

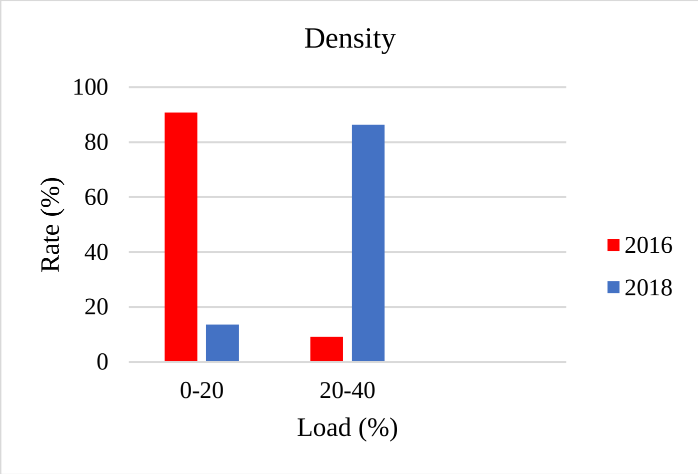


Graph 40: Daily COP trend of chiller-1



Graph 41: Chiller-1 performance curve

Percentage of times chiller is working in different loads is demonstrated in Graph 42. In 2018, it was working mostly in loads greater than 20, while in 2016, about 90% of the time, it is running in loads less than 20%. Meanwhile, the number of running times has declined from 587 to 287.



Graph 42: Percentage of times chiller-1 is working in various loads

This upgrade led to $765 and 3 CO_2-e tonnes financial and environmental savings. Table 20 is a summary of chiller performance in Case 4.

Table 20: Chiller-1 performance during June and July in two different years

Item	**2016**	**2018**
Mean energy consumption per hour (kW)	42.28	33.13
Total energy consumption (kWh)	6,204.82	2,377.18
Reduction in mean energy consumption (%)		21.64
Total energy reduction (%)		61.69
Financial saving ($)		1,148.29
CO_2-e tonnes		3.18
Running times (every 15 min)	587	287
Reduction of running times (%)		51.11

Table 20 illustrates that the number of running times has decreased by half. Also, it is working with higher efficiency (Graph 40 and Graph 41), which affects equipment long-life. While, in lack of comprehensive operation, it fails earlier. In this situation, compressor, the most important rotary element, should be replaced, resulting in further CO_2 emission. However, in this case, as the system is old, there is no data regarding compressor material, and CO_2 footprint through manufacturing process cannot be estimated.

7 Conclusion

The continuation of greenhouse gas emissions at the same pace will certainly lead to a catastrophic situation as previously discussed. Commercial buildings are one of the high energy users, which consume most of the energy in the HVAC system to achieve thermal comfort.

Therefore, operational management with continuous monitoring of HVAC system in these buildings is a key factor to reduce electricity usage.

Sustainable building is considered as a way for the building industry to move towards protecting the environment. The promotion of sustainable building practices is to pursue a balance between economic, social, and environmental performance.

7.1 Summary of findings

This project aimed to demonstrate the importance of operational management in a building's HVAC system and how this would result in a sustainable environment. In this regard, six chillers, as one of the most important parts in HVAC system, have been evaluated in four different buildings including an office, a shopping centre, and a hotel before and after having comprehensive optimisation; energy consumption reduction was investigated, and it was shown that a considerable level of energy savings contributing to a sustainable economy could be made. Also, at a lower level which is more pleasing to building owners and investment entities, it is shown through optimisation service life of equipment would increase incurring less cost per year. Increased service life also contributes to less greenhouse gas emissions by eliminating the need for good transport for replacements and all the associated activities. While this saving for a given building may be considered to a few people only, the large effect of such practice would certainly have a positive impact on a whole economy.

In Cases 1 and 3, as chilled-water pump data before and after optimisation had been recorded, this procedure is investigated for three different pumps as well.

Table 21 is a summary of chiller's performance results which achieved in chapter 6. All chillers are water-cooled except Case 4, which is air-cooled. They are all in Australia, and the age of them varies from 6 to 10 years old.

This table illustrates details of each project; total number of months observation took place before and after monitoring, total energy reduction achieved in specific period considered in each project based on available data, variation of running times, average of financial and environmental savings only for one month and finally CO_2 emission to manufacture a new compressor in each case.

Table 21: Summary of chiller performance

Item	**Case 1**	**Case 2**	**Case 2**	**Case 3**	**Case 3**	**Case 4**
	Chiller-1	**Chiller-1**	**Chiller-2**	**Chiller-1**	**Chiller-2**	**Chiller-1**
Building type	Office	Shopping centre	Shopping centre	Office	Office	Hotel
State	NSW	NSW	NSW	NSW	NSW	ACT
Compressor type	Centrifugal Oil-free Water-cooled	Screw Water-cooled	Screw Water-cooled	Screw Water-cooled	Screw Water-cooled	Screw Air-cooled
Observation period (month)	20	6	12	7	8	4
Total energy reduction (%)	64.48	56.60	65.80			61.69
Reduction in running times (%)	54.19	64	63.78			51.11
Average of financial saving in one month ($)	1,052.46	51.17	1,265.21	740.79	2,172.83	574.15
Average of CO_2-e tonnes in one month	2.912	0.14	3.50	2.05	6.01	1.59
CO_2 tonnes in the manufacturing process	1.35	1.86	1.86	1.85	1.85	-

Table 22 shows an average saving of these six chillers. According to this table average energy reduction is 62% and running times has decreased by 58%. Improving performance more than twice and reducing machine working time by half, would at least double machine long-life. On the other hand, it would save by average $976 and 2.7 CO_2-e tonnes per month. While in lack of operational management it would be $117,132.2 and 324.04 CO_2-e tonnes waste after 10 years for one building only in case of the chiller. In Australia since 2011 there are about 134,000 commercial buildings, while 40,000 of them are with NABERS less than or equal to 3, (Department of the Environment and Energy 2018) and they are producing (2.7×12 CO_2-e tonnes in a year $\times$ 40,000 buildings = 1.30 CO_2-e M-tonnes) more CO_2 emissions each year only in terms of chillers in whole HVAC system, which is a considerable amount.

Also, replacing a new compressor generates an average of 1.75 CO_2 footprint; however, as discussed before a significant amount of that can be saved due to recycling.

Table 22: Average of savings in six chillers

Item	Average
Total energy reduction (%)	62.14
Reduction in running times (%)	58.27
Financial saving per month ($)	976.10
CO_2-e tonnes in each month	2.70
CO_2 tonnes in the manufacturing process	1.75

Pumps are much less expensive than chillers, but they are used widely in industry. For instance, most of the commercial buildings are equipped at least with three water pumps, including chilled water pump, condenser water pump, and hot water pump. In this regard, their optimisation is a major issue that requires high attention.

Table 23 is a summary of the centrifugal pumps' performance, which analysed in Cases 1 and 3. Average of energy consumption per hour has decreased about 40%, and the system is working close to BEP for most of the time, as it has increased in average by 68% in contrast to before optimisation. This progress in performance would extend pump life. Also, it has resulted in an average of $601 and 1.66 CO_2-e tonnes savings for one month which will be $72,155 and 199.6 CO_2-e tonnes after 10 years. On the other hand, replacing a new pump would cause 0.41 CO_2 tonnes further emissions, which has the potential to be saved if the recycling process occurs.

Table 23: Summary of pump performance

Item	Case 1	Case 3 Pump-1	Case 3 Pump-2	Average
System age (year)	8	10	10	
Observation period (month)	24	8	10	
Reduction in mean energy consumption per hour (%)	39.88	40.85	38.41	39.71
The increment of times working around BEP	77	61.55	67.20	68.58
Average of financial saving in one month ($)	369.03	752.11	682.74	601.29
Average of CO_2-e tonnes in one month	1.02	2.08	1.89	1.66
CO_2 tonnes in manufacturing	0.32	0.46	0.46	0.41

Thus, in a simple commercial building with one chiller and a chilled water pump, after a year environmental impact in lack of operational management of HVAC system only for these two items would be about 52.32 CO_2-e tonnes. These results illustrate the high-potential of HVAC systems to achieve sustainability.

Having comprehensive management not only reduces CO_2 emission through the operation but also it will prevent additional emissions in manufacturing new equipment.

In summary, energy consumption and GHG emissions reduction potentials in commercial buildings have demonstrated the necessity of implementing proper energy management systems in buildings. It is important that old buildings be equipped with latest BMS technology, and all BMS systems are monitored and programmed regularly to optimise system performance and achieve the best efficiency for the HVAC system, to decrease electricity consumption and prolong equipment life-long.

This study could be employed as a motivation guideline for decision makers to utilise more sustainable energy management strategy and simultaneously alleviate GHG emissions.

7.2 Recommendation for future work

Further study is required to evaluate financial and environmental saving potential through predictive maintenance using machine learning, not only in chillers and pumps but also in AHUs and cooling towers.

Also, temperature set-point regulation in offices, which is already about 22.5, can be investigated more with occupants' opinions, as most of the time rooms are colder than they need to be for comfort. Increasing this set-point would result in significant savings in energy consumption.

Another important issue is the leakage of refrigerant liquid, which if not CFC free affects the ozone layer greatly. Although there are many legislations in this regard for new equipment, they are not applied to old buildings.

New legislation and incentives should be introduced to encourage building owners to reduce energy consumption, especially for old buildings that are not equipped with smart-grid BMS systems.

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