COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE

OPTIMIZATION OF ENERGY CONSERVATION MEASURES TO IMPROVE EFFICIENCY IN COMMERCIAL BUILDINGS

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Thesis submitted in fulfilment of the requirement for the degree of Master of Science in Mechanical Engineering

18 SEPTEMBER 2021

As the candidate's supervisor, I have approved this dissertation for submission.

Signed: ________________ Date: 18 September 2021

Name: Professor Freddie L. Inambao

DECLARTION 1 - PLAGIARISM

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DECLARTION 2 - PUBLICATIONS

This section presents the articles that form part and/or include the research presented in this thesis. The following papers have been published or have been accepted for publication:

Department of Higher Education and Training (DoHET) Accredited Journals

1. Amina Ismail and Freddie L. Inambao, Review of Factors Affecting Energy Efficiency in Commercial Buildings. *International Journal of Mechanical Engineering and Technology (IJMET), 10(11), 2019, pp. 232-244.* https://iaeme.com/MasterAdmin/Journal_uploads/IJMET/VOLUME_10_ISSUE_11/IJMET_10_11_021.pdf

2. Amina Ismail & Freddie L. Inambao, A Review of the Energy Flow Through a Centrifugal Water-Cooled Chiller Air Conditioning System, *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD),* ISSN (P): 2249–6890; ISSN (E): 2249–8001, Vol. 11, Issue 3, Jun 2021, 325-338, © TJPRC Pvt. Ltd. http://www.tjprc.org/publishpapers/2-67-1624341434-27IJMPERDJUN202127_compressed.pdf

3. Amina Ismail & Freddie L. Inambao, Air Conditioning System Design And Strategies For Improving Energy Efficiency – A Review, *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD),* ISSN (P): 2249–6890; ISSN (E): 2249–8001, Vol. 11, Issue 3, Jun 2021, 315–324, © TJPRC Pvt. Ltd. http://www.tjprc.org/publishpapers/2-67-1620711853-26IJMPERDJUN202126.pdf

4. Amina Ismail & Freddie Inambao, Energy Efficiency Opportunities for Lighting Systems and Miscellaneous Electrical Loads in Commercial Buildings – A Review, *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD),* ISSN (P): 2249–6890; ISSN (E): 2249–8001, Vol. 11, Issue 2, Apr 2021, 107–118, © TJPRC Pvt. Ltd. http://www.tjprc.org/publishpapers/2-67-1617428508-10IJMPERDAPR202110.pdf

5. Amina Ismail & Freddie Inambao, Potential Barriers and Drivers to Energy Efficiency in Commercial Buildings, *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)*, ISSN (P): 2249–6890; ISSN (E): 2249–8001, Vol. 11, Issue 2, Apr 2021, 171—186, © TJPRC Pvt. Ltd. http://www.tjprc.org/publishpapers/2-67-1625468347-IJMPERDAPR202114.pdf

6. Amina Ismail & Freddie Inambao, Implementing Energy Conservation Measures: A Case Study on Retrofitting A Commercial Building In South Africa, *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)* ISSN (P): 2249–6890; ISSN (E): 2249–8001, DOI: 10.24247/ijmperdaug202122, Vol. 11, Issue 4, Aug 2021, 273–292 © TJPRC Pvt Ltd. http://www.tjprc.org/publishpapers/2-67-1626239880-2IJMPERDAUG202122.pdf11.pdf

The author/candidate of this thesis is the main author of all the publications used in this thesis, whereas Professor Freddie L. Inambao is the Supervisor.

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"All the praises and thanks be to God, Who has guided us to this, and never could we have found guidance, were it not that God had guided us!" – 7:43

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ABSTRACT

In addition to international energy concerns, South Africa is facing its own electricity generation challenges. Periodic load shedding leads to a decrease in national revenue as the production of goods and services comes to a halt and investor confidence in the country declines. This particularly affects small businesses and contributes to unemployment. Many South African government buildings are old with poor energy management practices. These buildings tend to consume more energy than necessary, making the buildings highly energy intensive, thus compounding the energy demand on the grid. The country's energy challenge and the lack of energy efficiency in commercial buildings adds to excessive and wasteful consumption of energy, which negatively impacts the environment and the already hurt economy. The aim of this research was to evaluate energy efficiency in a public commercial building and identify the drivers and barriers to energy efficiency to improve energy management practices and ensure electrical and mechanical systems are energy efficient.

The outcome from this research indicates that energy consumption can be improved and reduced by using energy efficient technology, implementing energy efficient design techniques for systems design, and incorporating energy conservation measures where possible. Effective energy management of a commercial building involves operation and maintenance of electro-mechanical equipment and continuously improving energy consumption by monitoring the buildings energy use. Another important outcome from this research is that government regulations, building policies and other regulatory documents play an important role in encouraging the implementation of energy efficiency as well as monitoring and improving energy usage. A review of energy efficiency in heating, ventilation, and air conditioning (HVAC) systems indicated that energy efficiency can be implemented from the design stage, where the designer selects energy efficient technology so that energy efficiency of the system is optimised. A review of various articles concluded that energy efficiency of lighting systems and miscellaneous electrical loads (MELs) can be improved by the use of energy efficient light bulbs, occupancy sensors, day/night switches and other novel energy efficient technologies. The review on drivers and barriers to energy efficiency showed that drivers and barriers to energy efficiency can be found in various stages of a building's life cycle, and in some cases decisions made at the inception stages affect the energy consumption during the operation of the facility. The experimental results showed that the energy conservation measures implemented in the buildings in this study were relatively cost effective and produced a significant improvement in the consumption of electrical energy.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

COP 21	Conference of Parties
ECMs	Energy Conservation Measures
ERC	Energy Research Centre
GHG	Greenhouse gas
HVAC	Heating, ventilation and air conditioning
IEQ	Indoor Environmental Quality
IPCC	Intergovernmental Panel on Climate Change
NCCRP	National Climate Change Response Policy
NEES	National Energy Efficiency Strategy
MEL	Miscellaneous electrical loads
SANS	South African National Standards
UNFCCC	United Nations Framework Convention on Climate Change
WRI	World Resource Institute

CHAPTER 1: INTRODUCTION

1.0 Introduction

The world is currently facing a dilemma of finite fossil fuel reserves as well the threat of global warming. In addition to international energy concerns, in 2008 South Africa began experiencing periodic power outages (also known as load shedding) from the national electricity supplier, Eskom [1], [2]. Such power outages lead to a decrease in national revenue over the period of the power outage, as the production of goods and services comes to a halt, and investor confidence in our country declines. This particularly affects small businesses and contributes to unemployment. Load shedding affects the lifestyle of households and the lifespan of electrical equipment in these households. In commercial and industrial facilities, load shedding affects production time, damages electrical equipment due to power surges, and is recorded as downtime in the business. Since 2008 Eskom has faced challenges in providing the country with a stable energy supply.

According to the fourth assessment of the Intergovernmental Panel on Climate Change (IPCC), buildings play an important role in climate change and have the largest potential for significantly reducing greenhouse gas emissions [3]. Emissions from buildings consist of operational (carbon emissions emitted resulting from operation of the building) and embodied (carbon emissions resulting from the material fabrication for construction and the construction processes of the building) emissions which account for about 33 % and 8 % of the total annual global greenhouse gas (GHG) emissions respectively [4].

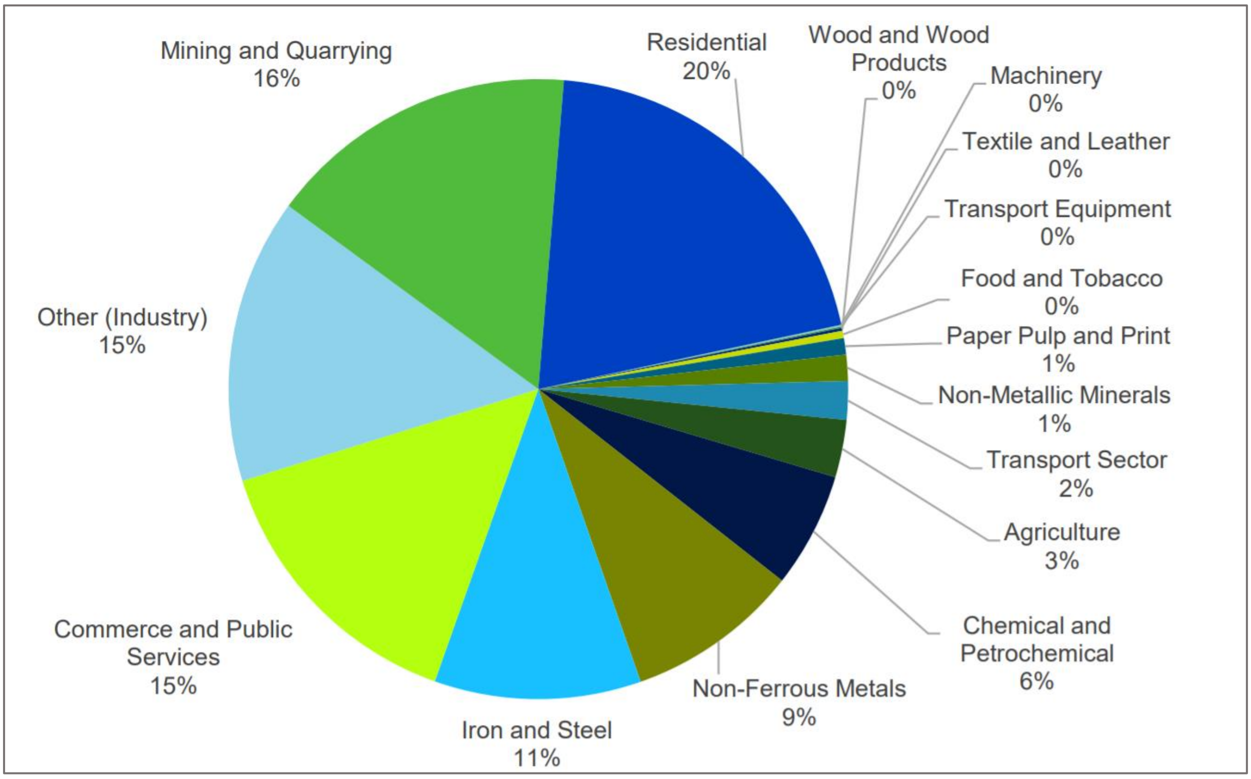
Many of the South African government buildings are old with poor energy management practices. These buildings tend to consume more energy than necessary, making these buildings highly energy intensive, thus compounding the energy demand on the grid. There is poor maintenance on these facilities, which often leads to “make shift equipment” to keep the system running. These practices often lead to inefficiencies in the system and poor energy management. Implementation of energy efficiency measures will assist in reducing the load on Eskom, reduce operating costs of state buildings, and contribute to the reduction of GHG emissions into the atmosphere, thus improving investor confidence in South Africa.

This study of energy efficiency in a state-owned commercial building aimed to determine the amount of energy consumed by the building and the associated losses of energy in the building operation. The overall outcome of this research can provide information on the use of electrical energy in commercial buildings, providing insight to the barriers and drivers of energy efficiency.

The results have been analysed to come up with practical and attainable recommendations for energy efficiency opportunities in state owned commercial buildings.

1.1. Rationale

Commercial buildings make up one of the biggest consumers of electricity in South Africa. According to studies carried out by Deloitte Consulting Pty (Ltd) in 2017, the commerce and public services sector consumes approximately 15 % of the electricity generated and is the 3rd largest electricity consumer in South Africa (Graph 1) [5].



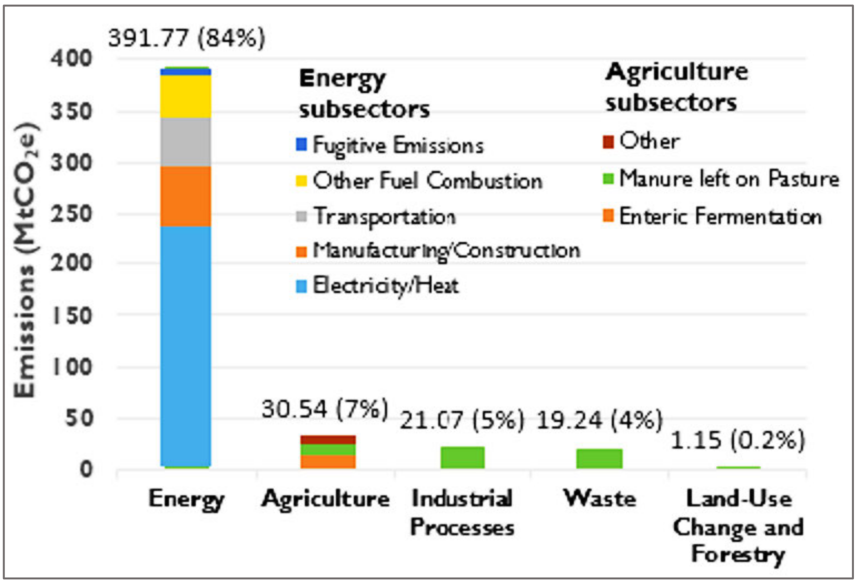
Graph 1: Electricity consumption, 2012[5]

Considering the amount of electricity consumed by the commercial field, it is essential to pursue energy efficiency in such buildings. Energy efficiency is seen as the easiest and most cost-effective way of reducing energy consumption. The implementation of energy efficiency practices in commercial buildings can potentially reduce operating costs of these facilities thereby contributing to mitigation carbon emissions.

The benefits of energy efficiency will be discussed below in relation to commercial buildings owned by the state. The benefits obtained from energy efficiency is also dependent on a country's legislation and on whether the country is aware of energy efficiency and promoting energy efficiency.

A. Reduction of greenhouse gasses in South Africa

The World Resource Institute (WRI) conducted research on the GHG emissions produced by South Africa and the results in Graph 22 show that 84 % of total GHG emissions is produced by the South African energy subsectors and more than 60 % of this is from the production of electricity and heat [6].



Graph 2: GHG emissions by sector in South Africa in 2012 [6]

South Africa is one of the highest GHG emitters on the African continent, with a high energy intensity (ratio of GHG emissions to Gross Domestic Product). For this reason, the South African government is actively participating in initiatives to mitigate GHG emissions. In 1994 South Africa ratified the UNFCCC (United Nations Framework Convention on Climate Change), acceded to the Kyoto protocol in 2002, and participated in Conference of Parties (COP 21) held in Paris in 2015 [4]. The National Energy Efficiency Strategy (NEES) of South Africa, first published in 2005 and later updated in 2008, provided a target of 12% for energy efficiency improvement by 2015 [4]. In 2006, the Energy Research Centre (ERC) was commissioned to examine the potential of mitigating national GHG emissions [4]. The UNFCC and the Kyoto protocol led to the development of the National Climate Change Response Policy (NCCRP) by the government. The NCCRP has two objectives: the first objective involves managing the impacts of climate change, and the second is to contribute to the international efforts to alleviate GHG concentrations in the atmosphere [4]. Crucial to the built environment, the South African Department of Minerals and Energy initiated the South African National Standards (SANS) 204 Energy Efficiency in Buildings to ensure that the building sector contributes to the energy efficiency targets in the NEES [4].

South Africa is committed to reducing GHG emissions as the government has instituted standards for the country to conform to. However, the measures that South Africa has introduced are taking a while to become fully executed throughout all industries and buildings. It is the responsibility of society, developers, companies, the government and entrepreneurs to ensure that they comply with these measures.

B. Sustainability

In the context of sustainability, energy efficiency plays a major role as an energy resource. This perspective looks at energy efficiency as being the negative use of energy. According to Sebitosi [7], energy efficiency is one of the best energy resources. The concept of energy efficiency in the built environment has a wide application from the inception stage of the building till close out including its operational life. With the implementation of energy efficiency measures, one can ultimately achieve sustainability.

The implementation of energy efficiency not only refers to technical applications – energy efficiency can be achieved through better organisational structure and management and improved economic efficiency [8]. Energy efficiency has been identified as a means to address issues such as energy security, social and economic impacts of high energy prices, and climate change concerns. Research has also identified energy efficiency as cost effective and as a stimulus for corporate competitiveness [8].

C. Environmental contribution

One of the greatest environmental benefits resulting from energy efficiency is the reduction of carbon emissions into the atmosphere. The use of less energy also curbs outdoor pollution by the reduction of fossil fuel pollution (such as sulphur dioxide, particulate matter, unburned hydrocarbons and nitrogen oxides) created by power generation [9]. By reducing air pollution, resilience to climate change increases thus reducing the effects of climate change and prolonging the climate change process [9].

Energy efficiency helps reduce the pressure that currently is placed upon the limited non-renewable natural resources. The need to explore challenging locations for natural resource extraction, such as ultra-deep offshore, the arctic and shale, is minimized. Energy efficiency indirectly reduces the cost of such projects as well as reduces any environmental uncertainties associated with natural resource extraction [9].

Energy efficiency plays an indirect role in the preservation and sustainability of the natural environment. With the use of energy efficient technology and activities, time is bought for research and development in renewable energy as well as net zero-energy buildings for further elimination of the natural environment degradation as well as for the benefit of human health.

The amount of energy used by government practicing energy efficiency will contribute to the prevention of degradation of the natural environment and will assist in stalling the effects of climate change, as well as contributing to providing a more sustainable environment for future generations.

D. Social Responsibility

Social benefits of energy efficiency play an important role in human interaction and response to the environment, including the health benefits experienced by people resulting from energy efficiency.

Energy efficiency within buildings can significantly reduce ill health and death related to air pollution. Energy efficient buildings offer better ventilation than conventional buildings. The reduction of air pollution (indoor and outdoor) can decrease the incidence of illnesses such as asthma and lung cancer, as well as minimize the rate of premature deaths [9].

Implementing energy efficient activity or behavior among building occupants and staff will help the state reduce costs and the energy efficient traits instilled are then carried into their families. Implementing such measures in universities can result in such traits being carried by students into the corporate world as well [9].

E. Economic Viability

The financial benefits of energy efficiency can be found in almost all energy efficient activities or operations and energy efficient equipment. It is one of the most rewarding aspects for corporate companies and industries. Government buildings, being part of a business venture, also reap the rewards of implementing energy efficiency activities and energy efficient technologies.

According to the South African Development Community [10], private companies enjoy financial benefits from lowered running costs because building energy efficiency reduces infrastructure costs and building expenses [10]. Reducing the operating costs can save a significant amount of money for government buildings as well. For example, finances can be saved by replacing all incandescent light bulbs with compact flourescent light bulbs which require less energy but produces the same amount of light, thus the state will pay for less energy used resulting in a saving. Efficiency improvements in energy and resource use eliminate a cost that the government does not need. Building efficiently also reduces building costs, and building for the first time offers large economic opportunities.

Figure 3 is a Venn diagram indicating most of the financial benefits of energy efficiency which in relation to commercial buildings. Energy efficiency reduces energy expenses by decreasing the amount of energy used for the same output. The state can therefore pay less for energy usage and as a result have a surplus of finances for other priorities. Making the state a better environment and improving the Indoor Environmental Quality (IEQ) for occupants will also improve staff productivity[11]. Being an energy efficient government, the government will have an edge in regard to rising energy prices. Lower operating costs from energy efficient measures allows for an increase in the operating budget. Energy efficiency can be associated with lowered operating costs and better indoor comfort for occupants and give staff a better environment to work in. This increases the building value and reduces financial risk, thus sparking the interest of investors and increases competitive differentiation [12].

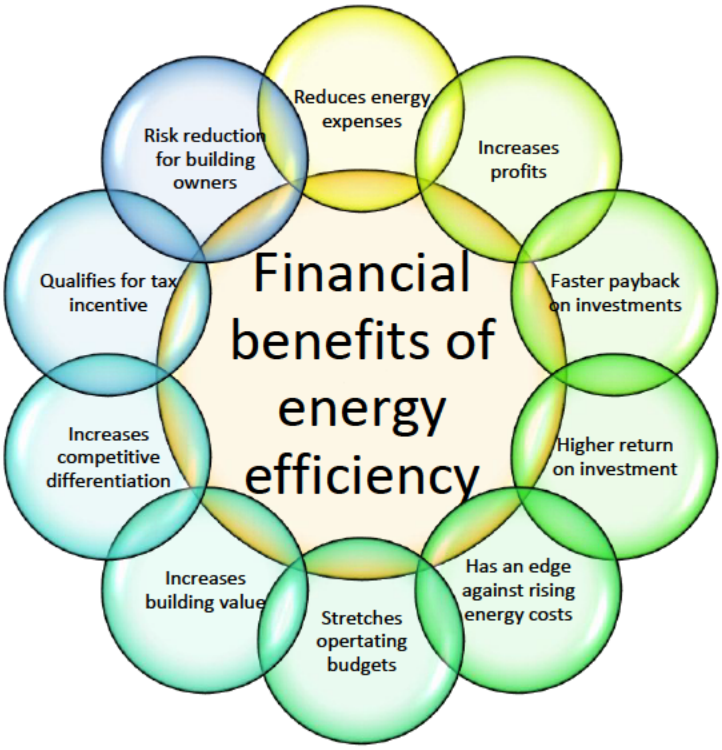


Figure 3: Financial benefits of energy efficiency

Operational benefits that are achieved through energy efficiency lead to financial benefits. As mentioned above, operating costs are reduced due to energy efficiency, but so are maintenance costs. Mechanical systems and buildings are modernized with energy efficiency operational activities and equipment. The life span and reliability of equipment is increased, thus reducing equipment downtime and operational efficiency.

1.2. Aim and objectives

The aim of this research was to evaluate energy efficiency in a public commercial building to identify the barriers and drivers to energy efficiency, thereby finding improved energy management practices and ensuring electrical and mechanical systems that are also energy efficient. The objectives of this study were to:

1. Identify energy losses in a government building, by studying energy consumption patterns in the building.
2. Identify energy efficiency measures that can be implemented in a government building without affecting service provision by the state.

3. Identify factors that are influencing the adoption of energy efficiency measures in a state owned building, that is, to study barriers and drivers to energy efficiency methodologies in this industrial sector.
4. Quantifying the energy efficiency of energy conservation measures of the retrofits implemented.

1.3. Research questions

The following research questions were answered in order to fulfil the objectives:

1. Where are the energy losses in a public commercial building prevalent?
2. What are the technical energy efficient opportunities for a commercial building?
3. What are the factors inhibiting energy efficiency?
4. What are the factors driving energy efficiency?
5. What are possible cost effective energy efficient measures to reduce the consumption of electrical energy?
6. What impact does the implementation of energy efficient measure, mentioned in point 5, have on cost and reduction of energy consumption?

1.4. Limitations

This study was constrained by the following limitations:

1. The availability of a suitable public commercial building to use as an experimental case study.
2. Gathering sufficient data as the public domain is known to have poor documentation management.
3. The lack of resources and knowledge on the scope of this research may be a challenge.
4. Cost implications to carry out the study may involve hiring of equipment or service providers to carry out specialised tasks.
5. The quality of data may be compromised due to the lack of proper record keeping and documentation.

1.5. Layout of thesis

This thesis consists of the following chapters:

1. Chapter 1 provides the background to this research, the rationale, research questions, aims and objectives, the limitations and the layout of this research.

2. Chapter 2 presents the background of factors that affect the rate and intensity of energy efficiency in commercial buildings.
3. Chapter 3 is a review of energy flow in heating, ventilation and air conditioning (HVAC) systems and energy efficient technologies and strategies for centrifugal water-cooled chiller systems in commercial buildings.
4. Chapter 4 presents a critical review of the energy efficiency opportunities for lighting and miscellaneous electrical loads (MELs) in commercial buildings and the current lighting and MELs control strategies that have been used to reduce energy consumption of lighting and MELs so that the potential for improving energy efficiency for lighting systems and MELs can be identified and implemented.
5. Chapter 5 presents identification of barriers and drivers to energy efficiency in occupied commercial buildings, thereby producing a systematic classification and explanation of barriers and drivers to energy efficiency. The identification of these barriers and drivers can be used by policy makers to further implement regulations that enhance and promote energy efficiency. Chapter 5, further explains the impact of barriers as well as energy efficiency drivers and proposes a taxonomy of potential barriers and some drivers that may be prevalent.
6. Chapter 6 presents experimental findings of the quantitative analysis of the energy savings after retrofitting of Energy Conservation Measures (ECMs) implemented in a state-owned commercial building to determine the electrical energy savings, the effectiveness of energy efficient retrofits, and the correlated cost implications. The chapter also provides identified barriers to energy efficiency such as: Lack of funding, resources and knowledge as the most prevalent barriers.
7. Chapter 7 presents the conclusions drawn from the research, and recommendations for future work.

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CHAPTER 2: REVIEW OF FACTORS AFFECTING ENERGY EFFICIENCY IN COMMERCIAL BUILDINGS

This chapter provides the back ground of other researchers work in establishment the common factors that affect energy efficiency in commercial buildings. This chapter has been published in the International Journal of Mechanical Engineering and Technology (IJMET).

Citation:

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REVIEW OF FACTORS AFFECTING ENERGY EFFICIENCY IN COMMERCIAL BUILDINGS

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ABSTRACT

The challenge with energy consumption in many commercial buildings in South Africa is poor energy practices, the use of equipment that is not energy efficient, lack of maintenance of electrical equipment, an exponentially growing population and a progressing economy, all of which contribute to an increase in energy consumption. Understanding the use of energy in commercial buildings requires insight into the amount of energy consumed and the different ways in which this energy is used. Factors that directly and indirectly affect the implementation of energy efficiency, include technical, social, economic and environmental factors. Various articles and reports on factors affecting the rate and intensity of energy efficiency are critically reviewed in this paper to determine the extent to which these affect the implementation of energy efficiency measures. It has been established that the rate and intensity of energy consumption in relation to these factors varies according to the location and climatic conditions of the area. Electro-mechanical equipment and systems can be easily controlled, but regulations and social dynamics play an important role in the consumption of energy of such equipment and systems, with social dynamics being the most unpredictable energy consumption factor. Energy management of a commercial building can optimise energy efficiency by managing the equipment of the building as well as the energy consuming activities taking place whilst the building is in operation. To succeed in developing energy efficient and sustainable buildings, buildings need to continuously evolve with technological advancements, and regulatory and legal requirements will have to be adapted to suite the dynamics of the built environment.

Keywords: Energy efficiency, commercial buildings, critical review, building in operation, understanding energy use

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1. INTRODUCTION

Within the past 20 years, the worlds' energy consumption has increased by 7 598 Mtoe with natural gas and coal having the greatest increase in consumption as shown in Figure 1 [1]. Possible primary reasons for this are increases in population and industrial development. An increase in population influences building development and energy consumption in buildings.

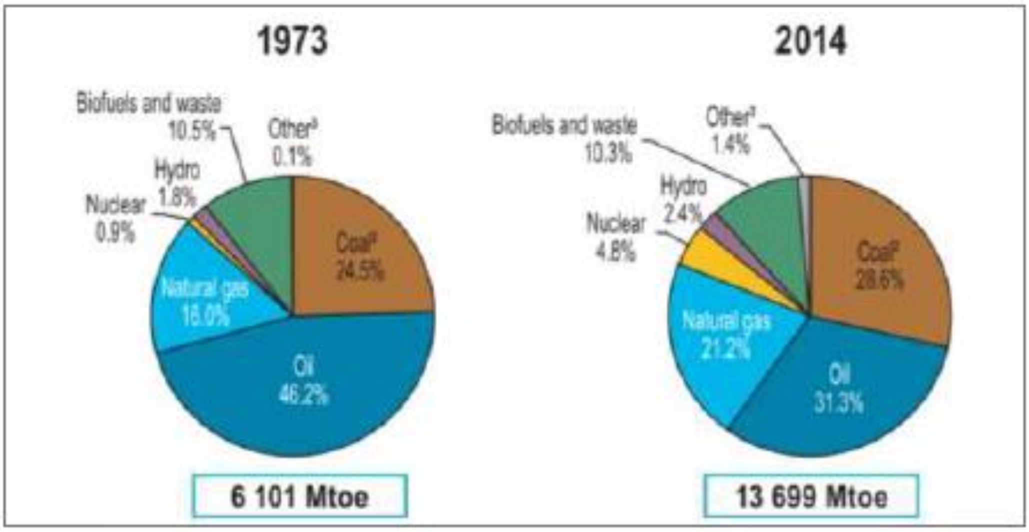


Figure 1 Total primary energy supply by fuel [1]

In the year 2017, the Environmental Information Administration (EIA) [2] published on their website that 70 % of the total energy consumption in South Africa is coal, with oil consumption being 22 % of the total energy consumption (Figure 2). Evidently, South Africa is highly dependent on coal for electricity generation, thus making South Africa one of the worlds' highest emitters of carbon dioxide [2].

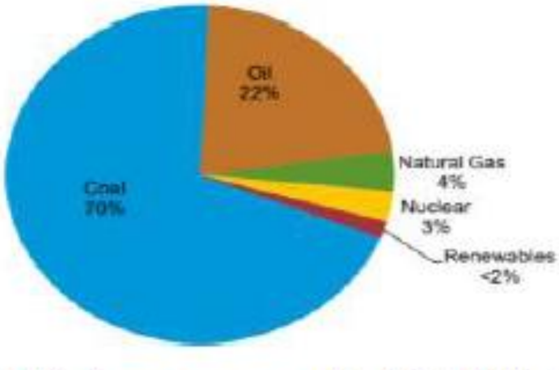
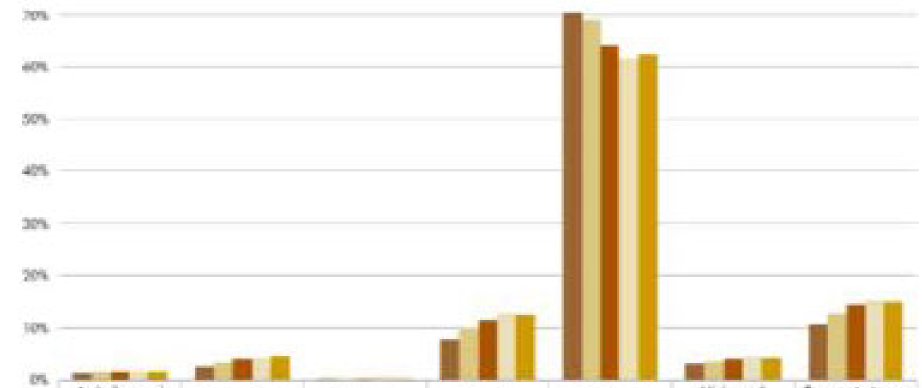


Figure 2 Total primary energy consumption in South Africa, 2016 [2]

According to Statistics South Africa [3], in 2006 the commercial sector consumed 4.6 % of the total energy produced in South Africa (Figure 3). This high energy consumption may be due to a rapidly growing population as well as development of industry and the advancement of technology, therefore increasing the demand for electrical energy.



	Agriculture and fishing	Commercial sector	Construction	Domestic	Manufacturing	Mining and quarrying	Transport, storage and communication
2002	1.2%	2.4%	0.3%	7.7%	74.7%	3.1%	10.6%
2003	1.4%	3.3%	0.3%	9.8%	69.1%	3.5%	12.6%
2004	1.6%	4.0%	0.3%	11.4%	64.2%	3.9%	14.4%
2005	1.5%	4.2%	0.4%	12.7%	61.7%	4.4%	15.3%
2006	1.4%	4.6%	0.3%	12.3%	62.2%	4.1%	14.9%

Figure 3 Final sectoral consumption of energy in terajoules, 2002–2006 [3]

In the commercial sector, buildings are the primary energy consumers. Energy is utilised from the planning stages and throughout a building's lifecycle. This paper analyses energy consuming systems and practices that affect energy efficiency in the operation and functioning of commercial buildings.

2. ENERGY EFFICIENCY

Energy efficiency is a term that is used in all energy consuming applications in all sectors and varies depending on the context in which it is applied. In some cases, energy efficiency refers to the utilisation of energy in the most lucrative way where energy waste is minimised, and overall consumption of primary energy resources is reduced. This latter case refers to the amount of energy being used and focuses on reducing the amount of energy used although the yield that the energy produces remains the same.

Technically, energy efficiency is a ratio of output to energy input and is used in industry by engineers and technicians. In engineering applications the energy efficiency of a motor, turbine or compressor is analysed by taking the mechanical work (which is the output) over the electrical work (which is the input), thus giving us the efficiency of the component. If the efficiency is low, there are losses somewhere and if the efficiency is high the losses are minimised. Losses, in the form of vibrations, heat and friction, reduce the efficiency of the component; thus, causing the component to use more energy than required.

According to the World Energy Council [4], energy efficiency refers to "a reduction in the energy used for a given energy service (heating, lighting, etc.) or level of activity". This definition, like the first definition, provides the idea that there is less energy used for a certain quantity of service or activity provided.

In the context of sustainability, energy efficiency can be viewed as a major energy resource; this perspective looks at energy efficiency as being the negative use of energy. According to Sebitosi [5] energy efficiency can be regarded as the best energy resource.

The general definition of energy efficiency refers to obtaining a greater output for a given amount of energy consumed or a reduction in energy used for a given output. Regardless of the variety of definitions for energy efficiency, the ideology behind energy efficiency remains consistent.

There are misconceptions that energy efficiency and energy conservation are interchangeable, but this is not the case. Energy efficiency refers to using the same amount of energy to yield a greater output, whereas energy conservation is the reduction in the amount of energy consumed with a reduction in the output as well. These two are completely different concepts, although they may have similarities in their benefits.

The implementation of energy efficiency does not only refer to technical applications; energy efficiency may be achieved through better organisational structure and management and improved economic efficiency as well [6]. Energy efficiency has been identified as a strategy to address issues such as energy security, social and economic impacts of high energy prices, and climate change concerns. Research has also identified energy efficiency as cost effective, and as a stimulus for corporate competitiveness.

3. ENERGY EFFICIENCY CHALLENGE IN COMMERCIAL BUILDINGS

In developed countries, buildings account for approximately 40 % of total energy consumption and contribute to about 30 % of carbon emissions [7]. There is a plethora of factors that affect energy efficiency in buildings, starting from the design stage until the operation and maintenance of the building and the demolition of the building. Focusing on factors that affect energy consumption of the building during operation and maintenance, taking into consideration that the building is occupied, six primary factors have been identified that impede energy efficiency during operation and maintenance of a building, which range from technical to operational and governmental (see Figure 4 and the sections below). The rate of energy consumption of energy consuming systems is affected by the occupancy, building design, building management system, energy management, lack of government interventions and regulations, and the weather.

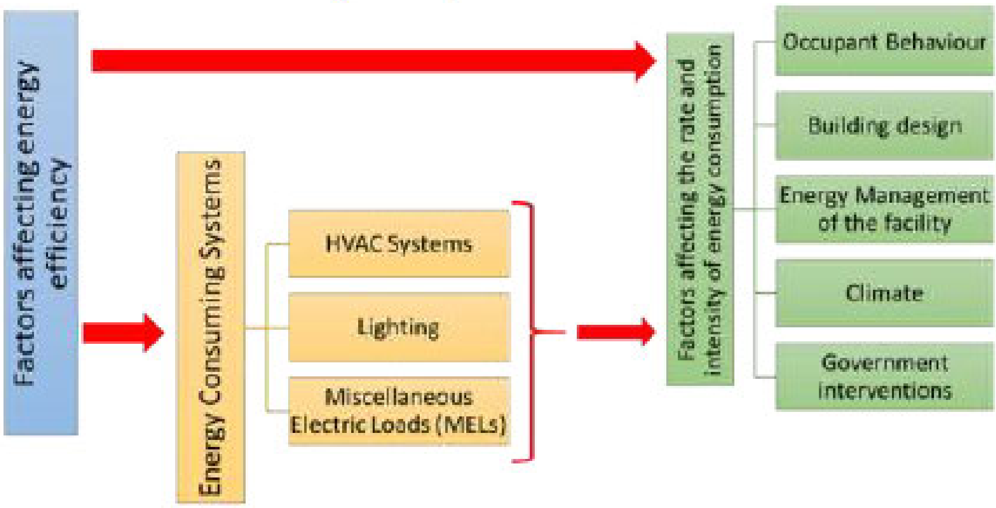


Figure 4 Factors affecting energy efficiency

3.1. Energy Consuming Systems

Commercial buildings contain a variety of electrical energy consuming equipment to enhance the indoor environmental for the comfort of human occupancy and for the efficient and effective operation of the building. Perez-Lombard et al. [8] state that the increase of energy consumption in buildings is as a result of the increase in population, economic development, the growth of the building sector and the spread of building services. In office buildings, lighting and equipment are the highest energy consumers. The functioning of the building itself plays an important role in the end use energy consumption. Using energy modelling, Abdul Hamid et al. [9] conducted an analysis of energy consumption of a commercial building and found that in the baseline energy assessment the cooling of the building accounted for 42.33 % of the total annual energy use followed by other electrical equipment and then lighting, as shown in Figure 5.

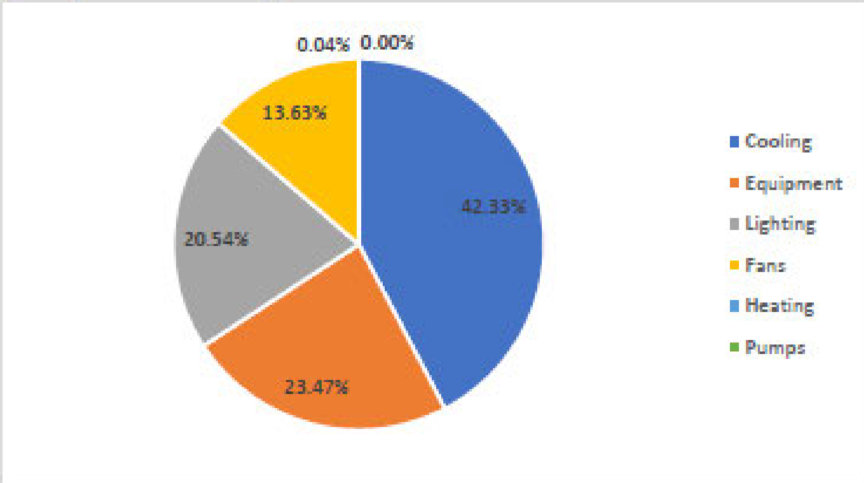


Figure 5 Baseline energy breakdown [9]

3.1.1. Heating, Ventilation and Air Conditioning Systems

Heating, ventilation and air conditioning (HVAC) systems in high rise buildings provide indoor thermal comfort and fresh air supply, which is often a necessity as per health and safety regulations. HVAC systems, an unavoidable asset, consume approximately half of the total energy usage in developed countries [8]. According to Perez-Lombard et al. [8], in developed countries energy consumption of buildings comprise 20 % to 40 % of the total energy used. From Abdul Hamid et al.'s [9] energy modelling analysis, HVAC systems consume the most amount of total energy in a building as revealed in Figure 5.

HVAC systems consume the most amount of energy since the system is made up of high energy consuming equipment, such as pumps, air handling units, fans and chillers. A well-designed HVAC system will be able to efficiently control temperature, humidity, air flow, thermal radiation, any odours, dust, noise and vibrations [9].

3.1.2. Lighting

Lighting is an essential component in buildings to ensure that building occupants are working in appropriate indoor environmental quality. Many internal offices in commercial buildings do not get natural light and other offices get shaded light, thus making artificial lighting a necessity. According to the results from Abdul Hamid et al.'s [9] research illustrated in Figure 5, lighting accounts for 23.47 % of the total energy consumption in a typical commercial building with no retrofits.

Lighting accounts for a significant portion of the total electrical consumption of all building types, particularly in commercial buildings [9]. According to studies conducted by the US Department of Energy [11], lighting load accounts for approximately 14 % of the total energy consumption in buildings on average. There are other studies demonstrating that lighting load can be significantly higher in commercial buildings, which may be as a result of weather patterns in that area. According to a European study, about 30 % to 40 % of total electricity consumption is allocated to interior lighting for medium to large commercial buildings [11]. Lighting in office type buildings can account for up to 25 % to 35 % of the total energy demand [12]. Within the tertiary sector in EU-27, approximately 21 % of electricity consumption is attributed to the lighting load, representing the largest fraction of electricity consumption [13].

Reduction in lighting energy consumption is a key item in South Africa's energy saving goals and would have a substantial impact in reducing the electrical load which would then reduce our carbon footprint [14, 15]. According to research, various types of lighting control schemes can significantly contribute to savings [16].

3.1.3. Miscellaneous Electric Load (MEL)

Miscellaneous electric load (MEL) refers to electricity consuming loads that are not related to conventional end uses [17, 18]. In other words, MEL refers to all the non-main electrical loads of a commercial building which excludes loads associated with the systems used for heating, cooling, ventilation, hot water generation and lighting [18].

MELs account for a large portion of energy consumption in commercial buildings [18]. The number and types of loads associated with MELs have increased [18]. Approximately 20 % of the primary energy used in commercial buildings is allocated to MELs, and over the next 20 years this figure is to increase by 40 % thus making MELs one of the most rapidly growing load categories [17, 19, 20]. This rapid growth is as a result of an increase in electronic equipment and building automation such as building management system and the use of cameras to ensure the efficient operation of buildings. Similarly, computers are essential pieces of equipment in any commercial building, thus giving rise to bigger server rooms [17].

Regulations often focus on the energy efficiency of HVAC systems and lighting, frequently overlooking plug loads, information technology (IT) and vertical transportation systems. Most companies do not keep a record of the energy consumed by IT and rarely are the IT electrical loads in the IT departments own budget, which means that IT managers do not know how much energy their department consumes. The findings in the research conducted by Kwong et al. [21] indicate that the office equipment in the commercial building in Malaysia which was studied consumed about 14 % of the total energy end use.

MELs represent an important, but not well researched category of energy consumption source. Mitigating the energy consumption of MELs requires more transparency and a consistent way to find out where the consumption is really coming from, measuring the details to establish its energy footprint [17]. Kwong et al.'s [21] findings demonstrate that approximately 19 % of the electric load consumption can be reduced with a change in behaviour and power management.

3.2. Building Location and Design

The location and design of a building plays an important role in energy consumption, primarily in relation to thermal comfort and lighting. For example, trees and mountainous areas provide shade for buildings in warmer climates reducing the cooling load of the building. In the southern hemisphere, north facing windows on a building allow more sunlight and heat energy into the building. In cold environments, a tight building design can reduce the heating loss by 25 % to 30 % [22]. The use of natural light during the day thus limiting artificial lighting to night time, and allowing for natural ventilation, are only two of the many solutions for better building design that encourage limited electricity consumption [23]. Energy consumption of a building can be reduced by selecting a suitable location and designing the building according to the terrain of the location to allow more natural light into the building and to allow natural ventilation to ventilate the building.

3.3. Occupant Behaviour

Occupant behaviour and interaction with the building environment plays a major role in building energy use and represents one of the most uncertain variables affecting energy efficiency [24]. Energy consumption associated with occupant dynamics refers mainly to switching on/off the lights, switching on/off the air conditioning system or adjusting the temperature, opening/closing the blinds and simple movement between spaces [24]. In addition, occupant behavioural practices such as types of clothing worn, consumption of hot/cold drinks, and changes in individual metabolic rates, all influence human comfort and in turn affect occupants' behaviour in relation to energy consumption [24].

Energy consumption within the built environment is connected to the energy use of the building's occupants, including the presence of occupants in the building and the dynamics of the occupants [26, 27]. Masaso and Grobler [28] highlight the implications of electricity consumption caused by negligent occupant behaviour during off-peak hours in a commercial building. The results of their study indicated that 56 % of the energy consumed by the building was used outside working hours associated with poor occupant behaviour and no zoning control, where electrical equipment and lights were left on after working hours. Occupant activity often leads to unnecessary and excessive energy consumption [29]. According to Virote and Neves-Silva [30], energy efficient technology in a building can be debilitated by occupant behaviour within the building.

Occupant activity is one of the most unpredictable energy consumption patterns, thus making it difficult for researchers to quantify and evaluate. In five different studies, Martinaitis et al. [31] demonstrated that it is difficult to predict the performance of buildings, regardless of the accuracy of the energy simulations, because occupant behaviour is a significant contributor to the discrepancy between building predictions and the actual building energy performance. Building occupant interaction and dynamics within a building affects the energy consumption of the building.

3.4. Energy Management of the Building

Energy management refers to the management of energy which is used to provide goods or services through various methods such as monitoring and improving efficiency of systems and human activity. According to Capehart et al. [32], energy management refers to "the judicious and effective use of energy to maximise profits (minimise costs) and enhance competitive positions". Hassan et al. [33] refer to energy management as "the strategy of adjusting and optimising energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems". Both definitions indicate that the aim of energy management is to produce goods and provide services with minimal consequences to the environment and with the least cost involved. Interestingly, Lackner and Holanek [34] simply refer to energy management as "structural attention for energy" and they go on to indicate that the objectives of energy management are:

a) To continually reduce energy consumption, and
b) To maintain the achieved improvements.

As shown in Figure 6, Deming's circle demonstrates how an organisation can produce continual improvement in energy consumption and management patterns through the cycle of making energy management policies, planning of action to be taken, implementation of the action plan, evaluation of the results of the action taken and thereafter improving the policy documents [34].

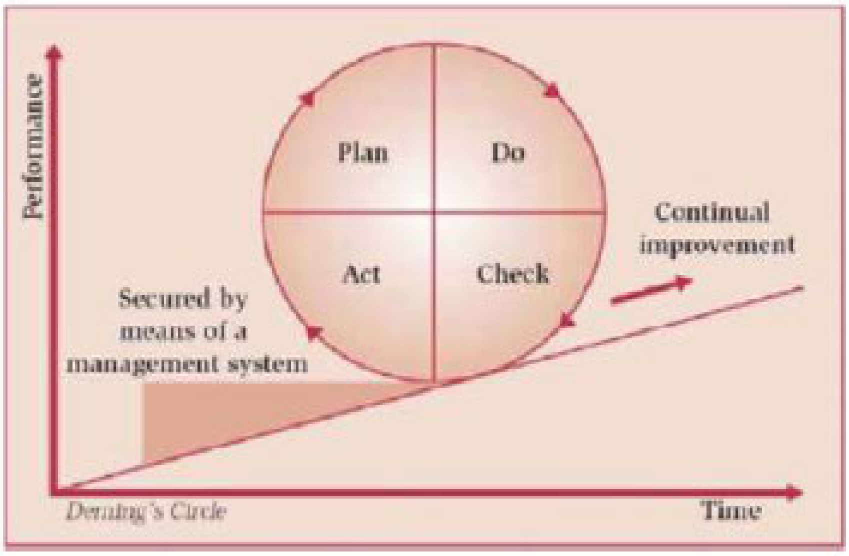


Figure 6 Deming's Circle [34]

Essentially, the facility manager (and for larger buildings a designated energy manager) of a commercial building will be responsible for ensuring that the building operates optimally with the least amount of energy consumed as well as continually improving the energy efficiency of systems and enhancing occupant knowledge on energy usage. Human actions (both, occupants and facility managers) are major elements of energy usage and can, through their behaviour, inhibit the optimum operation of the building, resulting in excessive energy consumption which defeats the purpose of energy efficient technology investment [35-37].

The size of the building is of no concern, the success of energy management practices is dependent on the commitment of the organisation and the determination of the energy manager to implement energy conservation and energy efficiency.

3.4.1. Building Energy Management System

Building energy management systems (BEMS) are integrated, computerised systems used to monitor and control a building's energy needs and consumption, allowing for the building to operate efficiently and smoothly whilst maintaining optimum consumption of energy.

Shyr et al. [38] developed an energy management system (EMS) using the internet of things (IOT) platform to control lighting in a university. They found that their system allowed people to understand their energy consumption, thus making better energy choices. The system also improved the energy efficiency of the lighting based on the rules of the user.

According to Yang and Wang [39], building control is required to create a comfortable building environment and enhance the energy efficiency of the building. They conducted a case study of a multi-zone building controlled with particle swarm optimisation (PSO) for intelligent building control and optimisation and presented the corresponding simulation results in their research paper. Results showed that a multi-agent PSO system has the ability to control complex building systems. The PSO maintained a high level of comfort within the building space, even during a period of shortage of energy supply.

Ock et al. [40] conducted a simulation of a conceptual framework for real time weather responsive control systems combined with BEMS. The control system was generated using data from weather patterns, resulting in energy consumption being adjusted according to the weather. The proposed advanced BEMS was restricted to lighting control and heating and cooling energy consumption. A daylight intensity data base was preconstructed to control energy used by lighting, with the data obtained being used to detect the level of natural light in the space and determine whether artificial lighting was required or not. One of the major barriers found in this study was the uncertainty of human behaviour which inhibits the optimal simulation of a conceptual framework such as the one implemented in the study.

Considering the global energy crisis, BEMS are becoming a saught after solution to curb energy consumption in buildings. Research shows that the use of BEMS in buildings have the potential to reduce the building energy consumption, however, BEMS are still in the early stage of develepment and cannot accommodate all factors affecting the energy consumption of a building. The functionality of BEMS needs to be improved as well as the operation and maintenance of the system. Presently, parts are not readily available for such a system which makes it expensive. Human behaviour is unpredicatable and is often a challenge to incorporate into a BEMS.

3.5. Government Interventions

Government interventions have the potential to increase energy efficiency in commercial buildings. These interventions refer to commercial building policies, regulations, incentives, programmes, conferences, and anything else that will create an awareness or regulate the amount of energy being used by commercial buildings. Government plays an important role by stipulating a minimum set of standards which all people involved with the building including building occupants must abide by. Government incentives for energy efficiency will encourage investors to explore and improve the field of energy efficiency in buildings. Becoming involved with international energy efficiency programmes and implementing energy efficiency strategies will enhance energy efficiency practices among South African developers and within industries. Government can create an awareness through seminars, energy efficiency debates and conferences in the South African context to promote and implement energy efficiency practices in homes and businesses. Yu et al. [41] conducted research on the impact of building energy codes on energy use and CO_2 emmissions and found that building energy codes have the potential to reduce the Chinese building energy consumption by 13 % to 22 % depending on the building type. An investigation of the relationship between energy efficiency and electricity intensity of nine energy efficiency programmes in the US was conducted by Ofori-Boadu et al. [42]. Their investigation found that there was a general decline in the electricity intensity and the five energy efficiency programmes contributed to approximately 9 % reduction in commercial building electricity consumption. Geller et al. [43] demonstrated that well designed policies can have a substantial energy saving impact.

3.6. Climate

Climate change, a current phenomenon characterised by increasing variability, is affecting the environment and agricultural practices, industrial and manufacturing processes and parameters, as well as socioeconomic dynamics, and so is affecting energy consumption. The Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) concluded that climate change is unequivocal and human activities are the most probable cause, and that changes in climate have been observed in all geographical regions [44].

Li et al. [45] reviewed the impact of climate change on energy use in buildings and found that there are regions with extreme cold in winter and moderate heat in summer and vice versa, and there are regions that have both extreme cold and extreme heat. Extreme cold and heat has a significant impact on building energy consumption, with hot summer weather and warm winters having the greatest impact on energy consumption. The authors found that the amount of energy used for heating in extreme winter conditions are comparable to the amount of energy used for cooling in extreme summer heat conditions. The authors conclude by noting that climate change has the potential to have a significant impact on energy and environmental policies. Depending on the rate of climate change in the future, the existing energy and environmental policies may not hold true due to the rapidly changing weather patterns.

4. CONCLUSION

Energy consumption in South Africa is steadily increasing with commercial buildings contributing to a large percentage of end user energy consumption. Electricity in South Africa is primarily generated by coal, meaning that South Africa is one of the highest carbon dioxide emitters in the world. To curb carbon dioxide emissions and maintain a high level of service and production output, energy efficient practices and equipment are critical in commercial buildings, as energy efficiency is one of the easiest ways to improve the level of carbon emissions.

Commercial buildings consist of a variety of electromechanical equipment, many of which are highly electronic so require cooling and therefore account for high electricity consumption during operation to support the function of the building. As stated previously HVAC systems consume the most electricity in buildings, followed by lighting of the building and MELs. These electrical loads can be reduced using energy efficient technology, energy efficient design of systems and energy conservation practices.

Engineers and designers must consider the building location, the weather patterns of the environment, energy regulations of the country as well as the general energy practices of the community when designing a building, as these variables affect the rate and intensity of energy consumption of the equipment. Energy management of the equipment of the building together with the operation of the building, which includes human activity, can optimise energy consumption.

Energy consuming systems, building location and design, energy management of the building, government regulations and climate all require detailed research to identify how energy consumption can be managed to reduce energy consumption.

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CHAPTER 3 PART A: A REVIEW OF THE ENERGY FLOW THROUGH A CENTRIFUGAL WATER-COOLED CHILLER AIR CONDITIONING SYSTEM

This chapter reviews works of other researchers to establish the flow of energy through a centrifugal water-cooled chiller. Energy losses in the system were also identified. This chapter has been published in the, International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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A REVIEW OF THE ENERGY FLOW THROUGH A CENTRIFUGAL WATER-COOLED CHILLER AIR CONDITIONING SYSTEM

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ABSTRACT

Heating, ventilation, and air conditioning systems consume a significant amount of electrical energy to transfer heat energy from the space into the atmosphere. This paper aims to analyze the flow of heat energy to provide space cooling and the losses involved. Energy losses from complex energy consuming equipment will be discussed to further understand how systems can become more energy efficient.

***KEYWORDS:** Centrifugal Water-Cooled Chiller, Energy Efficiency, Thermal Energy & Energy Losses*

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Original Article

1. INTRODUCTION

Heating, ventilation, and air conditioning (HVAC) systems consume a significant amount of energy and there is a growing demand for HVAC systems. To restrain the amount of energy consumed by HVAC systems, it is important to understand how energy is transferred, used and lost in the system. This paper primarily analyses the flow of energy from the space being cooled to the atmosphere and the electrical energy used by complex heat transfer equipment used in the process. The flow of heat energy and electrical energy is discussed to highlight and surface opportunities to reduce energy consumption and improve the energy efficiency of the system. This article will use centrifugal water-cooled chiller system as the basis for discussion.

2. ENERGY CONSUMING CHILLER EQUIPMENT AND ENERGY LOSSES

Water cooled chillers, known for their high efficiency, use the vapour compression cycle to chill water which is used to absorb heat from the air-conditioned space [11], [12],[13]. The chiller uses a working fluid, the refrigerant, to cool the chilled water returning from the space, and the heat absorbed by the refrigerant is then compressed to increase the pressure and the corresponding saturation temperature. The refrigerant then enters the condenser, the cool condenser water absorbs the energy from the refrigerant which returns to the evaporator. The heat absorbed from the refrigerant by the condenser water is then expelled into the atmosphere through a cooling tower. Figure 1shows the main energy consuming components of a chiller air conditioning system [13].

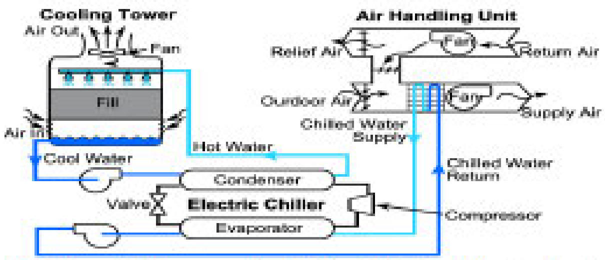

Figure 1: Schematic Diagram of a Chiller Air Conditioning System [14].

There are five heat energy loops within the air conditioning process involved in transferring the heat absorbed from the building and expelling it into the atmosphere. Understanding the relationship between electrical energy consumption and heat energy transfer will assist in understanding the flow of energy and the losses and how this process can be improved. In each link of the chain, heat is absorbed by the subsequent link until the energy is rejected into the environment. Figure 2 shows the heat transfer flow with the associated electrical equipment used to transfer heat from one loop to the next, thereafter each link will be discussed[8].

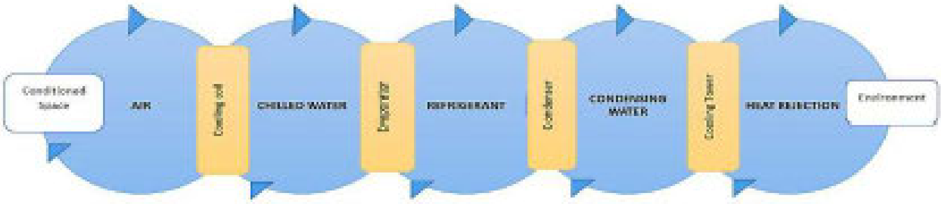

Figure 2: Thermal Chain for an HVAC System in Cooling Mode (Adapted from [8]).

2.1 Air Loop

With reference to Figure 2, heat is extracted from the air that occupies the conditioned space in the air loop.A fan is used to pass the warm air through a cooling coil where heat energy is absorbed by the chilled water, thus reducing the temperature of the air within the space. The air loop can be considered as an open process because realistically, the air loop is subject to ventilation, air exhaustion and air leaks that occur in ducts and conditioned spaces [8]. Supply air fans are used to provide fresh air to the ventilated space, while return air fans extract the warm air from the cooled space. As much as these fans are not cooling or heating the air, they are the source of transportation for the air, with an electrical energy source. Static pressure drop and volumetric flow rate determine the fans capacity and energy consumption and a considerable amount of energy can be allocated to the ventilation fans in an HVAC system [15]. [15] indicates that there are various issues that can affect a fan's performance, such as dirty fan blades, mechanical wear and poor maintenance to aging fans [15]. Over time these factors increase the fans energy consumption. There are two main factors that affect electrical energy consumption of ventilation fans: 1) fan selection by the system design engineer, and 2) poor maintenance. Design engineers tend to "over specify" to compensate for being responsible for inadequate system performance [16]. However, over specifying reduces the efficiency of the fan operation, reduces the life span and increases operation cost [16]. HVAC filters, dampers, duct lengths (including bends, tees and expansion/reduction pieces), and the cooling coil, affect the static pressure and energy consumption of the fan which needs to be considered by the design engineer. Dampers and HVAC filter selection contribute to the fans' static pressure. As energy efficiency is an important aspect in HVAC design, engineers should ensure that dampers and filters specified for the system conserve energy and provide thermal comfort and air quality. According to research conducted by [17]the difference in energy consumption and indoor air quality (IAQ) depend less on the filter and more on the system design, the building operation and the operation time of the fans [17]. However, [17] indicates that their study found a difference in the fan energy consumption when filters were added to the system, but different types of fans were affected in different ways. The permanent split capacitor (PSC) motor fans used more power than electronically commutated motor (ECM) fans under normal conditions; when filters with a pressure drop of 150 Pa were used, PSC fans used less power than ECM fans [17]. The research conducted by [18] indicates that when dampers are not functioning properly a high pressure drop is created across the dampers which adds to the fans' static pressure load, but adding a control system to the dampers can reduce the fan energy by a maximum of 30%, depending on the numbers of hours the system operates [18].

2.2 Chilled Water Loop

The chilled water loop is a closed system, and a pump is used to circulate the water to and from the conditioned space, refer to Figure 2. The chilled water absorbs the heat energy from the air in the cooling coil, thus increasing the temperature of the chilled water. As the warmer chilled water passes through tubes in the chiller evaporator, the heat energy is transferred to the refrigerant[8]. When heat is absorbed by the refrigerant from the chilled water it becomes vapour and the chilled water temperature drops. The chilled water is then recirculated to the cooling coils in the AHU, the process repeats itself. The cooling coil and the chiller evaporator are both heat transfer components of the system and the circulating pump converts electrical energy to kinetic energy in the chilled water[19].The chilled water circulating pumps are used to provide chilled water at the calculated flow rate and static head of the HVAC system. Pump designers manipulate the vane design to achieve optimum output velocity for an impeller [19]. Centrifugal pumps have reached the peak of design, however, VSDs are commonly used to improve energy efficiency and it is the responsibility of the design engineer to select the right pump to create optimal operating conditions.

2.2.1 Cooling Coil

The performance of the cooling coil plays an important role in improving thermal energy transfer between the chilled water and air to be conditioned. Ambient temperatures affect the sensible (Q_S) and latent heat gains (Q_L) of the space, rising the dry bulb and wet bulb temperatures and affecting IAQ. Figure 3shows the common change in air properties during the cooling process across the cooling coil. Outside air (at ambient temperature and humidity) enters the cooling coil then if the cooling coil is 100% effective, the air will be cooled to apparatus dew point (ADP) or dew point temperature which is located at point C on the saturation curve in Figure 2. Realistically, a limited surface is never 100% effective, therefore the final temperature of the cooled and dehumidified air will be somewhere along the line between entering coil conditions (point A in Figure 2) and ADP (point C in Figure 2).The amount of condensed vapour will be the difference in specific humidity between the specific humidity of air entering the coil and the specific humidity of air leaving the coil; this process decreases the specific humidity and increases the relative humidity[20], [21].

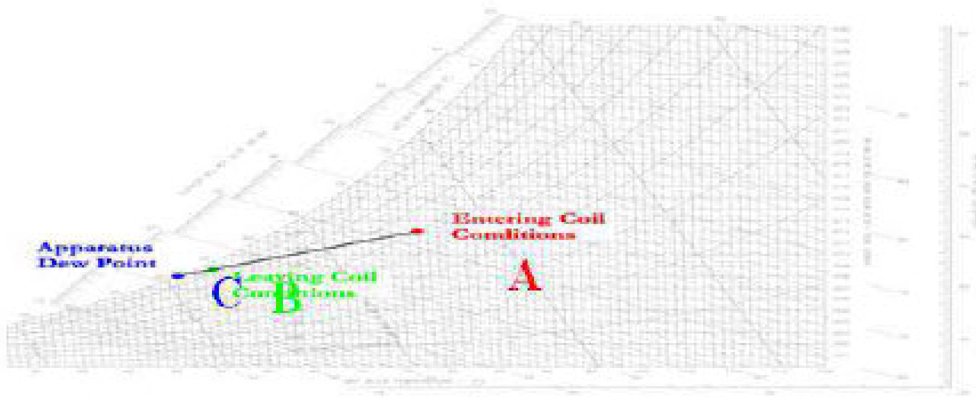

Figure 3: Psychometric Chart with the Properties of Air Entering and Leaving the Coil[20].

The contact factor (β) and the bypass factor (BPF) are both used to express the efficiency of the cooling coil, the

BPF describes the percentage of air that is not cooled to ADP whereas the β is used to describe the percentage of air that has been cooled to ADP, as described in equations (1) [20], [21], [22].

$$\beta = \frac{\omega_A - \omega_B}{\omega_A - \omega_C} = \frac{h_A - h_B}{h_A - h_C} \approx \frac{T_A - T_B}{T_A - T_C} \quad (1)$$

Where:

β = Contact factor

ω = Humidity ratio or specific humidity relative to dry air (kg/kg)

h = Enthalpy (kJ/kg)

T = Temperature (°C)

The following equation (2)calculates the bypass factor:

$$BPF = \frac{h_B - h_C}{h_A - h_C} = \frac{T_B - T_C}{T_A - T_C} = \frac{\omega_B - \omega_C}{\omega_A - \omega_C} \quad (2)$$

Where:

BPF = Bypass factor

In summer, the outdoor ambient temperatures are much higher than the conditioned space, therefore the latent and sensible heat gains will be transferred to the interior, increasing the temperature and relative humidity of the interior [23]. The total heat flow in a cooling coil can be analysed using the equation (4). The difference in enthalpy between points A (entering the cooling coil) and B (leaving the cooling coil) provides an overall analysis of the energy requirements of the total cooling process[21], [22].Equation (3) is used to calculate the total heat flow in the cooling coil.

$$\dot{q}_T = \dot{m}(h_A - h_B) \quad (3)$$

Where: $\dot{q}_T$ = Totalheat flow rate (kJ/s) and$\dot{m}$ = Mass flow rate of air in (kg/s)

At any given point on the psychometric chart, the mass flow rate can be determined by using the volumetric flow rate and the density of air.The total heat flow rate is the sum of the latent heat and the sensible heat. The sensible heat flow rate is a function of temperature change and can be calculated using the equation(4) [21], [22]:

$$\dot{q}_s = \dot{m}C_p(T_A - T_B) \quad (4)$$

Where:$\dot{q}_s$ = Sensible heat flow rate (kJ/s); C_p = 1.01 Specific heat capacity of air (kJ/kg°C)

The latent heat flow rate is a function of the specific humidity relative to dry air and can be calculated with the equation (5)[21], [22]:

$$\dot{q}_L = \dot{m}h_{we}(\omega_A - \omega_B) \quad (5)$$

Where:$\dot{q}_L$ = Latent heat flow rate (kJ/s) and h_{we} = Water evaporation enthalpy (2502 kJ/kg)

With reference to Figure 3, the following mass and energy equations can be used to analyse the heat and mass transfer across the cooling coil for cooling with dehumidification[24]. According to the conservation of mass principle, the mass at point A must be the same as the mass at point B in a controlled volume, as mathematically described by equation eqution. (6)[24].

$$\dot{m}_{airA} = \dot{m}_{airB} \quad (6)$$

A and B refer to state points A and B inFigure 3.During the cooling and dehumidification process, the moisture in the air condenses, reducing the amount of moisture to dry air. The psychometric chart provides the kg of humidity per kg of dry air at a specific condition on the chart, therefore with equation (7) the amount of condensate formed can be calculated.

$$\dot{m}_{wA} = \dot{m}_{wB} + \dot{m}_{cond} \quad \rightarrow \quad \dot{m}_{airA}\omega_A = \dot{m}_{airB}\omega_B + \dot{m}_{cond} \quad (7)$$

Where the subscript "Cond" refers to the amount of condensate formed.

The conservation of energy is applied to the amount of energy entering and leaving the cooling coil to analyse the flow of energy across the cooling coil, as mathematically described in equation (8) [24]. The total mass flow rate of air and its enthalpy is the sum of the heat flow rate at point A on entering the cooling coil, the mass flow rate of air at point B and its' enthalpy at point B, and the mass flow rate of the condensate formed and the enthalpy of the condensate.

$$\dot{m}_{airA}h_A = \dot{Q}_A + \dot{m}_{airB}h_2 + \dot{m}_{cond}h_{cond} \quad (8)$$

2.3 Refrigerant Loop

In the evaporator, the refrigerant absorbs the heat from the chilled water by means of a vapour compression cycle. The refrigeration process then undergoes a change of thermodynamic properties, transferring heat energy to the condensing water in the condenser [8]. With reference to Figure 4, the refrigerant leaves the evaporator as a low pressure and low temperature gas [25]. It then becomes a high pressure and high temperature gas before being used again, thus the refrigerant flows from the evaporator to the compressor where pressure and temperature is increased (see state point 2 in Figure 4) before entering the condenser [25]. In a water cooled chiller, the condenser uses water to absorb heat energy from the refrigerant, thus the refrigerant condenses to a liquid once again [25]. The liquid refrigerant leaves the condenser at a high pressure and temperature and flows through the expansion valve. The expansion valve separates the high-pressure side of the refrigerant from the low-pressure side, acting as a pressure reducing valve. Only a small amount of refrigerant is allowed to pass through the valve into the evaporator as a cooled liquid [25].

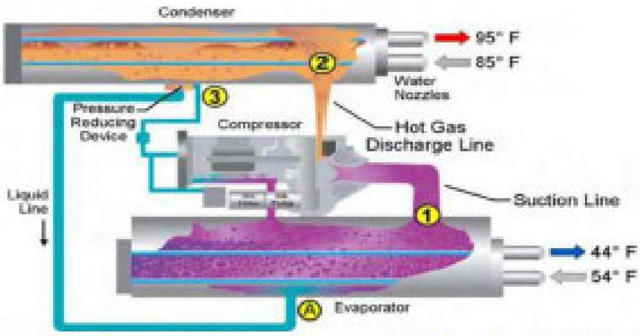

Figure 4: Refrigerant Cycle in a Water Cooled Centrifugal Chiller [12].

2.3.1 Centrifugal Compressors

The centrifugal compressor converts electrical energy to mechanical energy to increase the pressure and temperature of the refrigerant. Centrifugal compressors are of a turbine type, moving gas by converting kinetic energy to pressure energy. Refrigerant, in vapour phase, enters the compressor through a suction vane and passes through the impeller. Centrifugal compressors are more energy efficient and robust when compared to other compressors for use in water cooled chillers [26], [27]. In general, the energy consumption costs of compressors are higher than the typical investment and maintenance costs[28]. Electric motors account for a considerable proportion of energy consumption. In the European Union alone, 70 % of the total electrical demand can be allocated to motors and electric motor driven compressors account for 18 % to 25 % of the energy consumption [27]. As a result, electric motor driven compressors have potential for energy efficiency improvements [27].The energy efficiency of a centrifugal compressor design has been improved to such a high level that the potential for further improvements lie in the diffuser development [27]. There are three main types of diffuser designs:vaneless diffuser, low solidity vaned diffuser and vaned diffuser, all of which influence the compressor performance and operating range differently [27]. [27] focuses on energy improvement in centrifugal compressor component design and the energy efficiency benefits of each diffuser type and the results show that improvements in compressor energy efficiency have a significant effect on the total energy usage of the system, with energy savings of between 2.5% and 4.9% [27]. Clearly component design is an important aspect when considering energy efficiency of the entire system. In the case of refrigeration compression, a change in operating conditions or a change in the medium viscosity decreases the Reynolds number[30].A decrease in the Reynolds number increases the boundary layer thickness and the frictional losses which then leads to lower efficiency and pressure ratio [30]. According to a study by [31], the shape of the diffuser and a low Reynolds number contribute to the deterioration in the performance of centrifugal compressors [31]. To improve the performance of a centrifugal compressor the growth in the impeller hub and the diffuser boundary layer should be reduced [31]. The manufacturer's data and tests conducted on the centrifugal compressor do not always favour the real operating conditions of the compressor. In some cases, the efficiency of the system is compromised. In chilled water air conditioning systems, it is essential to select an energy efficient compressor that will also improve the energy efficiency of the system as a whole.

2.3.2 Expansion Valve

An expansion valve is a small orifice which controls the flow of liquid refrigerant pumped from the high pressure condensing side to the low pressure evaporator [32], [33]. The refrigerant exiting the orifice will be rapidly expanding, it will be at a low pressure in the form of liquid vapor[32],[33]. The expansion valve regulates the refrigerant flow keeping the pressure difference between the high and low pressure side of the refrigeration system[32],[33].The expansion valve works in conjunction with the compressor to achieve the desired results at the evaporator. There are various types of expansion valves depending on the type of refrigerant, the evaporator capacity, liquid refrigerant temperature and the pressure drop requirements. Thermostatic expansion valves are commonly used in air conditioning; however, electronic expansion valves are becoming popular as they reduce energy consumption on start-up of the HVAC system. [34] found that the energy efficiency ratio (EER) was low after each start up in all tests conducted. This is a result of the refrigerant leaving the evaporator in liquid phase, thus entering the compressor in a liquid phase and endangering the operation because the thermal expansion valve cannot differentiate between the different cooling demands[34]. When the compressor stops,liquid refrigerant migrates through all parts of the evaporator and there is an imperfect control of the expansion valve which causes swings in the system when in operation [34]. The compressor will have to replace a larger volume of refrigerant, thus leading to energy wastage. The use of thermostatic expansion valves may lead to energy increases as great as 23% during start up. [34] also found that electronic expansion valves always had a higher EER as the electronic expansion valve has the ability to control refrigerant flow in the evaporator and thus limit liquid refrigerant in the compressor [34].With the use of a thermal expansion valve, the greatest energy loss occurs during start up because thermal valves are either opened or closed and cannot control the required amount of refrigerant for the cooling load. However, electronic expansion valves easily control the flow of refrigerant entering the evaporator and entering the compressor as vapour. To improve energy efficiency of the HVAC system, the designer should consider the use of electronic expansion valves.

2.4 Condensing Loop

Referring to Figure 2, the heat absorbed from the refrigerant in the condenser and is then transferred to the environment through the cooling towers [8].The heat from the refrigerant is absorbed by the cooling water and is pumped to the cooling towers where the heat from the water is dissipated into the atmosphere, thus cooling the water. Thereafter the cool water from the cooling tower is pumped to the condenser, as shown in Figure 56[35]. The cooling fan in the cooling tower induces cooling of the condenser water through convection. The recirculating pumps and the cooling tower fans contribute to the total power consumption of the HVAC system. Improving the efficiency of the cooling tower fan and the recirculating pumps will improve the overall efficiency of the HVAC system.

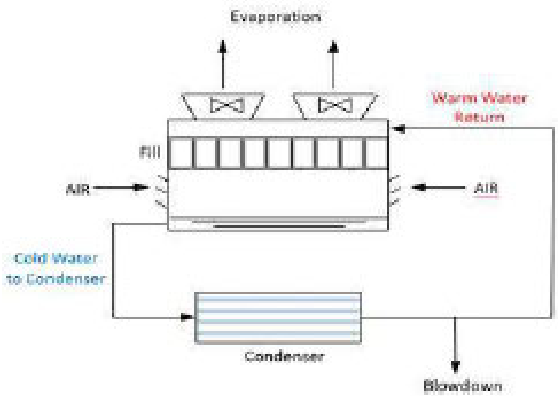

Figure 5: Schematic of a Condenser Water Loop[35].

Regular maintenance on a condenser can easily improve overall efficiency of the condenser [36]. Annual brushing of the condenser water pipes will remove any scale build up and maintain the efficiency of the heat transfer surface. Water treatment of the condenser water is critical to prevent fouling as untreated water damages the tubes and piping. Cooling tower blowdown is the most effective way to remove solids and contaminants [36]. Reducing the water temperature before it enters the condenser can improve the chiller's efficiency[36].A condenser is rated according to the amount of heat it rejects into the atmosphere. The total heat rejected from the refrigerant in the condenser refers to the de-superheating, the condensation and the subcooling of the refrigerant and is mathematically expressed using equation (10)[26]:

$$Q_{rejected} = \dot{m}_{refrigerant}\,(h_{leaving} - h_{entering}) \qquad (10)$$

The temperature of the condenser water leaving and entering the shell-tube condenser has an impact on the condensed refrigerant temperature, the compressor input power, the condenser water pump power and the cooling tower fan input [26].

2.5 Heat Rejection to the Atmosphere Loop

The main mechanical equipment that uses energy or distributes or loses energy to dispel the heat energy from the cooled space to the atmosphere, are the cooling towers, cooling tower fans and the condenser water recirculating pumps.

2.5.1. Cooling Towers

Cooling towers are used to dissipate the heat energy absorbed through the air conditioning cycle into the atmosphere. Recirculated condenser water from the chiller condenser is evaporatively cooled by contact with atmospheric air [24]. Mechanical draft cooling towers are commonly used for large commercial buildings [24]. A fan is used to extract atmospheric air, passing it through the condenser water as it is sprayed downwards across the fill, thus absorbing the heat energy and reducing the temperature of the condenser water, see Figure 6 [24], [34]. About 1% of the water evaporates as it flows concurrently with and is absorbed by the upward flow of air. Drift eliminators trap the larger droplets, while those droplets that leave the tower are referred to as drift [24]. Among the different types of cooling towers, the counte rflow induced draft cooling tower will be discussed here. The counter flow induced draft cooling tower allows for the driest air to contact the coldest water, thus increasing the performance of the cooling tower [24]. Another advantage of the counter flow induced draft cooling tower is that the fill creates an even distribution of air across the water spray and is discharged at a higher velocity from the fan outlet [24].

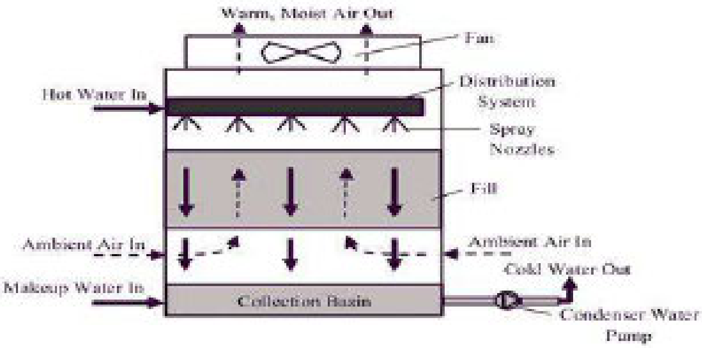

Figure 6: Counterflow Induced Draft Cooling Tower [34].

2.5.1.1. Thermal Analysis of Cooling Towers

The cooling tower coefficient refers to the heat transfer unit or the size of the fill which primarily affects the efficacy of the cooling tower [24]. A higher cooling tower coefficient refers to a larger tower size or capacity for a given flow rate [24]. According to [24], if the thermal resistance of the saturated air film is neglected, the energy balance between the condenser water and the air can be calculated using quation (10)), wherein the amount of heat leaving the water droplet is equal to the amount of heat absorbed by the air

$$\dot{m}_{condenser} C_p dT_{condenser} = \dot{m}_{air} dh_{air} \quad (10)$$

Where:

$\dot{m}_{condenser}, \dot{m}_{air}$= mass flow rate of water and air (kg/s)

C_p= Specific heat of water

$T_{condenser}$ = Temperature of condenser water (°C)

h_{air} = Enthalpy of air (kJ/kg)

If the saturated film of air is assumed to have no thermal resistance, then the combined heat and mass transfer from the saturated air film to the bulk air stream can be calculated using equation (11)[26]:

$$\dot{m}_{air} dh_{air} = K_m (h_s - h_{air}) dA \quad (11)$$

Where:

K_m = Mass transfer coefficient (kg/sm^2)

h_s = Enthalpy of saturated air film (kJ/kg)

A = Surface area at air-water interface (m^2)

Sensible and latent heat is transferred from the water droplets to the surrounding air which can be modelled using equation (12). The cooling tower coefficient is calculated by combining equation (10) and equation (11) to get the following equation (12)[26]:

$$\frac{KaV}{\dot{m}_{condenser}} = \int_{T_{condenser\,1}}^{T_{condenser\,2}} \frac{dT_{condenser}}{h_s - h_a} \quad (12)$$

Figure 7 shows the characteristics of heat and mass transfer between the condenser water and air in a counterflow cooling tower. The condenser water enters the cooling tower at temperature *we (29.4°C)* and exits the cooling tower at *wl (23.9°C)*, which is the range of the cooling tower. The temperatures of the saturated air film correspond with the condenser water temperatures and can be represented by line labelled water *(we-wl)* [26].

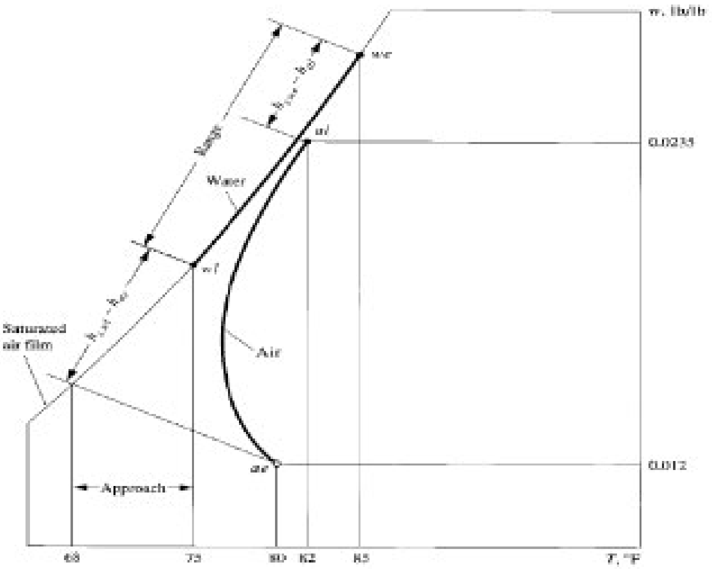

Figure 7: Graphical Representation of a Cooling Tower Characteristics [26].

The temperature of air entering the cooling tower is higher than the temperature of water leaving the cooling tower, therefore the air is evaporatively cooled as the air temperature approaches the condenser water temperature [26]. Thereafter, the air absorbs the heat energy and some of the water mass causing the air to become humidified and heated, as shown by the curve *ae-al* in Figure 7. The difference between the saturated air film and the air is the driving potential of heat and mass transfer between the condenser water and the saturated air film [26].

2.5.1.2. Cooling Tower Performance Parameters

The role of a cooling tower is to effectively remove heat from the condenser water and minimise the electrical consumption of the system [24]. The performance of the cooling tower is directly affected by the tower range, water-air ratio, approach, fill configuration and water distribution system [24]. A cooling tower is rated on the following conditions; Unit of heat rejection at condenser, water circulation rate, water temperature entering the condenser, water temperature leaving the condenser, outdoor wet bulb temperature, range and approach [24].

2.5.1.2.1 Range and Water Circulating Rate

The primary parameters that should be specified during design are the range and the corresponding water circulation rate(kg/s) [24]. The relationship between the range and rate of circulation can be expressed using equation (13) [24]:

$$T_{condenser\ E} - T_{condenser\ L} = \frac{Q_{rej}}{C_p \dot{m}_{condenser}} \tag{13}$$

Where:

$T_{condenser\ E}$= Condenser water entering the cooling tower

$T_{condenser\ L}$ = Condenser water leaving the cooling tower

Q_{rej}= Amount of heat rejected from the condenser (W)

$\dot{m}_{condenser}$= Rate of the condenser water circulation (kg/s)

A smaller range and greater $\dot{m}_{condenser}$ imply that the system will require a lower condensing pressure and temperature, greater pumping energy, greater tower sizebecause of the smaller range and higher airflow rate for a fixed water to air ratio [24]. The designer of the system will need to calculate the energy efficiency and cost implications in relation to the lifespan of the system.

2.5.2 Cooling Tower Fans and Recirculating Pumps

The cooling tower fans play an important role in optimizing the chilled water system by regulating the condenser water inlet temperature. To prevent surging, centrifugal chillers require a minimum temperature for the water entering the condenser [37]. Cooling tower fan cycling may be achieved by a simple ON-OFF control, variable speed drives (VFD) and using 2 or 3 speed motors[37]. The condenser water recirculating pumps are essential to provide the condenser water with a flow rate that creates a balance for optimum heat transfer between the refrigerant and the condenser water. The cooling tower may require a second pump to supply make up water if needed. It is essential that both the cooling tower fans, and the recirculating pumps are driven by VSDs. VSDs allow the fan or pumps to run at a wide range of speeds to match the capacity of the load. When the system senses a high load, the VSDs will increase their speed in relation to the load and continue operating the system within a range set by the designers. Research conducted by [38] showed by using VSDs the energy consumption for the chillers and cooling towers was reduced by 5.8% for the same amount of cooling.

3. DISCUSSIONS

This article provides a review of a holistic approach to identifying electrical and thermal losses within the air conditioning process and how energy usage can be optimised from the component level to an operational level by using the thermal energy loop as a map, thus identifying electrical energy consuming components and thermal losses. The primary cause for energy loss in the air loop are the ventilation fans. The two primary reasons that affect electrical energy consumption of the ventilation fans is fan selection by the design engineer and poor maintenance. Regarding design of an air conditioning system, design engineers tend to over specify, thus incurring initial cost and operational costs. The design engineer must be careful not to over design the system and specify components with a greater capacity than calculated for. Ventilation fans must be sized for their application and maintained throughout their service life.

In the chilled water loop, the cooling coil and the chiller evaporator are responsible for heat transfer while the chilled water circulating pump converts electrical energy to kinetic energy. The design of the cooling coil can be improved to increase the heat transfer surface area. Another important aspect is material selection for the cooling coils.This area requires further research to ensure that the material used provides the least resistance for heat transfer between the chilled water and air flow.

The compressor and the expansion valve are the two most important components in the refrigerant loop. The systems design engineer must ensure that the compressor selected is suited for its application and that it contributes to the energy efficiency of the air conditioning system. The expansion valve has minimal impact on the energy consumption of the HVAC system – the greatest loss occurs during start up. Electronic expansion valves are more energy efficient as they easily control the flow of refrigerant entering the compressor as a vapour.

In the condensing loop, recirculating pumps are used to provide kinetic energy to the condenser water. Maintenance of the condenser is critical to ensure that the heat transfer surface provides maximum heat transfer from the refrigerant to the condenser water.

Cooling tower fans and condenser water pumps are the major energy consumers in the heat rejection to the atmosphere loop. The design and selection of the cooling tower is important to ensure that the condenser inlet water temperature is regulated according to the systems design parameters to prevent surging of the compressor. The condenser water pumps must create a balance for optimum heat transfer between the condenser water and the refrigerant. To improve energy efficiency both the fans and the pumps should use VSDs.

4. CONCLUSIONS

The five heat energy loops within the air conditioning process involved in transferring the heat absorbed from the building and expelling it into the atmosphere has been analysed and discussed. A holistic approach to understanding and identifying energy losses has been used. Heat and electrical energy lost to the environment has been identified, this can further be used when designing air conditioning systems and selecting complex energy transfer components.

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CHAPTER 3 PART B: AIR CONDITIONING SYSTEM DESIGN AND STRATEGIES FOR IMPROVING ENERGY EFFICIENCY – A REVIEW

This chapter reviews methods and techniques used in air conditioning system design to improve energy efficiency of air conditioning systems. This article has been published in International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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AIR CONDITIONING SYSTEM DESIGN AND STRATEGIES FOR IMPROVING ENERGY EFFICIENCY – A REVIEW

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ABSTRACT

Centrifugal water-cooled chiller systems consume approximately 50% of a building's total energy and are an essential component providing indoor environmental quality (IEQ) and enhancing occupant productivity in large scale buildings. Therefore, research into reducing energy consumption required for air conditioning while maintaining the desired level of IEQ has been stimulated. The relationship between thermal energy and electrical energy in this system can be used to reduce the energy consumption of the system which will involve the overall design and operating parameters of rotating equipment, static equipment for heat transfer as well as how this equipment operate in relation to each other. This review provides a holistic approach to chiller system design and the potential it has to improve energy efficiency of the system. Based on the research, energy efficient equipment selection, the use of new technology, energy efficient design techniques/practices and the use of control systems will optimize the energy consumption of the HVAC system.

KEYWORDS: Centrifugal Water-Cooled Chiller, Energy Efficiency, Thermal Energy, Electrical Energy & Energy Efficient Technology

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Original Article

1. INTRODUCTION

In 2018 the world energy demand grew by 2.3% which is the fastest over the last decade, with fossil fuels constituting 70% of this growth [1], people spend approximately 90% of their time indoors [2], and there is a growing reliance on building thermal comfort especially when compared to acoustics and visual comfort [3]. Heating, ventilation and air conditioning (HVAC) systems form an essential component in the built environment as buildings are becoming more advanced and require a certain level of thermal comfort for occupant satisfaction as well as a high level of employee productivity. Therefore, the development of HVAC systems that utilise renewable energy sources with energy efficient primary and secondary system equipment will reduce the total energy consumption of a building [4]. Looking at HVAC energy consumption per building worldwide, the United States (US) accounts for more than 48% of a building's energy consumption [5], Spain and Italy more than 50% [5] and Australia about 70% [4]. In the Middle East, more than 70% of a building's energy consumption is for indoor thermal comfort [6]. On an average, HVAC systems are known to consume approximately 50% of the total energy demand of a commercial building [7], [8]. According to [9] and [10], in South Africa, HVAC systems consume between 30% to 50% of a commercial building's total energy consumption. To alleviate this challenge, it is essential to develop energy efficient HVAC systems and utilise renewable energy as the main source of electrical energy supply. Energy efficient HVAC systems also enhance the value of a property, protect property owners from increasing energy costs and contribute to the protection of the environment from harmful greenhouse gas (GHG) emissions.

With advances in science and technology, there are several ways to achieve energy efficient HVAC systems for commercial buildings. However, to successfully design the system, it is important to know and understand the function of the building, the indoor thermal comfort requirements of the occupants, and the climatic conditions of that location. Research indicates that energy efficiency and thermal comfort can be achieved by a well-designed air-conditioning system and an appropriate selection of air conditioning equipment and control strategies to reduce energy consumption and enhance indoor environmental quality (IEQ) [4].

Chiller plants are widely used throughout South African government buildings because they are most suitable, considering the climatic conditions and thermal comfort requirements as well as the maintenance of chillers. The HVAC industry is extensive; therefore, this research will focus on reviewing recent novel technologies and strategies related to optimizing the energy efficiency of centrifugal water-cooled chillers. Referring to Figure 1. This article will present the main energy consuming components of the water-cooled chiller and energy losses in the system followed by new technologies that enhance the performance of energy efficiency. Thereafter, a review of innovative chiller systems designs to improve energy consumption will be discussed. Lastly, recent developments in chiller control strategies and smart chiller sequencing methodologies that enhance energy performance of the chillers will be explored.

2. ENERGY EFFICIENT TECHNOLOGY

The major components of the centrifugal water-cooled chillers are the compressor, the cooling tower, the pumps (with reference to the chilled water pumps and the cooling water pumps) and the fans in the air handling unit. Essentially, each component contributes to the efficiency of the whole system, therefore a wholistic approach is important in achieving a low energy input per unit of cooling. This section intends to provide a breakdown of recent technologies that can lower the kW/ton of cooling in a water-cooled centrifugal chiller.

2.1 Compressor

The design of a centrifugal compressor plays an important role in improving its efficiency and contributing to the overall efficiency of the air conditioning system. Each component of the centrifugal compressor contributes to the optimization of the compressor. By improving the efficiency of the components, overall efficiency of the compressor can be achieved. In 2009, Timaki et al carried out a computational fluid dynamics (CFD) analysis to develop a high efficiency centrifugal compressor for a turbo chiller [1]. A 1000 ton turbo chiller with a coefficient of performance (COP) of 6.0 was used as a baseline against which the performance of the chiller was gauged [1]. The authors reduced the thickness and increased the number of the compressor blades for stage 1 and stage 2 [1]. The length of the splitter blades on the shroud side was increased. The impeller outlet angle was increased to increase the stable operating range of the 1st impeller stage [1]. The shape of the leading edges of the 1st and 2nd stage impellers were modified from an arc to an ellipse to improve the flow pattern inside the impellers [1]. The splitter blade shape was also modified to smooth out the flow between the splitter blades and the full blades [1]. Timaki et al. concluded that the new design of the turbo compressor improved the COP of chiller capacities ranging to 700 tons of refrigerant to a COP of 6.3 [1]. According to [2], variable speed centrifugal chillers perform more efficiently at part load ratio of the cooling demand and at partial compression ratio of lift head when compared to constant speed centrifugal chillers. The benefits of variable speed drives are further improved with magnetic bearing technology [2]. The overall results show that optimal chiller staging only improves the system performance by

1.2% for a constant flow system. However, using a VSD with magnetic bearings increased the energy savings to 13.7% [2].

2.2 Variable Speed Drive

Systems and processes often have variable flows or operate within certain parameters when accommodated by the conventional constant speed motors that provide a constant output. To improve the efficiency and accuracy of the operation, modern technology has advanced, thus, developing the variable speed drive (VSD). A VSD is a device that regulates the rotational speed and force of a motor according to the required output. VSDs are used to drive pumps, fans, compressors, and other equipment. The use of VSDs have the potential to closely regulate the fluid flow according to the operating conditions and thus reduce unnecessary energy consumption. The research carried out by Al-Bassam and Alasseri found that VSDs are energy efficient as the results from their research indicate that water consumption was reduced by 13% when compared to the commonly used motors and the chiller and cooling tower power consumption was reduced by 5.8% [3]. Chuang et al. showed that a stepless VSD combined with a control system can save at least 20% of the energy consumed [4]. Saidur et al. concluded that VSDs are reliable and cost effective and save energy thus promoting energy efficiency [5]. Saidur et al. also indicated that VSDs not only provide energy efficient capacity control, but they also have a low starting current and reduce the mechanical stresses on motors and belts [5].

2.3 Thermal Storage Systems

A thermal storage system (TSS) is a technology that stores thermal energy by either heating or cooling the medium, so the thermal energy can be used for heating or cooling at a later period. A TSS system is able to balance the energy demand between peak and off-peak hours [6]. During off-peak hours, cool energy is usually stored in the form of ice, phase change materials, chilled water, or eutectic solution. This energy is used during peak hours; as the phase of the material changes, heat energy is absorbed providing cooling to the working fluid [6]. Rahman et al. carried out an investigation to determine the feasibility of a TSS and concluded that a TSS can save up to 61.19% of the electricity cost required for cooling when compared to conventional systems [7]. The research carried out by Saddat-Mohammadi et al. shows that chilled water storage with the use of robust optimization reduces the overall electricity costs and that a TSS is more efficient for systems that have a high cooling load during peak hours [8]. The research carried out by Lin et al. involved analysing two new air-conditioning systems with TSS [9]. The results from their research indicated that TSS contributes to financial savings as well as energy savings [9].

3. SYSTEM DESIGN

Air conditioning system design plays an important role in energy consumption. Energy efficiency can be enhanced by utilising energy efficient equipment within an energy efficient system. System design can ultimately decide whether energy is being conserved or not. The design engineer should incorporate various techniques and methodologies to ensure that energy efficient measures are implemented.

3.1 Air-to-Air Heat Exchangers

One of the primary ways of reducing energy consumption of an HVAC system is to utilise an air-to-air heat exchanger (AAHE). A mechanical heat exchanger unit is used to transfer energy between two streams of air, the exhaust air and the fresh air supply, refer to Figure. The main role of this device is to pre-cool the fresh air supply before entering the AHU, thus reducing the amount of energy required to condition the fresh air. Wanli et al. proposed five solutions to enhance energy efficiency of air handling units (AHU) [10]. Their study used AAHE to reduce the cooling and heating loads on the coil [10]. To reduce the AHU power consumption, they analysed the energy and exergy losses of all five AHU layouts against the base design [10]. The energy balance calculations from their investigation revealed that AAHEs affect the power consumption and can reduce the power consumption in the coils [10]. Zhang et al. investigated two scenarios to enhance the performance of conventional evaporative cooling and condensation dehumidification systems and found that the COP of the base system increased by 8.5% and the COP of the first and second systems increased by 12.09% [11]. Eades carries out an investigation to examine ways of reducing energy and water consumption in laboratory HVAC systems. The author's model predicts energy savings of up to 13.5% and shows the efficiency of using AHU condensate for energy recovery purposes [12]. One of the most effective methods of HVAC systems design is thermal energy recovery and transporting energy from one space to another where it is required.

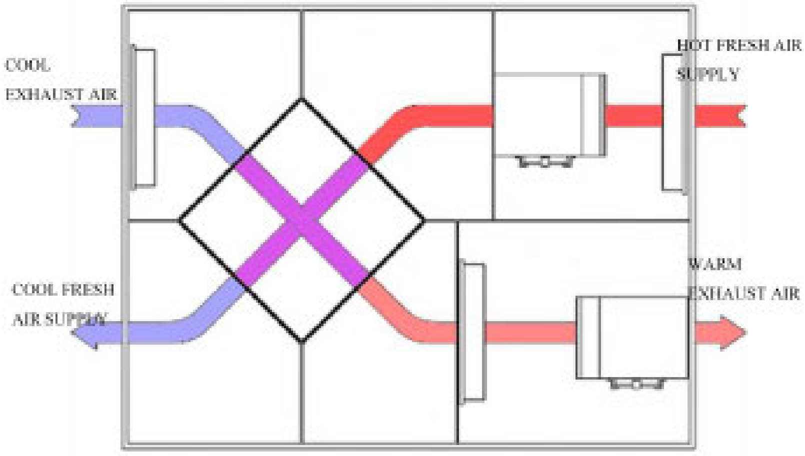

Figure 1: Air-to-Air Heat Exchanger Mixing Box (Image Adapted from [13]).

3.2 Solar Assisted Air Conditioning

There are various means of harnessing solar energy with one of the most popular methods being electrical energy produced with photovoltaic panels. This electrical energy is then stored in batteries and then used to power the HVAC system [14]. Another method is the solar thermal method that converts solar energy to heat energy, therefore, heating up the working refrigerant using solar energy and reducing the compressor power input. Figure 1 is a schematic of a solar absorption cooling system used for solar assisted air conditioning [14], [15]. An interesting study was carried out by Aguilar-Jimenez et al. in an off-grid school in Mexico where an absorption cooling system with 35 kW capacity driven by solar thermal energy was installed [16]. The outcome from the study showed that the cooling system was able to run continuously taking advantage of the stored energy and only utilizing less than 75% of the cooling capacity [16]. The system effortlessly provided cooling for all four classrooms during a five-day week from 7 am to 3 pm [16]. Hashe reviews the sustainability of solar heating and cooling and concludes that solar energy is a sustainable alternative to reduce the use of fossil fuels [17]. Solar irradiation and air conditioning are quite coincidental where air conditioning energy consumption increases as the heat gain increases, therefore, making solar thermal energy and cooling a favourable option for reducing energy consumption for cooling systems [18]. In 2009, Fong et al conducted a comparative study to investigate which system has the greatest energy saving potential [19]. The authors investigated the performance of five solar cooling systems; a) solar electric compression refrigeration, b) solar mechanical compression refrigeration, c) solar absorption refrigeration, d) solar adsorption refrigeration and e) solar solid desiccant cooling [18], [19]. The key finding from Fong's et al investigation indicated that solar electric compression refrigeration and solar absorption refrigeration yielded the highest potential for energy saving [18], [19]. Another investigation was carried out by Zhai and Wang in 2008 wherein five different absorption and adsorption chiller configurations were compared and summarised [20]. One of the outcomes indicated that solar absorption cooling systems are suitable for air conditioning large buildings and solar adsorption cooling systems are suitable for smaller buildings [20]. Their research highly recommends the design of solar powered integrated systems in public buildings [20].

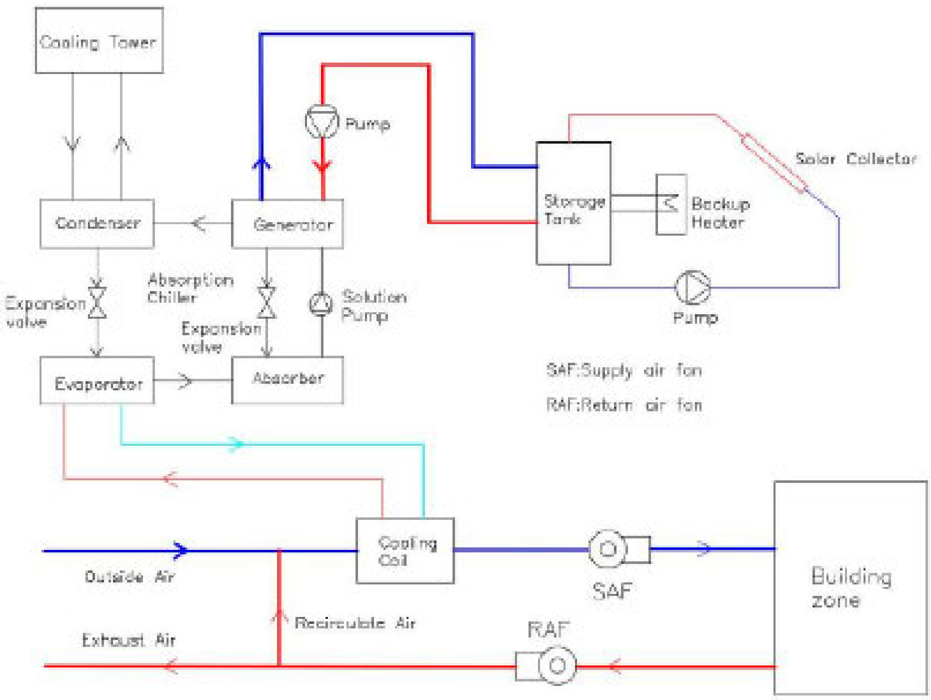

Figure 1: Schematic Diagram of Solar Absorption Cooling System [15].

4. OPERATIONAL MANAGEMENT AND CONTROL SYSTEM

The dynamics of the fourth industrial revolution have made the vision of an intelligent air conditioning system achievable. Management and control systems can be used to achieve optimal indoor air quality and environmental conditions and yet keep energy consumption relatively low. A concerted effort is made to study intelligent air flow and control strategies to address improved IAQ and to contribute to the development of sustainable buildings by reducing energy consumption [18]. Currently, there is extensive research in the field of HVAC control systems to develop intelligent air quality, air temperature, humidity, and velocity control. Monitoring and adjusting these IEQ parameters involves adjusting the operating conditions of the compressor, the pumps, fans, and dampers in the system. Developing an intelligent control system for a large-scale air conditioning system involves a holistic view and understanding of the functioning of the system.

A CO_2 based adaptive demand controlled ventilation (DCV) strategy was implemented and monitored in a high rise building in Hong Kong [21]. A dynamic multizone ventilation equation for multi-zone air conditioning systems was used for the adaptive DCV strategy wherein the total number of occupants in the space was detected using the CO_2 concentration in the air, this data was then logged onto an online occupancy detection system [21]. It was found that the DCV is able to significantly reduce energy consumption during summer, however, it may not be suitable for outdoor air control in winter [21].

Freire et al. [22] conducted a study on the effects of minimizing energy consumption while maintaining adequate indoor thermal comfort. Predicted mean vote and the comfort zone on the psychometric chart was used to define the occupants comfort levels for this investigation [22]. The methods used are based on model based predictive control (MBPC) and simulation results were presented for two case studies [22]. The control algorithms proposed use only one actuator system that can be associated to a heating or cooling system [22]. The simulation results obtained indicated that the algorithms used can simultaneously reduce energy consumption and promote thermal comfort while remaining 100% of the time in the comfort zone [22].

Another study proposed a risk based online robust optimal control strategy for multi-zone air conditioning systems [23]. As the core of the strategy, a risk-based online control decision scheme is developed for decision-making by considering the ambiguities in the information, the failure risks and energy benefits of different modes are compromised [23]. The results from this study showed that the proposed strategy made the optimal online control decisions while allowing for any uncertainties [23]. The proposed strategy achieved approximately 20% overall energy saving in the test period when compared to commonly used control strategies [23].

To achieve distributed optimal control of building HVAC systems, an agent based optimal control strategy was proposed for deployment in smart sensors integrated in internet of things (IoT) based field networks and local controllers in field networks of current local area network (LAN) based building automation systems [24]. The component agents and a coordinator agent are designed to deal with simple tasks assigned to them [24]. The tasks are simplified by applying the dual decomposition to an original complex optimization task [24]. The performance and implementation variables of the proposed agent based optimal control strategy have been assessed by tests on a simulated central cooling plant [24]. One of the key findings of the proposed agent based optimal control strategy is that it can achieve significant energy savings when compared with conventional control strategies [24]. When compared with the near optimal control strategy, savings of 3.36% and 4.6% were achieved [24].

Control strategies for large-scale HVAC systems have become more frequently researched. There are various techniques and control strategies that can be adopted to improve the energy consumption of large facilities while maintaining the recommended IAQ and IEQ comfort levels.

5. DISCUSSIONS

The three main types of equipment to enhance energy efficiency that need to be considered are the type of compressor, variable speed drives and the thermal storage system. The design of the compressor impellers, the use of magnetic bearings and VSDs; all improve the efficiency of the compressor. VSDs coupled to pumps and fans in the system improve the energy efficiency of these pieces of equipment. A thermal storage system is useful for energy efficiency and financial savings.

The design of the air conditioning system has the potential to improve the energy consumption by using various design practices, for example, transferring waste thermal energy to where it can be used. Air-to-air heat exchangers have proven beneficial in reducing the amount of energy required to cool down ventilation air before entering the space. The use of solar thermal panels to assist or run air conditioning systems is another popular consideration that has gained momentum in the research realm and is highly recommended.

Operational management and control systems are proven to enhance the efficiency of HVAC systems. However, there are various control strategies that can be implemented with each strategy having unique advantages and disadvantages. Due to the extent of large-scale air conditioning systems, control strategies are becoming increasingly complex. There are certain levels of control to monitor IEQ parameters and regulate the system accordingly, however, to optimally control a HVAC system to maintain the desired level of IEQ and thermal comfort with minimal human interference is currently a popular topic in research.

6. CONCLUSIONS

Chiller systems are an essential component used for air conditioning in commercial buildings consuming approximately 50% of the buildings total energy. This has stimulated research into reducing the energy consumption required for air conditioning while maintaining the desired level of IEQ with minimal to no human interference. A holistic approach to system design has the potential to improve energy efficiency of the system. This review reveals that equipment selection, the use of new technology, energy efficient design techniques/practices and the use of control systems can optimize the energy consumption of the HVAC system.

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CHAPTER 4: ENERGY EFFICIENCY OPPORTUNITIES FOR LIGHTING SYSTEMS AND MISCELLANEOUS ELECTRICAL LOADS IN COMMERCIAL BUILDINGS – A REVIEW

This chapter is a review of available opportunities to improve energy efficiency of a commercial building through lighting and miscellaneous electrical loads. The article has been published in International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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ENERGY EFFICIENCY OPPORTUNITIES FOR LIGHTING SYSTEMS AND MISCELLANEOUS ELECTRICAL LOADS IN COMMERCIAL BUILDINGS – A REVIEW

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ABSTRACT

Lighting and miscellaneous electrical loads (MELs) are important utilities that enhance indoor environmental quality (IEQ), the visual comfort of building occupants and directly affects occupant health and productivity and these utilities consume a significant portion of the total energy in a commercial building, in some cases close to 20% of the total energy consumption can be attributed to lighting and MEL electrical loads. This article aims to review the energy efficiency opportunities for lighting and MELs in office buildings and the current lighting and MELs control strategies that have been used to reduce energy consumption of lighting and MELs, so that the potential for improving energy efficiency for lighting systems and MELs can be identified and implemented. Articles on energy efficiency opportunities and control strategies and frameworks were reviewed. The articles reviewed indicated that there is substantial energy saving potential in the implementation of intelligent control systems.

KEYWORDS: Energy efficiency, lighting systems, MELs, control systems

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Original Article

INTRODUCTION

Lighting and miscellaneous electrical loads (MELs) are important utilities that enhance indoor environmental quality (IEQ), the visual comfort of building occupants and directly affects occupant health and productivity. In 2012 lighting (one of the subsystems in a building energy system [BES]) United States (US) accounted for 17% of a buildings total electricity consumption, the second highest energy consumer after air conditioning systems[1], [2]. With an increased use of light emitting diodes (LEDs)in commercial buildings, with LEDs making up close to 50% of lighting type in buildings, the electrical energy consumption per meter square has decreased drastically [3].However, this does not suggest that the energy efficiency targets have been met and we have reached the peak of sustainable buildings.

In 2018 the research carried out by Kwong et al (2018) indicates that the number of electronic devices purchased over the past few years and that correlates to the increase in electrical energy consumption, concluding that MELs have a significant contribution towards energy consumption in commercial buildings [4]. Among the energy consuming system, the energy consumed by electrical appliances falls under the category of MELs (also referred to as plug loads) has been identified by researchers as a significant energy consumer [4]. It has been identified that MELs use 15 – 20% of the total energy consumption in the buildings. A previous study highlighted that MELs, advancing technology and population growth have also contributed to the increase in energy consumption[4]. There is extensive research covering HVAC systems and lighting, however, MELs are often neglected owing to the unpredictable use of these equipment. This has created a niche to identify current MEL trends and future developments. For this research article, MELs will refer to all office equipment and plug loads.

There is room for improvement of energy efficiency in lighting and MELs within the research field and much of the potential to improve energy consumption of lighting and MELs can be found in intelligent control systems for commercial buildings. This article aims to review the energy efficiency opportunities for lighting and MELs in office buildings and the current lighting and MELs control strategies that have been used to reduce energy consumption of lighting and MELs, so that the potential for improving energy efficiency for lighting systems and MELs can be identified and implemented.

This article is structured such that energy efficiency opportunities for lighting and MELs in commercial buildings will be reviewed, the outcome will provide feedback on the popular energy efficiency measure for lighting and MELs. Thereafter, trending control strategies will be reviewed to determine the best energy efficiency opportunity for lighting and MELs.

Energy Efficiency Opportunitiesfor Lighting and Mels in Commercial Buildings

Lighting Energy Efficiency Opportunities

The three main strategies towards energy efficient and sustainable buildings are retrofitting existing luminaires with energy efficient luminaires, such as LEDs, reducing design illumination levels and implementing control systems [1]. A well-designed lighting system can save energy and provide visual comfort for building occupants.

Part of the review carried out by Dubois et al (2015) compared retrofits of existing standard fluorescent lighting (T12) with T8 magnetic and electronic ballasts and T5 electronic ballasts found that the T8 lamps can replace the T12 without any modification to the fixture while the use of T5 lamps require electronic ballasts that can reach a lamp luminous efficacy superior to 100 lm/W [5]. The review indicates that the T5 electronic ballast saves 40% more energy than a T12 and the T8 electronic ballast saves 17% energy when compared to the T12 [5]. According to the review, LEDs have a high energy saving potential, however they indicated drawbacks such as flickering of the light, low illuminance levels and poor beam distribution [5]. Another research article by Chiradeja et al (2015) indicated that a T5 tube with electronic ballast uses less energy that the T8 lamps and the harmonics in the T5 electronic ballast lamp can be reduced by using a passive low-pass filter[6]. In 2013, Asif ul Haq carried out an investigation to determine the energy savings, among other findings, of a project to replace all existing T8 lamps with ore efficient T5 lamps in the UniversitiTeknologi Malaysia (UTM) [7]. An Average of 8.5% energy savings was achieved from the three buildings blocks analysed [7]. In 2013, Fabrico et al, simulated general lighting retrofit, comparing LEDs, compact fluorescent lamps (CFL) and fluorescent tubulars, which demonstrated that CFLs have the highest annual cost and toxic waste disposal, fluorescent tubulars are a more economical alternative, however, if their lifespan shortens, LED prices drop and achieve a higher energy efficiency, thus making LEDS a more sustainable and economically attractive alternative [8]. In 2013, Gan et al, examines the feasibility of replacing conventional fluorescent lamps with LEDs, it was concluded that LED luminaires have the potential to replace fluorescent lamps, however, LEDs have certain inherent characteristics such as poor total harmonic distortion performance and the quality of illumination [9]. However, with advancing technology, LEDs have developed to overcome their shortfalls, thus currently comprising of 90% of all lighting systems according to [2].

LEDs are a prominent energy efficient lamp with a relatively high photometric performance, and it is simple to control. In 2007, Enkivist et al, carried out a study that indicated investment in energy efficient lighting is one of the most cost effective methods for improving energy efficiency in buildings [10]. Ahn et alexamined energy use in commercial buildings by evaluating lighting energy saving approaches and the effect of using a dimmer control [11]. The study concluded the energy consumption of the reference commercial building was reduced by 20.9% by replacing the linear fluorescent lights (LFL) with LEDs [11]. Currently the use of LEDs has gained moment and has replaced close to 50% of all lighting in buildings. In 2017 Montoya et al carried out a study to analyse the evolution and milestones of indoor lighting [12]. Using research, one of the primary conclusions indicate that the different techniques used in indoor lighting followed three paths simultaneously i.e. better photometrical performance, better energy efficiency and better performance of the installation users [12]. The demand for compact fluorescent lamp (CFL) and LEDs is growing in popularity due to the reduction in energy consumption and its sustainability, now being used in street lamps and robots [12]. However, the high level of performance in LED lighting has not prevented further research in the field of lighting, new and more versatile light sources are being explored, like the Organic Light Emitting Diodes (OLED) [12].

Daylighting is a suitable energy efficient means of reducing illumination levels of a space. The use of daylighting combined with controlled artificial lights substantially increases energy savings. However, daylighting is very dependant on the daylight zones, where certain zones must be controlled independently [13]. The orientation of the building and the design of the building ultimately determines zones with high and low levels of daylighting, standards and buildings codes define these zones accordingly. Lighting design and the daylight harvesting techniques adopted play an important role in determining the number of luminaires (and the lux levels) to be used in the zone, this ultimately governs the the energy savings to be achieved[13]. A study carried out by Mantzourani et al aims to investigate the influence that daylight zones have on energy efficiency in five office spaces [13]. The three different definitions used to estimate the daylight zones are a) EN 15193.1 as implemented in Greek regulation of Energy Efficiency in Buildings, b) CEN Technical Committee 169/WG11 Daylight, and finally c) using dynamic daylight metrics for typical working hours for all four cardinal orientations [13]. It was found that the definitions for daylight zones, yielded different results per space and obviously each daylight zone yielded energy savings according to the amount of natural light the space captured[13]. The energy efficiency results yielded from the investigation are dependant on the method of calculation of daylight zone depth used, the results vary from 61-89%, 53-72% and 69-91% [13].

Ubiquitous control systems are finding a way to make systems smarter and now more intelligent to enhance human life and, in this case, improve energy efficiency. Research by [14] suggest that the average obtainable savings from daylighting in actual buildings simulations are overestimated by a minimum of 10% [14]. The meta-analysis carried out goes onto show that individual control strategies save between 25-30% of the lighting energy used and multiple control strategies can save up to 40% of energy [14]. Lighting systems can be controlled in various ways, at the user level, there is the simple on and off switch and dimming regulators that provide users with the option of controlling the brightness [1]. More advanced electronic switches can be programmed to operate in ways such as toggling or changing light intensity in steps [1]. More flexibility in lighting control is provided with building automation, the user can control lighting from their smart phones or their pc. Lately, lighting is being controlled over the internet using smart apps and the control of lighting is inclined towards artificial intelligence control. From the review carried out by [1] control systems can provide significant energy savings and result in energy cost savings [1]. Bunjongjit et al (2020) proposed a control circuit for LEDs based on the amount of daylight[15]. The desired illuminance in a work place was achieved using natural daylight and artificial light[15]. The test results showed that the LED control circuit reduced power consumption of the lighting system whilst maintaining the desired illuminance levels [15].

Miscellaneous Electrical Loads Energy Efficiency Opportunities

MELs are often defined as all electrical loads that do not fall under conventional end uses such as lighting, Heating, ventilation and air-conditioning and refrigeration (HVACR), therefore MEL will often be office equipment, plug loads and ICT equipment[16]. In the research carried out by [17], MELs get referred to as the diverse electric loads emanating from electronic devices not responsible for HVAC or lighting [17]. The number of MELs have been increasing due to the number of electronic equipment, however, the main loads in commercial buildings are becoming more efficient, therefore resulting in MELs accounting for a larger percentage of the buildings electrical load [16]. According to the literature survey carried out by Kamilaris et al in 2014, MELs account for more than 20% [18]. Another study by Syed and Hachem carried out a simulation study of greenhouse retail complex and found that MELs account for 23% of the buildings total energy consumption [19]. The total annual energy consumption for key MELs in commercial office buildings is given in Figure 1. The annual unit consumption for personal computers (PCs) is equivalent to 450 kWh, the highest energy consumer in commercial office buildings[16]. In the research by McKenney et al. the energy consumption is further broken down for PC equipment as shown in Figure 1[16].

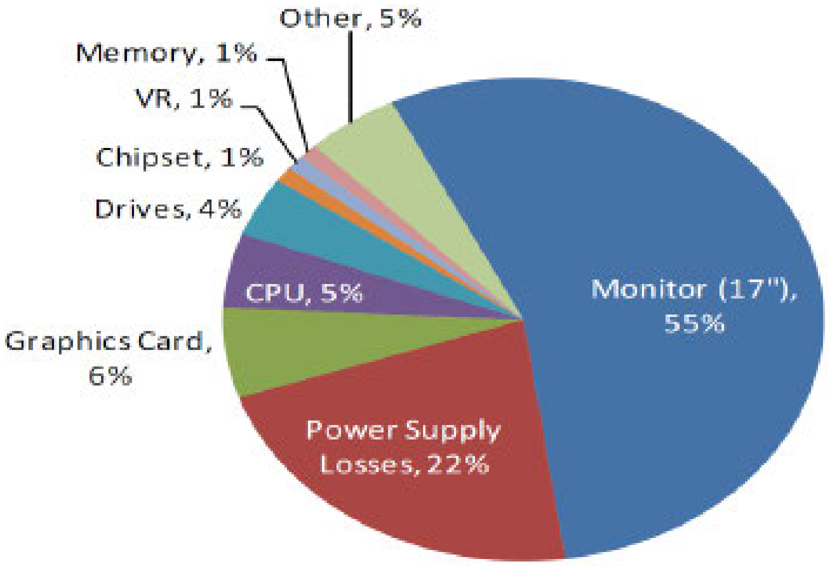

Figure 1: Estimate Power Consumption for PCs [16]

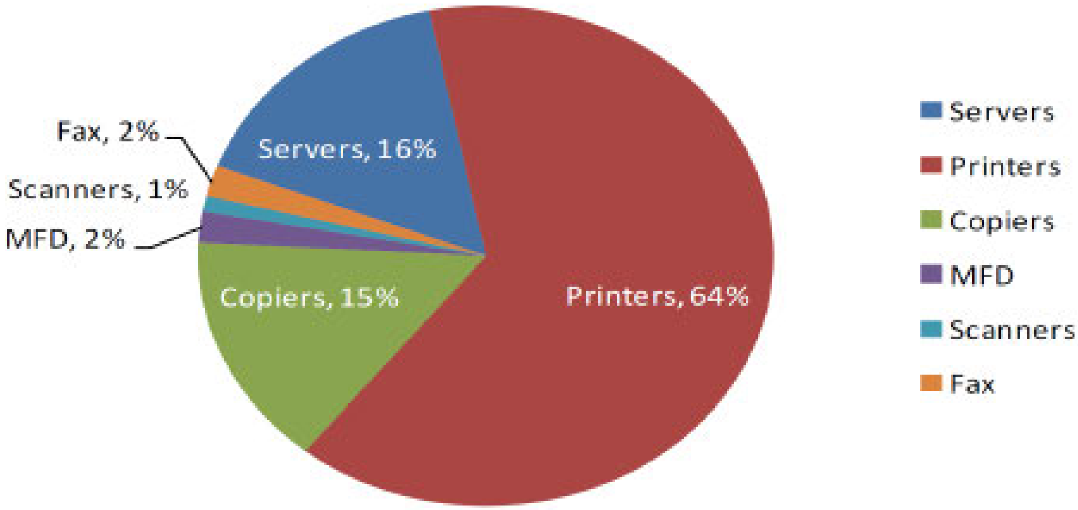

Figure 2: Annual energy consumption for key MELs in commercial buildings [16]

Depending on the use of the office commercial building, the size and occupancy, key MELs will vary. However, McKenney et al (2010) provides a breakdown of other office MELs with printers consuming more than 50% of the energy consumption as shown in Figure 2. The high energy consumption of printers is attributed to the high installed base load and the relatively high average power draw on standby mode of up to 70% [16]. Laser printers account for 75% of energy consumed by printers with the remaining consumption being inkjet and impact printers [16]. The next highest energy consumer, servers, consume about 16% with copiers consuming 15% of total MELs energy consumption. The energy consumption of multi-function devices (MFDs), faxes and scanners are negligible.

Energy consumed by MELs can be reduced through various control strategies, industry standard specifications and power management (PM). Under industry standard specifications called Advanced Configuration and Power Interface (ACPI), operating systems provide interfaces for users to configure the conditions under which their PCs go into low power mode or switch off [16]. PM reduces the energy consumption of PCs by controlling the operating voltage and/or clock frequency in response to computational loads obtained from the operating system [16]. Currently most PCs are purchased with factory enabled PM, however the settings are user defined which makes it, dependant on the whether the user enables power saving mode or not.

Energy star is a program used to promote energy efficiency by providing the energy consumption of appliances and electrical/electronic devices using different standardised methods. Energy star also provides an energy rating depending on the amount of energy consumed, enabling building managers and building owners to know how much of energy is consumed by all the equipment and the level of energy efficiency of the device. Energy star performance criteria for most IT and office equipment have focused primarily on having equipment enter low-power mode and capping power draw values for different equipment types in low power mode [16]. Network software can facilitate and provide a means to centralize PM across a range of equipment connected to the network [16]. Another method for reducing energy consumption is maintaining fuser rolls at a high temperature could reduce energy consumption by 50% in laser printers and copiers [16]. Advances in fuser systems with a lower melting temperature can contribute to energy savings in laser printers and copiers during stand-by mode [16]. Another method that significantly saves energy is automating device shut down or low power mode based on the PCs activity[16].

Energy reductions can be broadly categorised by software and hardware-based [18]. PM and virtualization, are common software based techniques which claim significant energy savings of up to 60% [18]. Current PM and virtualisations products are reliable and efficient, offering advanced features and significant savings [18].Hardware-based savings involve physical equipment such as smart plugs and SPS for controlling IT devices and indicate substantial energy savings[18]. Replacing hardware with more energy efficient equipment can be effective and result in 40-60% energy savings [18]. According to [18] savings resulting from hardware need to be quantified to allow for the calculation of ROI when considering these options [18].

Reviewing Control Strategies and Frameworks

The popularity of smart sensors and building management system, building operations have become more information intensive and a large amount of data is recorded to provide a basis for the building performance.Part of the building data can incorporate energy consumption data and thus be monitored and controlled electronically. There are various control strategies that could be implemented for lighting and MELs. With the progress of artificial intelligence, most of these control strategies are leaning towards intelligent control systems.

Lighting Control

The integration of sensor technologies, advanced architecture and intelligent control techniques have provided a perfect situation for implementing intelligent lighting control systems to reduce energy consumption. An intelligent lighting control system is capable of enhancing the visual comfort of occupants whilst reducing energy consumption [1]. The lighting control system can be broadly categorised into three main techniques, controller-based control, optimization-based controland a hybrid system [1].

The paper by [1] presents current state of the art interior lighting system control techniques for commercial buildings with a focus on sensing technologies, objective functions and constraints, techniques, tools and energy performance[1]. The outcome from the analysis indicated that the optimization-based control technique is widely used, as it achieves a greater energy savings whilst satisfying visual comfort of occupants and simultaneously solving multi-objective problems [1].

Studies have presented that energy efficient smart LED lighting systems provide better visual comfort working environment and are more energy efficient when compared to conventional lighting systems. An article by [15] proposes a control circuit for LED luminaires based on the amount of daylight, using natural light and artificial light to maintain the desired illuminance of the space [15]. A light sensor was used to determine the illuminance of the space and compared it with the desired value set on the microcontroller, thereafter sending a control Pulse Width Modulation (PWM) signal to the LED driver, thus regulating the light intensity of the LED as represented by Figure 3[15]. The results from the field test showed that the LED control circuit was able to reduce power consumption by maintaining he illuminance level of the work space [15]. The results from both, the simulation and the experimental, showed that the maintaining the desired illuminance level in the space by controlling the lighting can improve energy efficiency [15].

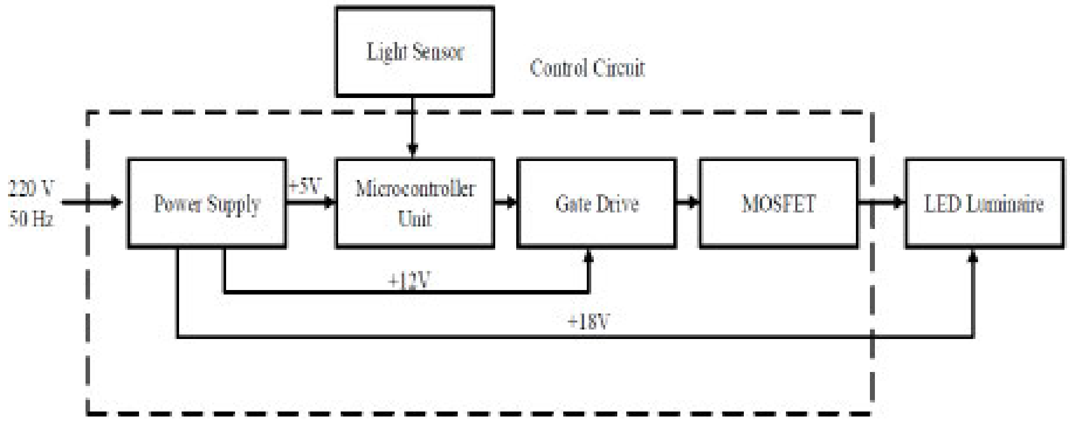

Figure 3: Daylight CONTROL CIRCUIT for LED Luminaire Strategy [15]

Daylighting systems can regulate the light intensities using smart sensor communication technologies to meet the required illuminance levels of the space. Without compromising occupant visual comfort, [20] implemented a smart LED lighting system using different energy efficient techniques with the aim of reducing energy consumption by 60-70% [20]. ZigBee and Wi-Fi communication protocol was used to control the lights according to the natural light lux levels to provide satisfactory visual comfort for the occupants [20]. The results indicated that the implemented control system was able to provide the recommended lux levels between 300 to 750 lux [20].

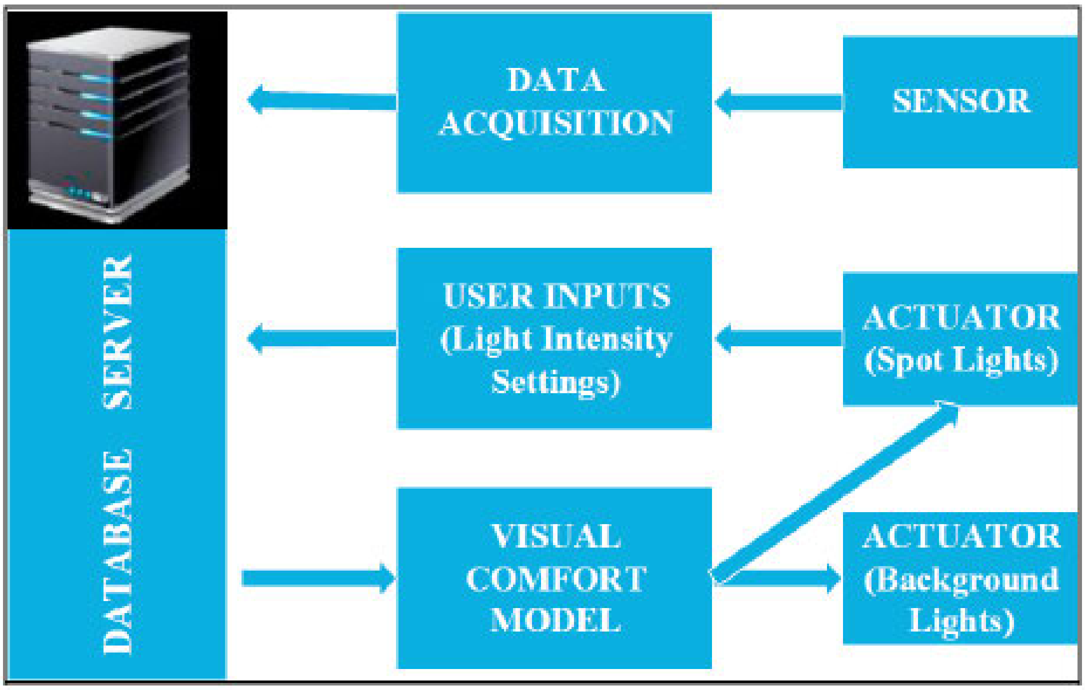

Figure 4: Personlized Visual Comfort WSAN Framework [20]

MELs Control

Understanding the MELs energy consumption patterns is important to optimize the operation of all MELs and to manage and forecast building energy consumption. Occupant behaviour is closely related to energy consumption of MELs, making it difficult to predict the energy consumption of MELs. However, recent research has found a niche for understanding, monitoring, and evaluating the relationship between occupant behaviour and energy consumption in buildings.

Energy consumption in office buildings largely depends on occupant behaviour and managing these behaviours could improve energy efficiency [21]. [21] proposes an occupant-level energy usage approach which uses data from the internet of things (IoT) to provide information on occupant energy use behaviour of workstations and shared appliances [21]. An energy behaviour index which quantitatively compares individual occupants energy consuming data to identify high energy consumers and inefficient behaviour [21]. The proposed approach used the comprehensive occupant-level energy-usage (COLE) framework to provide personalized energy use behaviour [21]. Figure 5 demonstrates the COLE framework used, where the occupants first entry and last departure events in working schedule is detected, the building load data is then correlated with this information lastly the correlated load data is normalised to identify personalised energy usage [21]. The experiment conducted in an office building demonstrated the feasibility of the proposed approach to classify occupants in different energy usage categories [21].

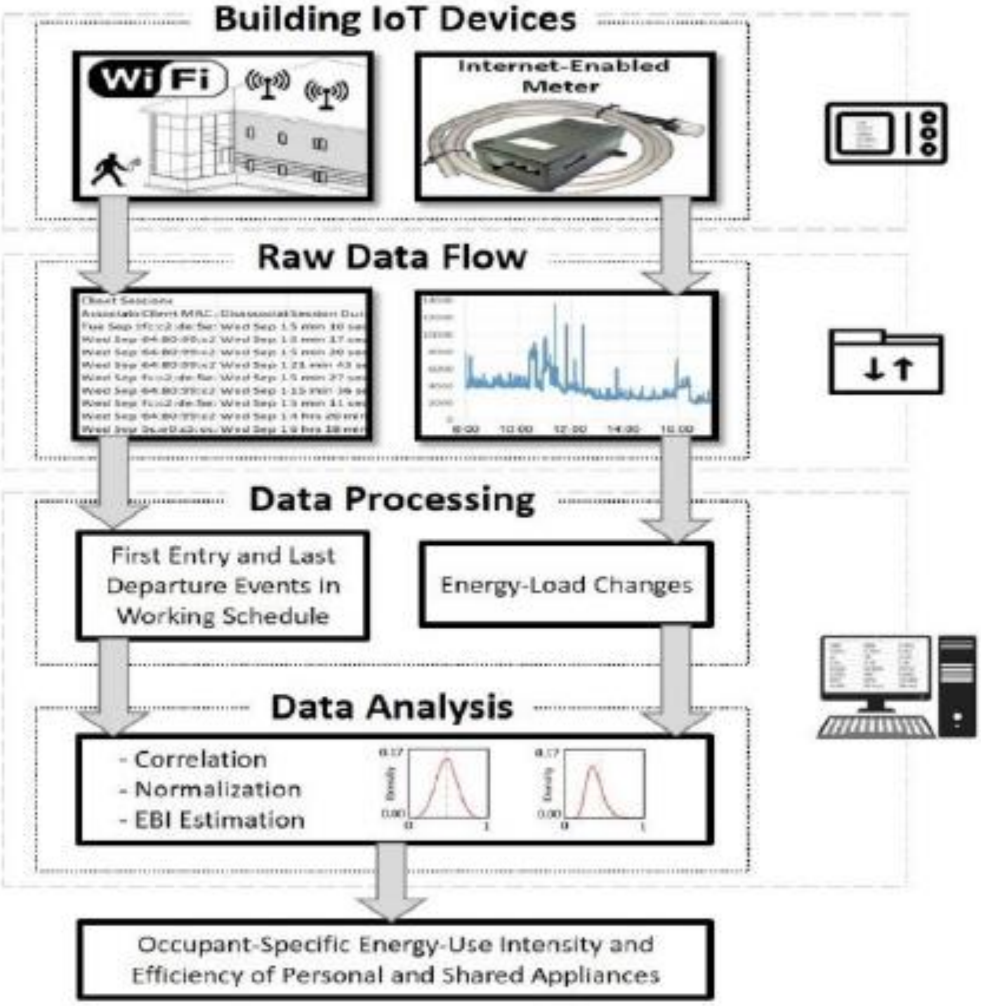

Figure 5: Comprehensive Occupant Level Energy Usage Framework [21]

An analysis on using a deep learning method to predict MEL energy consumption was carried out by [17]. The data set was made up of the energy consumption of each occupants MEL and the associated device utilization, which was used to develop the baseline long-short term memory (LSTM) model for MEL energy consumption predictions over a short period of time [17]. The results from the baseline model was compared with two other deep learning models, Bi-Directional Short Term Memory (Bi-LSTM) and Gated Recurrent Units (GRU), which showed that the Bi-LSTM and GRU were better than the baseline LSTM model [17].

Monitoring the changes of the operational states of MELs over time is important in analysing the dynamics of operations in smart buildings, this data can then be used for various energy management applications, inferring the occupant behaviour and energy usage patterns [22]. [22] proposed a self-configuring event detection framework for detecting changes in operational appliances [22]. The contextual characteristics from the environment are learnt autonomously by the framework, thereafter adapting to the event detection parameters [22]. Figure 6 illustrates the components and the process of the framework there are 2 essential steps to the framework, 1) the self-training stage for motif processing and 2) the proximity-based event detection [22]. The results indicate that the proposed event detection framework outperforms the conventional event detection in detecting the operational states of different classes of load across different environments [22]. The proposed framework has the potential to facilitate human-building interactions in training smart home applications [22]. Considering the potential that the self-configuring detection framework has in monitoring operational changes of appliances and adapts to the environment's parameters, it could potentially be used to monitor energy usage of MELs and occupant behaviour associated with the energy consumption of MELs.

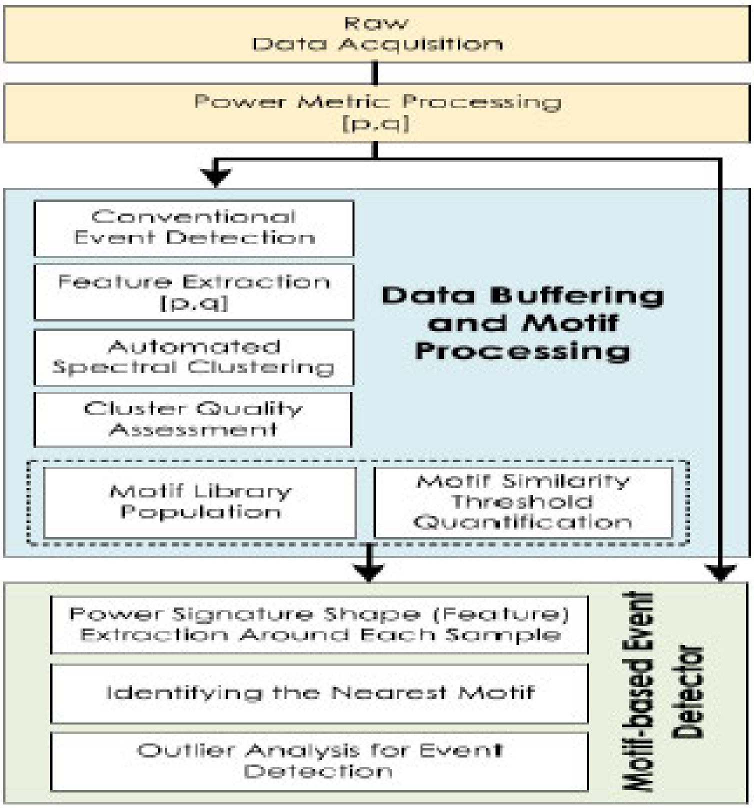

Figure 6: The Framework for the Motif-Based Event Detection [22]

Discussion

Energy efficient lighting opportunities and trending control strategies to reduce energy consumption was reviewed to identify the potential for improving energy efficiency for lighting systems and MELs.

Energy Efficiency Opportunities

According to research, the 3 main techniques for reducing energy consumption of lighting systems is by retrofitting conventional lighting with more energy efficient lighting systems, design lighting systems with a low illuminance level and the use of a lighting control system that controls the lux levels in the space. The use of LEDs in lighting systems is more prominent that other types of lights due to the ability to control LEDs and LEDs are more energy efficient than other types of lights. Another plausible energy efficiency opportunity is daylighting which has proven to reduce the energy consumption of lighting systems. The amount of energy saved with daylighting depends on the type of daylighting system implemented. A control system for lighting is becoming more common as smart homes and offices take over, lighting control systems have proven to reduce energy consumption drastically and with advancing technology, lighting control systems are developing to a greater level of accuracy and energy savings.

The research articles reviewed indicated that the three ways of reducing energy consumption of MELs is through using software and energy efficient hardware and the third method is occupant behaviour. the use of energy efficient hardware and software that promotes energy efficiency have been proven to contribute to the reduction in energy consumption. However,the unpredictable nature of building occupants has made it difficult for researchers to identify suitable means of reducing energy consumption related to occupant behaviour. however, this challenge has opened a new avenue in the field of artificial intelligence (AI).

Reviewing Control Strategies and Frameworks

There are various control strategies and frameworks that have been researched to reduce energy consumption in lighting systems and for MELs in commercial buildings. Control strategies and frameworks can be broken in two categories, 1) smart systems and 2) intelligent systems. Smart systems are often used in cases where the control system is programmed to perform a certain task without human intervention whereas intelligent systems are designed to learn occupant behaviour and adjust the system accordingly. Energy efficient of lighting systems can be improved significantly by implementing a type of lighting and/or MEL control system in the commercial buildings. The control system must ensure that the desired lux levels are maintained to ensure visual comfort. The optimization-based control system has been confirmed to achieve greater energy savings whilst maintaining visual comfort. The other control system, a form of daylighting, controls the LED lux levels based on the amount of natural light in the space has also proven to improve energy efficiency of the lighting system.

The energy consumption of MELs is closely related to occupant behaviour which is relatively unpredictable. However, research has presented opportunities to monitor and predict occupant behaviour thus evaluating the relationship between MEL energy consumption and individual occupant behaviour. Using the IoT as a tool to monitor occupant behaviour can be used to evaluate the amount of energy consumed based on occupant dynamics. Deep learning methods and a self-configuring event detection control system, both have the potential to improve energy consumption of MELs.

CONCLUSIONS

Energy efficiency of lighting systems and MELs in commercial buildings have the potential to be improved and the methods discussed have indicated energy savings. The implementation of a control system to monitor, predict and adjust electrical energy consumption according to occupant needs has a great potential to increase energy savings. Therefore, intelligent control systems are gaining more attraction in the field of research. To improve on energy consumption of lighting and MELs, it is important that future research looks at an intelligent control system that encompasses lighting systems and MELs.

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CHAPTER 5: POTENTIAL BARRIERS AND DRIVERS TO ENERGY EFFICIENCY IN COMMERCIAL BUILDINGS

This article is a critical review of barriers and drivers to energy efficiency in commercial buildings within a South African context. This article has been published in International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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POTENTIAL BARRIERS AND DRIVERS TO ENERGY EFFICIENCY IN COMMERCIAL BUILDINGS

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ABSTRACT

Energy efficiency is one of the cheapest and easiest ways to reduce electrical energy consumption, however, the outcomes of these energy efficient measures are not being realised due to various barriers. Barriers are obstacles that prevent the realization of energy efficiency after the implementation of energy efficient technology. While barriers inhibit the benefits of energy efficiency, drivers promote energy efficiency and help reduce energy consumption and increase return on investment. Barriers need to be understood so that effective drivers can be identified and successfully implemented. The aim of this article is to qualitatively review the relevant literature to identify potential barriers to energy efficiency in commercial buildings within the South African context and then propose a taxonomy of potential barriers, ranking them from most critical to least critical. This article uses previous research to identify drivers to energy efficiency. The identification of these barriers and drivers can be used by policy makers to further implement regulations to enhance and promote energy efficiency. Landlords, stakeholders and building owners can take precautionary measures in terms of these when implementing energy efficient measures. Energy efficient system designers can also foresee these barriers and put in place drivers to limit the barriers.

***KEYWORDS:** Barriers, Drivers, Energy Efficiency & Commercial Buildings*

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Original Article

1. INTRODUCTION

The implementation of energy efficiency measures is gaining traction in the built environment because this is a cost effective and fast way to reduce the impact of climate change on global economies. Researchers have had an interest in barriers to energy efficiency for the past four decades and recently there has been a renewed interest in this field (Olsthoorn, Schleich, & Hirzel, 2017; IEA, 2018). The rate of energy efficiency improvement is around 1 % per year. However, with advancements in technology and policies, there is the potential to further reduce energy consumption and promote energy efficiency (United Nations, 2011). Energy efficiency improvements are being implemented in South African commercial buildings although the effects of energy savings are not always witnessed, or it is not as lucrative as perceived at the onset of the project. There are various challenges that are prevalent in commercial buildings, especially state-owned buildings. For example, the client and the energy service companies (ESCs) may have complications with the benefits of the shared savings contract, or the building occupants may be negligent when utilizing energy consuming devices.

Globally, investments in energy efficiency have not reached economically optimal levels despite profitable business opportunities and a large market potential (Marquez, Mcgregor, & Syme, 2012). This raises the question of whether savings from the implementation of energy efficient technology are apparent. There are numerous research articles that aim to answer this question thus creating a whole new spectrum for the improvement of the implementation of energy efficiency. In this regard, it is necessary to have an understanding of the factors that hinder the positive outcome of implementation of energy efficient strategies or technology, and the impact that such barriers have.

In the literature, the phenomenon that hampers energy efficiency is often referred to as Jevons Paradox, Energy Paradox, Energy Efficiency Gap (or simply called the energy gap) or Rebound Effect (RE) (Berkhout, Muskens, & Velthuijsen, 2000; Brännlund, Ghalwash, & Nordström, 2007; Greening, Greene, & Difiglio, 2000; Jaffe & Stavins, 1994; Lin & Liu, 2015). This phenomenon occurs because of underlying causes often know as *barriers* (Jaffe & Stavins, 1994; Kangas, Lazarevic, & Kivimaa, 2018). Barriers to energy efficiency refer to mechanisms that inhibit behavior or investments that would improve the efficiency of energy consumption (United Nations).

The aim of this research paper was to identify barriers and drivers to energy efficiency in occupied commercial buildings, thereby producing a systematic classification and explanation of barriers and drivers to energy efficiency. This paper explains the impact of the barriers as well as energy efficiency drivers, and proposes a taxonomy of potential barriers and some drivers that may be prevalent. The focus will provide policy makers a platform to evaluate and warrant the extent of future energy efficient interventions as well as the overall energy efficient potential of these interventions, and will provide a reason for government to consider fiscal initiatives for energy efficiency. The identification of these barriers and drivers can be used by policy makers to further implement regulations that enhance and promote energy efficiency. Landlords, stakeholders and building owners can take precautionary measures against these barriers when implementing energy efficient measures. Energy efficient system designers can also foresee potential barriers and introduce drivers to limit the barriers.

1.1. Energy Efficiency Gap

Research has indicated that the calculated savings or return on investment (ROI) is not the same as the actual savings or ROI, a phenomenon known as the *energy efficiency gap* (in some cases it is also known as the energy gap or the efficiency gap) (Bhattacharya, 2020). In the review carried out by Azevedo (2014), the energy efficiency gap is defined as "the difference between the current level of energy consumption and the level of energy consumption that would occur if consumers were to select cost effective, life-cycle, energy efficient and end-use alternatives". From an economic perspective, the energy efficiency gap refers to the agent's failure to pursue cost effective investments in efficiency improvement and technologies (Azevedo, 2014). The energy efficiency gap is attributed to various factors such as imperfect information, market failures and market barriers, misplaced incentives, lack of capital or financing options, uncertainty about the future price of electricity or fuels, consumer behavioral traits, unwanted features in products, and energy prices not reflecting the true cost (Azevedo, 2014; Bhattacharya, 2020).

1.2. Jevon's paradox

Jevon's paradox was introduced in 1865 when Jevon stipulated that energy efficient improvements in technology would reduce the price of providing such services therefore increase the demand for that service (Azevedo, 2014; Jevons, 1886). Jevon's paradox initiated debates regarding the RE until the 1970s, after which it re-emerged in research carried out by Brookes in 1979 and Khazzoom in 1980, later becoming known as the Khazzoom-Brookes Postulate (KBP). Jevon's paradox is explained by Saunders (1992) as follows: "with fixed real energy prices, energy efficiency gains will increase energy consumption above what it would be without these gains" (Saunders, 1992). Jevon's paradox is further explained by (Sorrell, 2007) as: "If energy prices do not change, cost effective energy efficiency investments will inevitably increase economy wide energy consumption above what it would be without those improvements" (Sorrel, 2007). Research by Sorrell (2009) indicates that evidence in favor of Jevons Paradox is not conclusive, however it suggests the RE is larger than is conventionally assumed (Sorrel, 2009).

1.3. Rebound Effect

Technological improvements are making electrical equipment more energy efficient, where less energy is used to produce the same output. The use of less energy causes the cost per unit of output to decrease. The reduction in price per output generally results in increased consumption and the energy efficiency benefits are lost. The lost part of energy efficiency is the RE (Berkhout, Muskens, & Velthuijsen, 2000). The authors concluded that scientists agree that the RE exists due to the substitution effect, the income effect, and the existence of the macro-economic RE. In the review by (Azevedo, 2014), the RE is broadly defined as the gap between engineering calculations of potential energy savings (PES) and the actual energy savings (AES) that is measured after the implementation of the energy efficiency measure, which is also mathematically expressed by equation (1) (Azevedo, 2014).

$$R = 1 - \frac{AES}{PES} \quad (1)$$

However, the above equation does not take into consideration the scope and boundary of analysis, therefore researchers have further sub-categorized the RE into direct, indirect and economy wide REs (Azevedo, 2014).

The energy efficiency gap, Jevons paradox and the RE are all phenomena that occur because of various factors that hinder the benefits of energy efficiency. Researchers and scientists have studied these factors, known as barriers to energy efficiency in detail, to determine what the causes are and how they can be eliminated.

2. RESEARCH ON THE TAXONOMY OF BARRIERS AND DRIVERS TO ENERGY EFFICIENCY

Taxonomy is essential to helpful in the study of barriers and drivers to energy efficiency, and the influence of barriers and drivers on the installation of energy efficient technology and the way these barriers and drivers can be modified. The heterogeneity of barriers and drivers depends on the application of energy efficient interventions and the environment in which the interventions are applied, because barriers and drivers are often related to and unique to the facility in which they arise. For this review, barriers and drivers to energy efficiency in occupied commercial buildings was studied.

2.1. An understanding of Barriers and Drivers in Commercial Buildings

An understanding of the nature of barriers to energy efficiency is outlined in this section to provide clarification on assumptions about the nature of occupant behaviour, and the importance of energy management structures to the economy (Sudhakara Reddy, 2013).

Barriers and drivers of energy efficiency impact the decision of investors and stakeholders. There are some barriers which result in an immediate negative decision, and there are other barriers that merely reduce the likelihood of a positive decision. Often, these two decisions are driven by the ROI or lack of feasibility or a combination of the two (Sudhakara Reddy, 2013).

In some situations, barriers to energy efficiency may not be perceived as such by investors and stakeholders and do not influence their decision to proceed (Sudhakara Reddy, 2013). In other words, the barriers are real, but do not influence investor decisions. On the other hand, there can be perceived barriers that are not real as well as perceived drivers that are not real.

Another characteristic of a barrier is the environment, where some variables may act as barriers in one situation and act as drivers in another situation. In some cases, multiple barriers may co-exist, reinforcing the effect of barriers on energy efficiency. This characteristic is also dependant on the country and the facility in question (Sudhakara Reddy, 2013).

Based on the above characteristics of barriers and drivers, it is important to carry out a detailed analysis of the barriers and drivers, their effects on ROI and energy consumption and to identify the barrier and the result of the barrier (Sudhakara Reddy, 2013).

2.2. A Review on Taxonomies for Barriers and Drivers to Energy Efficiency

This section provides a review of typologies for several types of barriers. However, this review does not provide an explanation of the barriers, rather it is the identification of barriers in previous research articles within different contexts. The taxonomies presented arise from a failure so far to provide a holistic perspective on potential barriers.

A study carried out by Reddy (1991) resulted in a typology for barriers to energy efficiency from the lowest level of the energy consumer to the highest level of global financial institutes. The barriers identified were: 1) Consumer related, 2) Equipment related, 3) Energy service provider related, 4) Financial institution related and 5) Government related.

In 1991, the book "*Energy Efficiency and the Environment: Forging the Link*" by Vine, Crawley and Centolella grouped market barriers into: 1) Lack of evidence about energy use, 2) Lack of access to information regarding financing investments and energy efficiency technologies, and 3) Lack of prioritising energy efficiency in decision making (Satish & Nagesha, 2017).

Sathaye and Gadgil (1992) suggested methods to recognise barriers, establish programs for overcoming them as well as to assess and modify these programs regularly to enhance the outcome. Various programs like standards, labels, financial incentives, rebates and technology, etc. used for this purpose were observed and evaluated (Sathaye & Gadgil, 1992; Satish & Nagesha, 2017).

Painuly and Reddy (1996) recognised six important barriers to dealing with barriers in electricity conservation, namely: 1) Technical (lack of accessibility, dependability and knowledge of efficient technology), 2) Institutional (lack of right technical input, financial support and appropriate programmes), 3) Financial (lack of clear financial implications), 4) Managerial (lack of adequate training, management techniques, accountability), 5) Pricing (lack of rational pricing of energy sources), and 6) Information (lack of reliable, suitable information, information diffusion problems).

According to Weber (1997), there are several typologies of barriers relative to circumstances, however, based on the review carried out by the author, four typologies of barriers to energy efficiency were proposed: 1) Institutional, 2) Market, 3) Organisational, and 4) Behavioural.

A very interesting perspective on barriers to energy efficiency from the neoclassical theory can be found in the paper published by (Berkhout, Muskens, & Velthuijsen, 2000). The authors found that barriers initiate and promote RE, thus inhibiting energy efficiency. RE is caused by the following barriers to energy efficiency from a market related perspective: 1) Substitution effect (as the cost of energy decreases, the consumer uses more), 2) Income effect (lower energy prices result in more disposable income, thus more spending on energy use) and 3) Macro-economic effect.

A report by Brown, Chandler, Lapsa and Sovacool (2011) aimed to identify and describe the barriers obstructing the commercialization and implementation of climate change mitigation technologies. Six barrier categories, twenty barrier types and approximately fifty detailed barriers were identified and discussed for various energy efficient technologies. Figure displays a breakdown of the barriers researched by. Brown, Chandler, Lapsa, and Sovacool (2011) concluded that economy wide market failure is the most critical barrier caused by the absence of a price on Green House Gas (GHG) emissions.

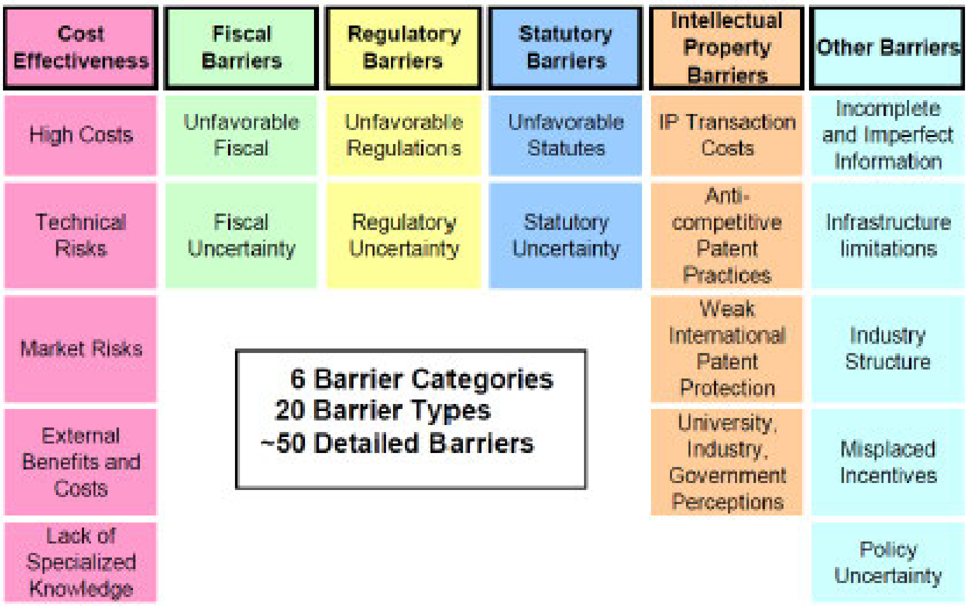

Figure 1: Typology of Barriers to the Implementation of Energy Efficient Technology (Brown, Chandler, Lapsa, & Sovacool, 2011)

Sorrell, Mallett and Nye (2011) carried out an investigation on barriers to energy efficiency in various industries and identified that it is difficult to draw general conclusions from the studies carried out. The authors established that the two most important barriers are hidden costs and difficulties in access to capital which are the most common explanation for the energy efficiency gap. Sorrell, Mallett and Nye (2011) concluded that multiple barriers coexist, reinforcing one another, and contextual factors have a great impact, for example the operation of capital markets and governments' contributions to promoting energy efficiency.

Using an actor-oriented approach, (Sudhakara Reddy, 2013) attempted to study barriers and drivers that influence investments in energy efficiency. To do this, Sudhakara Reddy (2013 developed a taxonomy broadly classifying barriers to energy efficiency into three typologies, i.e. 1) Micro-barriers (obstacles that are unique to the particular project), 2) Meso-barriers (barriers that are common to a wide variety of projects that can be overcome with effective organizational design, human resource management and time management), and 3) Macro-barriers (barriers that are not project or organization specific and cannot be altered by changing the project or organizational design). Sudhakara Reddy (2013) discusses specific examples of drivers related to the barriers identified and discussed in the article. The following six examples of specific drivers are discussed: 1) Awareness, 2) Decrease in technology prices, 3) Increase in energy prices, 4) Technology appeal, 5) Non-energy benefits, and 6) Environmental regulations.

Satish and Nagesha (2017) carried out a case study to identify barriers and drivers to energy efficiency in the residential and commercial sectors and identified the following barriers, 1) Awareness and information barriers, 2) Behavioural and lifestyle barriers, 3) Economic and financial barriers, 4) Market barriers, and 5) Technical barriers. The following potential drivers for energy efficiency were also identified: 1) Financial benefits, 2) High level of awareness, 3) Decrease in the cost of energy efficient technologies, 4) Increase in energy prices, 5) Technology appeal and 6) Non-energy benefits. With a primary focus on commercial buildings, Satish and Nagesha (2017) found that the economic and financial barriers as well as lack of awareness and information barriers were the main obstacles to energy efficiency, thus indicating that people are not aware of energy efficiency and environmental concerns. The highest-ranking driver for energy efficiency in commercial buildings is a high level of awareness among people.

Table provides a summary of all articles reviewed to identify barriers and drivers prevalent from a global perspective. The table highlights the barriers and drivers to energy efficiency found in a specific sector and provides comment on the limitations and overall aim of the research. The heterogeneity of barriers is a result of the context in which they occur, therefore a variety of articles from various sectors have been reviewed to identify the different barriers and the reason for their occurrence. There are two primary reasons for the implementation of energy efficient measures in commercial buildings, the first reason being related to the neoclassical theory of economics and the other is the implementation of energy efficient technology to reduce the use of electrical energy as a means to inhibit climate change and reduce a building's carbon footprint. The typology under which the barriers occur are not mentioned in the table as not all articles presented a typology of the barriers.

It is evident from the reviewed articles that barriers are unique to the environment in which they occur, however, there are certain barriers which are prevalent across the board (though these may not be ranked in the same way). Not all articles focused on drivers to energy efficiency, however it was mentioned or proposed as a measure to reduce the barriers or eliminate the barriers. Most articles share similar drivers such as creating an awareness, the implementation of energy efficient policies and government incentives.

Table 1: A Summary of Reviewed Articles Identifying Barriers and Drivers to Energy Efficiency

SECTOR	BARRIERS IDENTIFIED	DRIVERS IDENTIFIED	COMMENTS	REF
Residential and commercial sector	1. Awareness and information barrier 2. Behavioural and lifestyle barrier 3. Economic and financial barrier 4. Market related barrier 5. Technical barrier	1. Financial benefits 2. High level of awareness 3. Decrease in the cost of energy efficient technologies 4. Increase in energy prices 5. Technology Appeal 6. Non-energy benefits	This research is carried out for the residential and commercial sectors in India. The ranking of barriers in the residential and commercial sectors were the same. The ranking of drivers in the residential and commercial sectors are also the same. The researcher/s did not provide categories to which these barriers belong.	Satish & Nagesha, (2017)
Trade, commerce, and service	1. Rented space 2. Investment costs 3. Other investment	1. Energy audit 2. Energy Service Companies (ESCOs) and	The aim of this research is to contribute to research field by decomposing the	Olsthoorn, Schleich, and Hirzel,

	costs 4. Lack of capital 5. EEM is uneconomical 6. Too time consuming 7. Technology and price uncertainty 8. Postponed due to re-organization 9. System already efficient 10. Internal disagreement 11. Lack of internal know-how 12. Risk to quality 13. Risk to production	Energy Performance Contracting (EPC) 3. Complimentary measures (e.g., eco-labelling) 4. Acquire, assimilate, and exploit energy related knowledge. 5. Energy policies	heterogeneity of organizations and empirically investigated barriers to adoption of energy efficiency measures (EEMs). The research focuses on barriers to the implementation of four primary EEMs (lighting, insulation, heating replacement and heating operation) found in the trade, commerce, and service sectors. The barriers are ranked from the most relevant barrier to the least relevant barrier.	2017
Micro-, small-, medium-sized Enterprises	1. High investment costs 2. Investment priorities 3. Uneconomical 4. Lack of capital 5. System already efficient 6. Too time consuming 7. Rented space 8. Technological and energy 9. Lack of know-how 10. Technical risk for production 11. Product quality risk 12. Internal disagreement	1. Energy policies 2. Fiscal support 3. Landlord and tenant incentives 4. Awareness creation	The aim of this paper is to determine the propensity of Micro-, small-, and medium-sized enterprises (MSMEs) to adopt energy efficiency measures. however, part of the study identifies the barriers related to MSMEs.	Cunha and Neves (2020)
Manufacturing sector	1. Expensive energy efficient technology 2. Complex finance mechanisms 3. Lack of internal energy efficient procedures 4. Limited public awareness 5. Lack of time 6. Technology not fully matured 7. External skills are costly 8. Lack of internal capital 9. Lack of public finance 10. No energy manager 11. Outdated policies 12. Numerous hidden costs 13. Slow rate of ROI 14. No prescribed energy efficient regulations	1. Adoption of energy efficient standards, e.g., ISO 50001. 2. Effort required to improve the quality of the energy efficiency profile. 3. Fiscal measures to be used to enhance energy efficiency. 4. Where energy is cheap, pricing models need to be developed to encourage companies to adopt energy efficient technology. 5. Companies to be made aware of benefits of energy efficiency. 6. Subsidies for smaller companies that cannot outlay capital investment.	The research establishes the energy efficiency gap in manufacturing companies, thereafter, analysing the barriers to energy efficiency measures. the barriers presented in this table are ranked from the most critical to the least according to the investigation carried out by [29]. The drivers are potential drivers based on the barriers identified from the investigation.	Singh and Lalk (2016)

	15. Lack of internal skills 16. Suppliers do not advise on energy efficient options 17. Heterogeneity 18. Production uptime risk 19. Lack of knowledge on specifications when purchasing energy efficient technology 20. Poor success rate among other companies 21. Energy efficiency benefits are not quantifiable to bottom line 22. Lack of managerial awareness 23. Do not break what is already working behaviour 24. No scope for energy improvement 25. Energy is already cheap			
Building sector	1. Socio-economic status of building users 2. Lack of funds, high capital costs, financial risks 3. Limited payback expectations/Investment horizons 4. Building stock characteristics 5. Split incentives 6. Complex/inadequate regulatory procedures 7. Lack of relevant legislation 8. Training and skills professionals 9. Lack of interest and undervaluing energy efficiency 10. Lack of trusted information and experience.	1. Policies to reduce the impact of barriers 2. Simplification of administrative procedures. 3. A clear vision for energy efficiency needs to be established from upper management. 4. Occupant awareness of the benefits of energy efficiency.	This paper evaluates the primary barriers under the following 3 main categories, 1) Economic, 2) Institutional and 3) Behavioural. The barriers are evaluated the building and transport sectors in a few countries within the United Kingdom (UK). It is to be noted that only the barriers in the building sector are highlighted in this table. The drivers to energy efficiency are merely proposals to reduce the negative impact of the barriers.	Bagaini, Colelli, Croci, and Molteni (2020)
Private Sector	1. Financial restraints 2. Level of detail around opportunities 3. Limited human resource capacity/time 4. Other/property management 5. Knowledge 6. Behaviour 7. Lack of understanding of the Private Sector Energy Efficiency report	1. Lower payback periods through further incentives 2. Accessible funding and subsidies 3. Ensured continuation and longevity of incentive programmes. 4. Client-specific cost alternatives. 5. Human resource and energy management	Among other objectives, one of the primary objectives of this research was to identify company and participant level perceptions of barriers to energy efficiency in the South African private sector.	Parker (2016)

	8. Lack of government support and resources 9. Report misalignment 10. Limited programme resources 11. Reliable technology	support. 6. Knowledge and skills training 7. Stable energy platforms with standardised, efficiency, readily available information for anything energy related 8. More stringent technological standards.		
Building sector	1. Low income 2. High investment costs 3. Occupants resistance 4. Low consumer appeal 5. High upfront costs 6. Lack of municipal support 7. Misconception on retrofitting technologies 8. Occupants disruption 9. Building orientation 10. Immature market 11. Lack of education 12. Lack of knowledge 13. Capital risk 14. Poor quality installation 15. Lack of technical expertise 16. Lack of cost-effective components 17. Building owners lifestyle choices. 18. Lack of capacity 19. Lack of information 20. Lack of incentive for investors 21. Lack of personal incentive 22. Lack of energy professionals 23. Lack of monitoring 24. Status quo 25. Lack of energy efficient materials and components	1. Government incentives 2. Policies and legislations 3. Awareness and knowledge	Barriers to energy efficiency retrofits have been identified in the study by [32]. This study has generalised the scope of a building in South Africa within the Gauteng region, therefore the barriers are not specific to a particular type of building, for example a school or a hospital.	Oguntona, Maseko, Aigbavboa, and Thwala (2019)

3. TAXONOMY OF BARRIERS TO ENERGY EFFICIENCY

To successfully develop and propose a theoretical framework for the taxonomy of potential barriers and drivers to energy efficiency in a commercial building within a state-owned building in South Africa, all stakeholders and role players must be identified and how energy is used must be established from a technical perspective. A framework of potential barriers and related drivers to energy efficiency in commercial building is proposed in this section.

The flow diagram in figure 2 highlights factors that affect the implementation of energy efficient measures and the associated outcomes. The factors retarding the implementation of energy efficient technology or any energy efficient measure, starts with the owner, stakeholders or decision makers, energy efficient system designers and those responsible for installation and/or implementation. After the implementation of energy efficient technologies or strategies, factors related to the user/s (such as building occupants/staff, public, ownership) and operation and maintenance of the energy efficient measures often hinder the outcome of the energy efficient measures. Considering the growing implementation of energy efficient technology in commercial buildings in South Africa, this article focuses on the barriers that hinder the outcome of energy efficient measures already implemented, circled in red in figure 2. However, in some situations, the decisions made before the implementation also affect the outcome of the implemented energy efficient measure, for example a poor understanding of all costs involved at the onset of the project will result in an energy efficiency gap, as the expected ROI will be reduced by the hidden costs. This also indicates that multiple barriers can co-exist, thus reducing the potential outcome of energy efficient measures.

With a primary focus on the impacts of energy efficiency barriers related to energy efficient technology in commercial buildings, the following typologies of potential barriers seemed to be the most prevalent:

- Economic and financial
- Technological
- Awareness and information
- Organisational and management
- Statutory/regulatory
- Behavioural and lifestyle

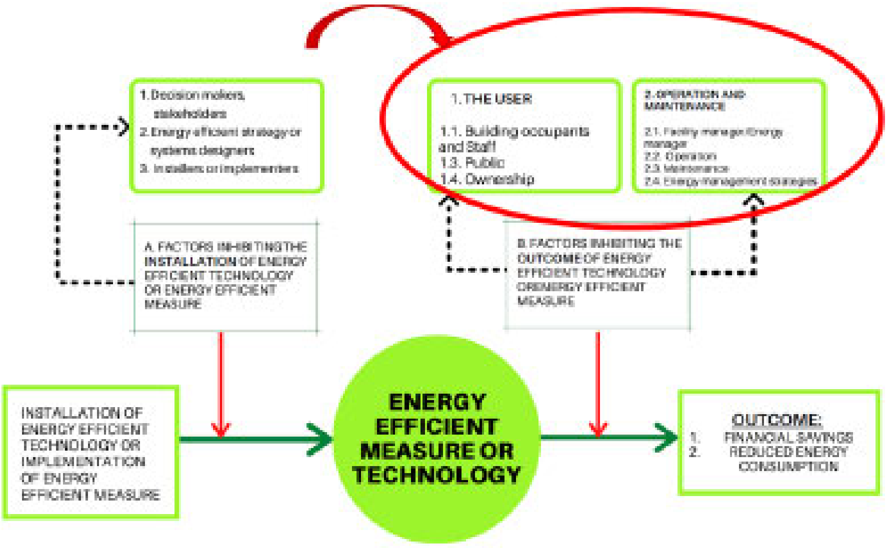

Figure 2: Flow Diagram Highlighting factors affecting the Implementation of Energy Efficiency and the Associated Outcome

A taxonomy for specific barriers for the above barrier typologies is presented in Table based on the articles reviewed and flow diagram in figure 2.

Table 2: Proposed Taxonomy of Barriers in Commercial Buildings

CATEGORY	BARRIERS	DEFINITION
Economic Or Financial Barriers	Hidden costs	Costs that were not foreseen at the onset of the project.
	Implementation risk	The costs of implementation not calculated properly due to lack of technology being implemented.
	Poor ROI	There is a low ROI due to unforeseen costs.
	Payback time	Intervention not profitable due to low returns over a long period of time.
	Maintenance costs	High maintenance costs as the technology are relatively new.
Organisational And Management Barriers	Lack of staff	Not enough staff to implement the energy efficient measures
	Resistance to change	Staff and occupants are not willing to embrace the change.
	Communication	Poor communication between management and staff or among staff themselves.
	Organisational system	Organisational goals, routines, structure, and other factors hinder the implementation of energy efficient measures
	Commitment and awareness	Manager lacks commitment and is not aware of the benefits of energy efficiency or the purpose of energy efficient measures.
	Vision, skills, and expertise	Manager lacks the vision to implement energy efficient measures, the skill and expertise to enhance energy efficient measures.
	Operating procedures not adhered to	Management does not adhere to the operating guidelines provided by the manufacturer. This again comes down to lack of knowledge and information barriers.
	No maintenance carried out on energy efficient technology	Maintenance may not be carried out due to exorbitant costs and possibly lack of expertise because the technology is relatively new.
	No energy efficient strategy in place to implement and enhance energy efficiency measures	Management does not have an energy efficiency strategy to improve and enhance energy consumption as well as reduce costs.
Awareness And Information Barriers	Lack awareness about the benefits of energy efficiency	Staff, building occupants and public lack awareness about the benefits of energy efficiency and the philosophy behind the energy efficient measures implemented.
	Lack of information, inadequate information, and misinformation.	Inadequate information provided to stakeholders/decision makers resulting in reduced outcomes. This could also relate to information given to the occupants and public. Results in lack of knowledge about energy efficiency.
Technological Barriers	Status quo of system incompatible with energy efficient measure	The current system in the building does not allow for the implementation of energy efficient technology.

	Spare parts and components for energy efficient technology	Being relatively new technology in South Africa, spare parts and components for maintenance are rather expensive or not easily accessible.
Statutory/Regulatory Barriers	Legal requirements	Lack of legal requirements from national governmental level with respect to the real needs of commercial buildings related to sustainability.
	Bureaucracy	Excessive, complicated and unnecessary administrative government procedures to get incentives for implemented energy efficient measures.
	Fiscal incentives	No economic incentives, and procedures to obtain incentives are tedious and time consuming.
Behavioural And Lifestyle Barriers	Skill	Lack of skilled staff to manage, operate and maintain energy efficient measures and technology.
	Incorrect behaviour	Occupants are often negligent, indifferent to the outcomes of the energy efficient measures or the technology implemented. In some cases, this behaviour extends to wastefulness.
	Ownership	Due to the lack of ownership, occupants tend to take advantage of various utilities increasing their consumption.
	Not involved	A lack of involvement among building occupants and staff do not give them an opportunity to be part of the energy efficiency measures being implemented.
	Awareness	A lack of awareness, among building occupants, about the energy efficient measures in place leads to ignorance regarding criticalities and issues that need support from the building occupants.

4. RECOMMENDATION AND ANALYSIS OF DRIVERS FOR ENERGY EFFICIENCY

Relevant information must be presented to consumers and stakeholders to provide them with a better understanding of measures that enhance or promote energy efficient measures (Sudhakara Reddy, 2013). Drivers of energy efficiency are dependent on the prevailing circumstances and the environment. It is not often that for every barrier a driver can be identified, and in some cases drivers can become barriers. The drivers proposed will be for energy efficient measures that have already been implemented and are discussed from the perspective of enhancing the outcome from the energy efficient measure as well as eliminating prevailing barriers.

From the reviewed articles, the following are potential driver categories to energy efficiency are discussed:

a) Awareness, information, and Knowledge

It is important for government, energy efficient technology manufacturers and other campaigns promoting sustainable living, to create an awareness about the benefits of energy efficiency within society. From a commercial building perspective, the building management team should ensure that building occupants are well aware of energy efficiency initiatives and measures, what these entail, what are the outcomes, and what is the role that the occupants can play to promote energy efficiency.

The creation of awareness around energy efficiency results in building occupants being more receptive to information about energy efficiency measures and technology thereby providing them with knowledge regarding energy efficiency and sustainability. Information is also imperative for building owners and tenants to understand the role of energy efficiency measures and technology and the mutualistic benefit that it can have.

A high level of awareness is not enough to promote energy efficiency and attract investors. From an investment perspective, the implementation and operation of the energy efficient measure or technology must be lucrative.

b) Economic and financial

The implementation of energy efficient measures and technology reduces consumption of electrical energy, thus reducing the price of utility bills, but this often leads to the RE. To eliminate the RE, landlords can ask for a higher rental, however, this must be in relation to the cost of operating and maintaining energy efficient systems. Often, the cost of operating the system and maintaining it is rather high due to the technology being relatively new in the market.

Another means to encourage building owners to implement energy efficient technology is for the ESCOs to formulate a shared savings contract with the owner. The monetary value of the shared savings can be shared between the landlord and the ESCO depending on the shares agreed upon at the onset of the project.

The price of energy efficient technology and components need to decrease, resulting in the technology penetrating the market faster.

c) Technological

The improvement of energy efficient technology's environmental impact and energy consumption performance is critical to promote sustainability and buy-in from investors and building stakeholders. An example of improving technology is the level of "smartness" or "intelligence" that is associated with the technology, along with the aesthetic appeal of the technology, resulting in consumers and investors purchasing such technology.

Energy efficient technology being implemented must be easy to install and require minimal resources to lower the cost of installation and reduce errors whilst installing. Along with easy installation process, the equipment should have improved functionality and reliability.

The use of control systems and Building Information Management (BIM) can improve energy efficiency by minimising or switching off electrical components when not in use.

d) Management and Behavioural

Occupant behaviour is a critical barrier that is difficult to control, therefore the drivers for occupant behaviour is something that needs to be worked through the building management and those in control of the facility. Creating an awareness in energy efficiency as well as providing informative workshops on energy efficiency to increase occupant knowledge on energy efficiency, can improve occupant behaviour regarding the use of energy and reducing energy consumption when not in use.

The building management team can initiate a culture to promote energy efficiency among occupants to get building occupants to be involved with various energy efficiency strategies and tasks, which gives them a role to play and a sense of responsibility.

Occupants with a high level of passion and enthusiasm are required to drive and promote energy efficiency measures in commercial buildings. This will encourage others to contribute to the energy efficiency measures in their own way.

Energy management is essential to promote energy efficient behaviour among the building occupants. Energy managers can make use of visual information, email notifications and regular meetings to create an awareness among building occupants and create a culture that promotes energy efficiency. The energy manager should conduct periodic energy audits to monitor the building's energy consumption so that he/she can detect anomalies in the consumption.

e) Legal, Regulatory and Policies

Legal or regulatory control measures can promote energy efficiency in terms of building codes, sustainability labels for buildings and company policies which require staff to implement energy efficient behaviour within the work environment. The Department of Environmental Affairs should consider the amount of carbon emissions due to energy consumption and initiate regulations to encourage building users to minimise electrical energy consumption or use renewable energy technology. Government should also consider retrofitting state-owned buildings with energy efficient technology and promote energy efficiency, this will set an example for other government departments to follow suite.

5. CONCLUSIONS

With energy efficient technology and measures already implemented, barriers and drivers to energy efficiency have been qualitatively analysed from various research articles to draw conclusive evidence of the potential barriers and drivers in a commercial building.

Barriers to energy efficiency are unique to the circumstances under which they occur. In an occupied commercial building with energy efficient technology, for instance, it has been identified that there are six categories of barriers. Specific barriers occur within each category resulting in an outcome that hinders energy efficiency such as the rebound effect or the energy efficiency gap. The analysis revealed that barriers to energy efficiency are a result of economic factors, social factors, technological factors, and regulatory factors that co-exist to hinder the positive outcome from energy efficient measures.

Drivers to energy efficiency are prevalent around particular circumstances, in some cases reducing barriers to energy efficiency, promoting energy efficiency, or enhancing energy efficient measures. Drivers to energy efficiency can be found in the following categories, 1) Awareness, information, and knowledge; 2) Economic and financial; 3) Technological; 4) Behavioural; 5) Legal, regulatory and policies. It was also found that in some cases, efforts that have been made to create drivers to energy efficiency through policies and regulatory requirements have in fact become barriers to energy efficiency.

Government plays a big role in implementing drivers to energy efficiency by developing regulations and legal requirements for building owners and occupants. National government should ensure that all system and component specifications include energy efficient measures and encourage designers and stakeholders to promote energy efficiency.

This article successfully identifies potential barriers and drivers to energy efficiency in commercial buildings through a qualitative review of previous research on barriers and drivers to energy efficiency.

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CHAPTER 6: IMPLEMENTING ENERGY CONSERVATION MEASURES: A CASE STUDY ON RETROFITTING A COMMERCIAL BUILDING IN SOUTH AFRICA

This chapter provides detailed results, discussions and conclusion after implementing cost effective energy conservation measures in a commercial building in South Africa. The study shows that the energy conservation measures implemented have a low capital cost and a high return due to the prevalent barriers in such building.

The outcome from this research has been published in International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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IMPLEMENTING ENERGY CONSERVATION MEASURES: A CASE STUDY ON RETROFITTING A COMMERCIAL BUILDING IN SOUTH AFRICA

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ABSTRACT

Energy efficiency is driven by global climate change concerns and the need to reduce carbon emissions and increase sustainability of the built environment. Currently, South Africa is facing an electricity crisis and alternate solutions to energy consumption of state-owned buildings should be explored. This study aimed to conduct a quantitative analysis of the energy savings after retrofitting and implementing ECMs in a state-owned commercial building to determine the electrical energy savings, the effectiveness of energy efficient retrofits, and the correlated cost implications. It was found that ECM retrofits saved an average of 398 431 kWh of electrical energy per month amounting to a 67 % improvement in energy efficiency. The total financial savings achieved was R1 902 301.26 per year. Barriers to energy efficiency were identified. Lack of funding, resources and knowledge were the most prevalent barriers.

***KEYWORDS:** Energy Efficiency, Climate change, Energy conservation measures, Barriers*

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Original Article

1. INTRODUCTION

Energy efficiency, a popular subject matter, is driven by global climate change concerns and the need to reduce carbon emissions and increase sustainability of the built environment. Numerous research articles highlight the benefits of implementing energy efficiency and sustainability in buildings, including implementation of regulations that encourage new buildings to be designed and built with sustainability energy conservation in mind [1], [2], [3], [4], [5], [6].

Since 2008, the main electricity service provider in South Africa, Eskom, has had challenges with the various electricity plants, causing periodic load shedding and an increase in electricity rates. Considering the utility service provider challenges and high capital costs for new installations, retrofitting is a suitable cost-effective means of improving energy efficiency. Retrofitting involves upgrading an old building with advanced materials, techniques, and technology to discover a particular modified outcome. In this context 'retrofit' refers to technological implementations that result in energy conservation measures (ECMs) intended to improve the energy efficiency of a building [7]. The objective of energy retrofits is to improve a building's energy efficiency by implementing a variety of energy conservation opportunities (ECOs) and energy efficient measures at an economical cost [7]. Retrofit techniques use ECMs that are technological upgrades for electric lighting, building envelope, equipment, heating, ventilation, and air conditioning (HVAC), hot water generation and other electrical building services. [8] carried out energy audit techniques (EAT) to identify ECOs and found that retrofitting a building with ECOs can save up to 49.3 % of the building's annual energy consumption [8]. A study carried out by [9] showed that the three most commonly installed energy efficient technologies in high performance buildings (HPBs) are daylighting, high efficiency HVAC systems and improved building envelope. The effectiveness of these technologies depend on the specific building characteristics such as location, size, orientation of the building, operation building envelope, electrical heating, cooling and ventilation system properties [9]. One of the conclusions from a study carried out by [10] was that the integrated effects of the ECMs does not equate to the sum of individual ECMs, therefore the total effectiveness of ECMs depends on the interaction between all ECMs [10]. [11] evaluated and simulated various ECMs divided into three categories: major investment ECMs, minor investment ECMs and zero investment ECMs. The results of their study showed that the ECMs implemented in the building considered can save up to 41.87% of energy without compromising occupant thermal comfort [11]. A study by [12] estimated the cost effectiveness of energy efficiency measures in new commercial buildings and the results showed that conventional energy efficiency technologies can reduce energy consumption in by 20 % to 30 % and up to over 40 % for some building types and locations [12]. The above studies show that retrofits are a cost-effective way of implementing ECMs to improve the energy efficiency of old buildings, thus making them more sustainable and effective.

1.1 Aim and Objectives

This study aimed to conduct a quantitative analysis of the energy savings after retrofitting of ECMs implemented in a state-owned commercial building to determine the electrical energy savings, the effectiveness of energy efficient retrofits, and the correlated cost implications. An energy audit was carried out to determine the most suitable, cost-effective ECM retrofits to install in the building. Utility bills were used to establish the baseline data. The implementation of ECMs was monitored for a period of one year after which the results were analysed. ECO's and barriers to energy efficiency observed through this experiment are highlighted. The electrical consumption obtained from the ECMs was compared with the baseline data to evaluate the improvements in energy consumption of the building and assess the level of energy efficient improvements. An estimated cost savings was calculated associated with the implementation of energy efficient measures. The results from this experimental study can be used to implement cost effective and efficient retrofits in buildings and to improve on energy efficient retrofits as well as be used to develop policies and national government standard specifications.

2. DESCRIPTION OF THE FACILITY

The building in this case study was established in 1971 in Durban and provides jurisdictional services to the public. An image of the facility is shown in Figure 1. The building has 12 floors, consisting of a basement (2 252.31m^2), ground floor (14 524.54m^2), 1st floor (12540.54m^2), 2nd floor (4 097.15m^2) and then the 3rd floor to the 12th floor have the same internal building layout with each floor spanning an area of 1 874.10m^2. The total area of the building is 52 155.54m^2.

Figure 1: Experimental Commercial Building

Being an old building there were no control systems in place to monitor and adjust the use of electricity consuming systems, neither were there any ECMs implemented. In 2008 the building was fitted with two gear-driven centrifugal water-cooled chillers and three cooling towers. The chiller consists of a compressor (with motor power rating of 380 volts AC, 50 Hz and 3 phase), oil pump motor (with power rating 380 volts AC, 50 Hz and 3 phase), the oil tank heater (with power rating of 115 volts AC, 50 Hz and 3 phase) and a control circuit (with power rating 115 volts AC, 50 Hz and 3 phase). The refrigerant system is filled with 340 kg of R-134A refrigerant, with a working pressure range of 15.2 bars on the low and high sides.

Figure 2: Chilled Water and Condenser Water Piping

Figure 3: Centrifugal Water-Cooled Chiller

The facility had 58 W T12 fluorescent lamps with magnetic ballasts, and the lighting system had a manual switch which depended on a person to switch it on and off. The use of magnetic ballasts uses the sudden spike in the physical disruption of current in an inductive circuit to produce a high voltage that is required for starting up, thereafter it relies on a reactive voltage drop to reduce the voltage applied across the lamp [13]. Prior to the installation of the control automatic on/off switch and the variable frequency drives, the system operated throughout the day and over the weekends. It is to be noted that the facility has only one municipal electricity meter.

3. METHODOLOGY, MATERIALS, AND EQUIPMENT

The measures taken to carry out this experimental case study is discussed in this section, concurrently describing the materials and equipment installed and used.

3.1 Energy Audit

A walk-through energy audit was conducted to identify suitable ECMs that could be implemented in the building. The aim of the audit was to identify suitable technical retrofits that could be easily implemented to achieve reduction of electricity consumption in hours of operation, air conditioning loads, lighting loads and off-peak loads, as well as to define the energy boundaries. Energy boundaries in this case refers to the sources of energy and the extent of energy consumption.

The energy audit consisted of analysing energy consumption and relevant costs using utility bills. Other documentation like drawings and technical specifications were also reviewed to understand the electrical systems in the building. The facility manager was interviewed to gather technical and administrative information like electricity usage patterns, the operation of the facility and energy management, and to obtain technical drawings and archived reports/studies. The reason for a detailed analysis was to determine annual trends and fluctuations in the energy consumption with the associated costs and to draft a list of possible energy saving actions to be taken.

The brief walk-through energy audit involved a qualitative investigation of the electromechanical systems and the building shell. A checklist was used to identify key energy efficiency opportunities, for example the type of lighting used, the use of day/night sensors, types of motors or drives used, etc.

Upon completion of the site investigation and the data analysis, the potential ECMs were identified. The proposed ECMs were relatively simple and inexpensive. Thereafter a proposal of suitable housekeeping and minimum capital investment energy saving options as well as other potential ECMs identified with associated cost estimates were presented to the client.

3.2 Establishing Baseline Data

According to [14], a facility-level approach is suitable to use in order to determine baseline data. Utility bills were obtained from the local municipality and analysed, thereafter the energy consumption was recorded in Excel and a graph was generated. The average annual consumption was calculated over a period of four years, from 2008 to 2011 and then five years from 2015 to 2020. The challenges faced were lack of accurate data collection resulting from poor document management, therefore not all utility bills were easily obtainable. All light fittings were counted, and all electrical equipment was taken into consideration. The power rating was then multiplied according to the number of hours used in a day and then multiplied by number of working days per year to obtain the total consumption per year. This calculation was compared with the utility bills to identify discrepancies and to consider electricity consuming equipment that should be operating under normal conditions. Upon establishing the baseline data, the energy use intensity (EUI) of the facility for the baseline year was calculated using equation (1). The EUI measures the facility's level of energy efficiency after the implementation of the retrofits and is often expressed as a function of the building size by identifying the annual energy usage per square area of the building.

$$\text{Energy use intensity} = \frac{\text{Total annual energy consumption}}{\text{Total unit of output}} \quad (1)$$

3.3 Installation of ECM Retrofits

For the purposes of this study, the system was retrofitted with VFDs for the pumps and a control system was installed to control the operating times of the system as well as the operation of the chilled water pumps and an on/off switch. The remote-control panel is situated outside the HVAC plant room, the main control panel is situated within the basement HVAC plant room, and the remote controlled 24 volts AC relays are located within each of the following switch gear panels – chillers, pumps, and fans.

The centrifugal water-cooled chiller was programmed to follow the following sequence of operation:

- Between Monday to Friday the data log timer was set to switch off the HVAC system at 18H00, this time could be set according to the building operating times.
- The data log timer was programmed to switch on the HVAC system at 06H00 between Monday and Friday, this time could be set according to the buildings operating times.

- The HVAC system was set to be switched off over the weekends.
- A remote-control panel installed in the control room, was able to manually switch on and off the HVAC system. A time delay off-timer automatically switched off the HVAC system after being manually switched on.
- The chilled water pumps were programmed to start 3 min before the condenser water pumps which was programmed to start 3 min before the chiller started up. Therefore, there was a 6 min delay before the chiller started up. The chiller was programmed to stop 6 min before the pumps stopped operating.

a) Automatic On/Off Control Switch

An Orbis data log time switch is a digital time switch that was installed to automatically switch on and off the HVAC system from 06H00 to 18H00. Figure 4 shows the data logger used. The connection scheme for this automatic on/off control switch is shown in Figure 5. Figure 6 shows a graphical representation of the response during weekday operating hours. Figure 14 shows the Orbis data log timer switch installed in the control panel, identified by the DL-T set data logger. The Orbis data log timer was connected to an electric circuit operating from the main power supply via a relay. The functionality of this data logger allowed for easy programming. It can contain up to 40 programs, is easy to activate and deactivate and can be used temporarily or permanently.

Figure 4: Orbis Data Log Timer

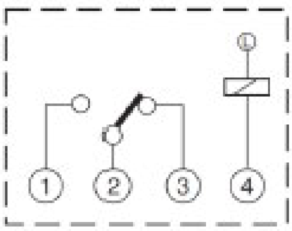

Figure 5: Connection Scheme - 1 Change over Switch [23]

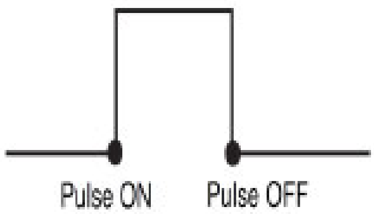

Figure 6: Step input from 06H00 to 18H00

b) Time Delay Switches and Multifunction Timer

An ACDC multifunction multi range (MFMR) timer was installed to allow the HVAC system to run for a maximum of 4 h before shutting down the system. When the system detects a power supply, the relay energises lighting up the light emitting diode (LED) and the timer starts. After the time period programmed, for example *t*, has elapsed, the relay de-energises and the LED goes off. See Figure 7 and

Figure 8 for the output relay signal indicating that the relay is energised for time *t* even though the supply power is switched on for a longer period. Figure 9 shows the switch installed on site to switch off the HVAC system when manually switched on.

Figure 7: ACD Multifunction Multi Range Timer

Figure 8: Output of the MFMR timer

Figure 9: Switch for Manual Operation of the HVAC System

An ACDC delay-on timer was installed in the wiring circuit for the chiller system in Figure 14 and shown in Figure 10. With this timer the applied voltage triggers the time delay relay, and when the delay begins, the power LED will be on. When the set delay time expires, the relay will energise, and the relay LED will turn on as shown by Figure 11. The timer will then remain in power until the system is turned off. With reference to Figure 14, the delay on the timer is connected in parallel with the MFMR timer and the automatic on/off control switch. The delay on the timer will allow the chiller system to start up 6 min after the power has been switched on manually or automatically by the Orbis data log timer switch.

Figure 10: ACDC Delay on Timer

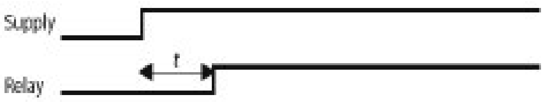

Figure 11: Output of the Delay On Timer

An ACDC delay-off timer was installed in the wiring circuit for the chiller system to switch off the pumps 6 min after the chillers were powered off. With this timer, the supply voltage energises the relays lighting up the power LED and the relay LED. When there is no voltage supply, the Inst. contact relay de-energises and the delay time starts. When the time delay period, *t*, expires, the time delay de-energises and the relay LED goes off, Figure 13. With reference to Figure 14, one can see that the delay-off timer was connected in parallel to the automatic on/off switch, the MFMR timer and the delay-on timer. The delay-off timer was connected to the circuit to delay shutting off the pumps by 6 min after the system was switched off. Figure 12 shows the delay-off timer and Figure 13 shows the output signal of the relay.

Figure 12: ACDC Delay off Timer

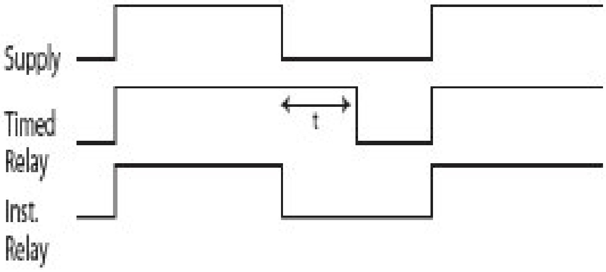

Figure 13: Output of the Delay off Timer

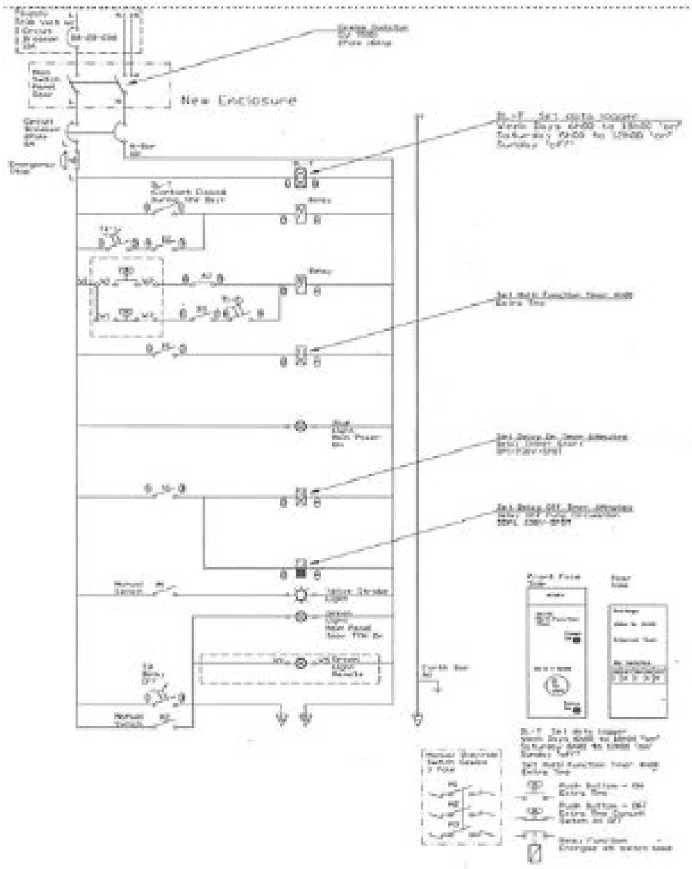

Figure 14: Control Panel Wiring diagram

c) Variable Frequency Drives – VFDs

WEG CFW700, WEG CFM500 and the INVT Goodrive 200 Inverter variable frequency drives were installed to regulate the 3x cooling tower fan speeds according to the system requirements (Figure 15, Figure 16 and Figure 17). VFDs were only installed in the cooling towers (Figure 11). CWF700 is a high performing VFD that controls the speed and torque of three-phase AC induction motors. The incoming AC current with a fixed frequency is converted into a voltage with variable amplitude and frequency, resulting in a voltage conversion.

Figure 15: WEG CFW700 variable frequency drive

Figure 16: WEG CFM500 variable frequency drive

Figure 17: INVT Goodrive 200 Inverter variable frequency drive

The VFDs were connected to the cooling tower control wiring to regulate the fan speed. The integrated proportional-integral capabilities of VFDs to automatically adjust fan speeds as conditions vary, while maintaining the required flow, eliminates the need for an external set-point controller [15]. Therefore, by reducing the speed of the motor, the VFD can reduce the energy consumed by the fan. With reference to Figure 17, the power of the fan was directly proportional to the cube of its speed, therefore small speed reductions resulted in large power reductions [15]. VFDs act as soft starters, increasing/decreasing speed at a programmable rate, thus reducing the large amounts of energy consumed when starting the fan [15]. These capabilities of VFDs ultimately optimize the fan speed to maintain the temperature of the condenser water leaving the cooling tower.

d) Lighting System Retrofits

All the T12 fluorescent lights were replaced with T8 36 W fluorescent lights with electronic ballasts and telescopic lamp holders. All outdoor lighting was replaced with 16 W lamps. Motion sensors were installed within the facility, except for the spaces that did not allow for motion sensors due to their function. Day-night switches were installed in the passages and for the outside lights of the facility. Figure 18 shows the type of day-night switch installed.

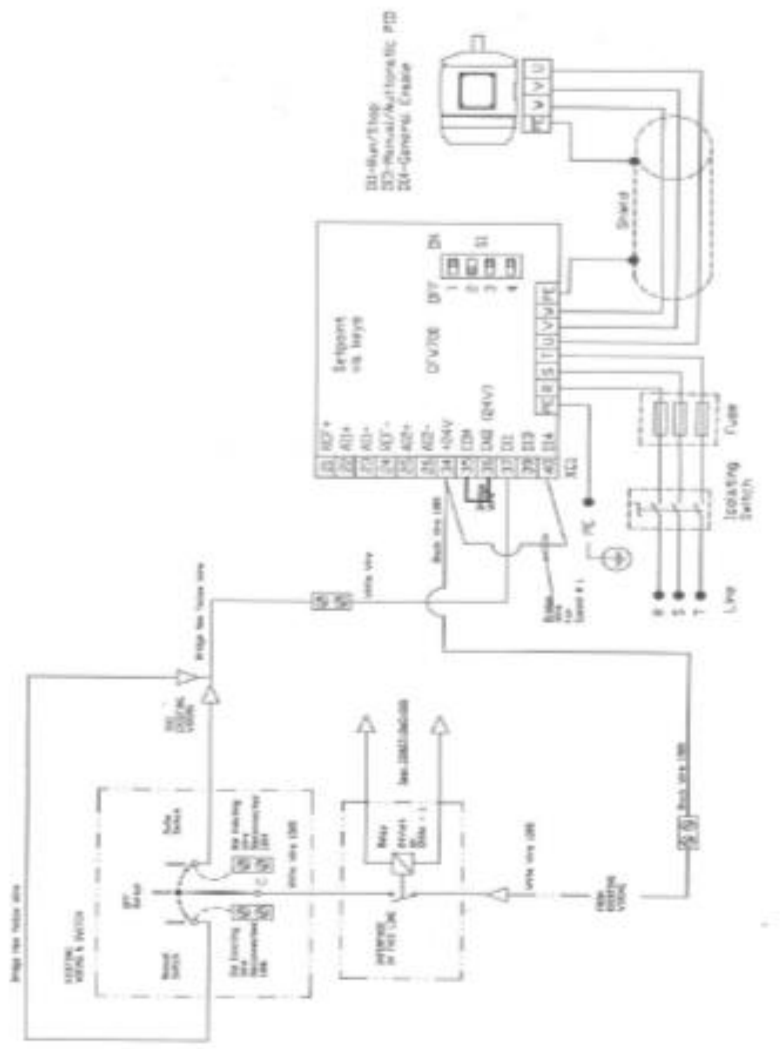

Figure 18: Circuit wiring diagram showing the VFD connection

Figure 19: Day-Night Switch Installed in the Facility

3.4 Data collection

Power Watch™ is software used to monitor and record utilities. PowerWatch™ software was used to monitor the energy consumption of the HVAC system in real time from a remote location. Data was collected before and after the ECMs were implemented to compare the energy consumption and the effect the retrofits had on the total energy consumption of the retrofits. Smart meters were installed to monitor and record the amount of electricity consumed by the lighting and the HVAC systems. The smart meters supplied input data to PowerWatch™ which recorded and monitored the data.

4. RESULTS AND DISCUSSION

This section provides the energy consumption results obtained from the installation of the ECM retrofits and compares these to the results prior to the installation of the retrofits to determine the impact that the ECM retrofits had on improving the energy efficiency of the facility.

4.1 Energy Audit

On completion of the walk-through audit, it was concluded that the facility was not energy efficient and the following ECMs could be implemented to improve the efficiency of the building:

- All light bulbs to be replaced with more energy efficient lighting.
- Day/night switches to be installed for all outdoor lighting and lighting in the communal passages.
- Occupancy sensors to be fitted in the remaining spaces.
- The HVAC to be fitted with an automatic on/off switch.
- VSDs to be installed for the cooling tower fans.

The utility bills were analysed from which the baseline data was established, and electricity cost for energy consumption was determined. This report only discusses the implementation of the HVAC retrofits.

It is essential to compare expenditure on the ECM and the savings over the lifetime of the ECM equipment because most ECMs have a delayed reward, i.e. expenses come at the beginning of a project while the benefits come later [16]. For an energy efficient retrofit to be financially feasible the capital investment needs to be lower than the sum of savings obtained by the reduction in operating costs over the lifespan of the ECM [16].

4.2 Baseline Data

A four-year period was used to establish the baseline data for the lighting interventions from January 2008 to December 2011 (refer to Table 1). ISO 50001 defines energy baseline as *"quantitative reference providing a basis for comparison of energy performance"* [17]. The baseline data was established taking into consideration the lights that were not working and other electricity consuming equipment that should be operable under normal circumstances.

Table 1: Monthly Electricity Consumption in kWh for a Period of four-Years from 2008 to 2011

	Year 2008	Year 2009	Year 2010	Year 2011	Baseline 1
	kWh	kWh	kWh	kWh	kWh
January	368000	420000	387875	436000	589612,9
February	495642,9	480000	492000	476000	495642,9
March	532357,1	316000	472000	476000	532357,1
April	472000	364000	464666,7	496000	496000
May	432000	353821,1	355333,3	360000	440000
June	344000	312195,1	380000	324000	380000
July	352000	322601,6	252000	292000	368000
August	408000	291382,1	352000	252000	408000
September	340000	355555,6	328000	284000	376000
October	450876,4	355555,6	356000	236000	450876,4
November	409887,6	288888,9	420000	256000	420000

December	355236	468125	380000	192000	468125

Figure 20 graphical representation of the facilities energy consumption from 2008 to 2011. The light blue graph, BASELINE, indicates the datum line against which the ECM was measured. Noteworthy is that in 2010 energy efficient lighting, occupancy sensors and day/night switches were installed in the facility resulting in a decrease in energy consumption by the end of 2011. The other varying trend lines could be as a result of other factors such as load shedding, downtime of electro-mechanical equipment and social dynamics (for example protests or labour strikes).

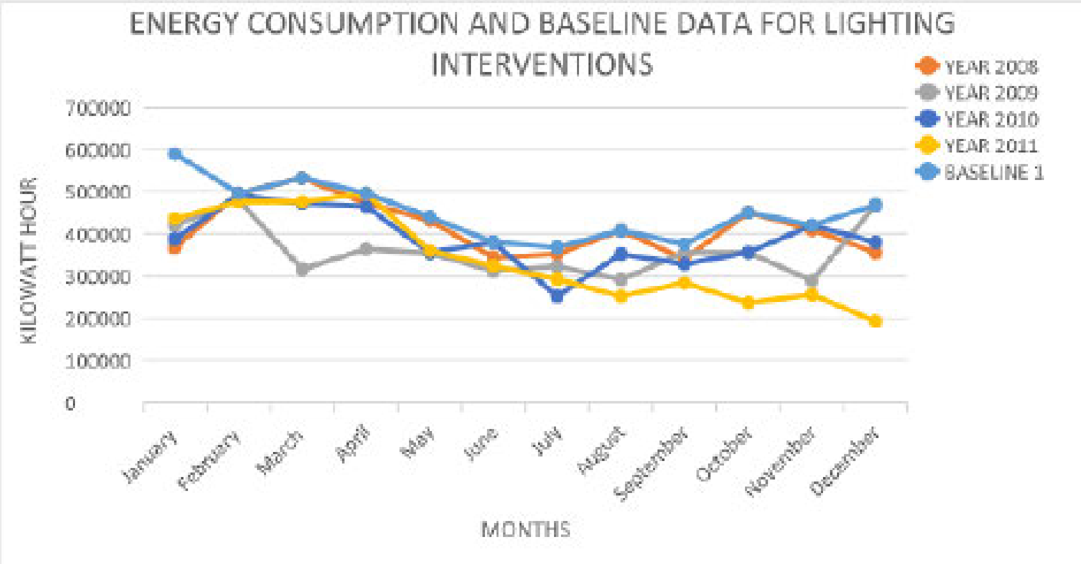

Figure 20: Monthly Electricity Consumption in kWh and Baseline Data for Lighting Interventions from 2008 to 2011

A 5-year period was used to establish the baseline data starting in 2015 and ending in 2020. Table 2 provides a breakdown of the energy consumed by the facility from April 2015 to November 2020.

Table 2: Monthly Electricity Consumption in kWh for a Period of five-Years

	Year 2015	Year 2016	Year 2017	Year 2018	Year 2019	Year 2020	Baseline 2
	kWh	kWh	kWh	kWh	kWh	kWh	kWh
January		354 000,00	354000	420000	417000	387000	479357,9
February		399 000,00	318000	432000	294000	348000	487357,9
March		532357,1	375000	348000	393000	303000	497357,9
April	489000	314 689,70	441000	492000	324000	321726,3	498357,9
May	390000	255 000,00	423000	351000	393000	268105,3	467357,9
June	435000	279 000,00	351000	378000	279000	259168,4	410357,9
July	393000	228 000,00	351000	381000	306000	255000	418011
August	444230	258000	384290,3	435000	210000	240000	452357,9
September	380769,2	312000	242709,7	306000	270000	243000	431357,9
October	330000	255000	270000	348000	270000	318000	425357,9
November	297000	276000	300000	282000	354000	303000	539357,9

December	312000	363000	351000	336000	309000		422357,9

Figure 21 shows the overall energy consumption. The green graph, BASELINE, indicates the datum line against which the ECM was measured. The HVAC ECMs were installed in 2019 and by 2020 dramatic reductions in energy consumption could be seen. The other varying trend lines could be as a result of other factors such as load shedding, downtime of electro-mechanical equipment and social dynamics (for example protests or labour strikes).

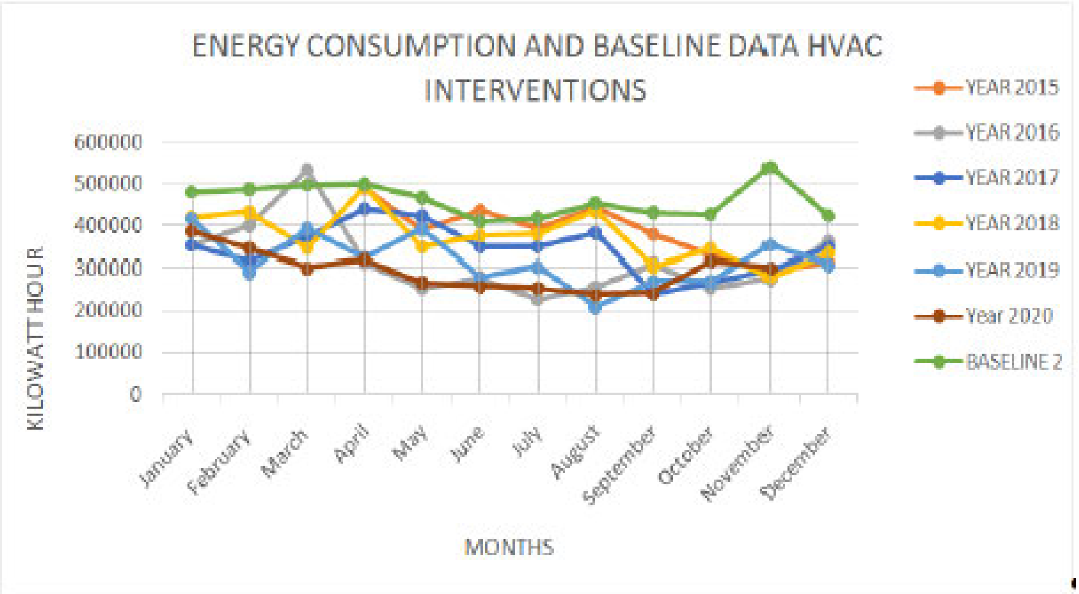

Figure 21: Monthly Electricity Consumption in kWh and Baseline Data

4.3 Data Analysis

Figure 22 indicates the energy consumption in kWh for the five-month period between 17 August 2015 to 17 December 2015. This graph was generated by PowerWatch™ software and indicates the total building energy consumption after the implementation of lighting interventions. With reference to Figure 22, before the 18 Oct period, the troughs of the graph hovered around 400 kWh each day, indicating that the minimum energy consumed in the day was 400 kWh even when there was no activity in the building. The maximum peak was 603.876 kWh whereas the average peak consumption was between 550 kWh and 600 kWh. After the 18 Oct, it is clear that the graph troughs were reduced to below 150 kWh, with the minimum trough around 117.83 kWh. The overall trend of the electricity consumption can be viewed by the grey graph below the x-axis of the blue graph in Figure 22.

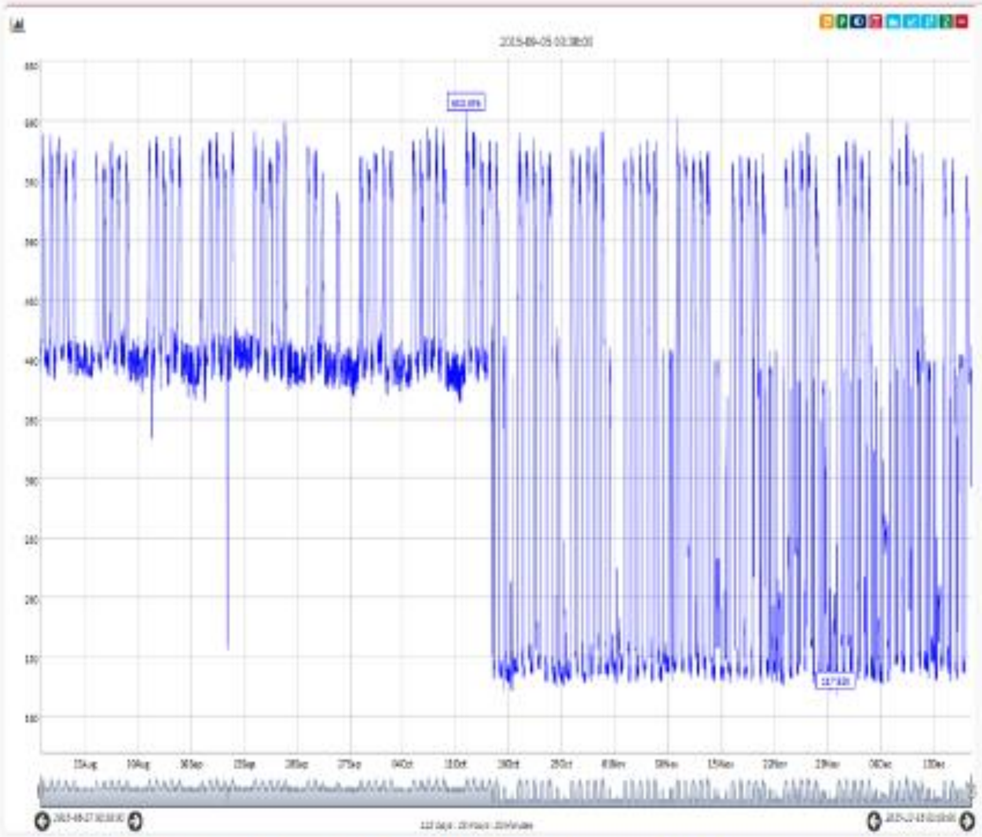

Figure 22: Energy Consumption (in kWh) from 17 August 2015 to 17 December 2015

Figure 23 shows the overall load profile of electricity consumption after the implementation of the lighting retrofits in 2015. There was a distinct reduction in the building's total electricity consumption after 2015.

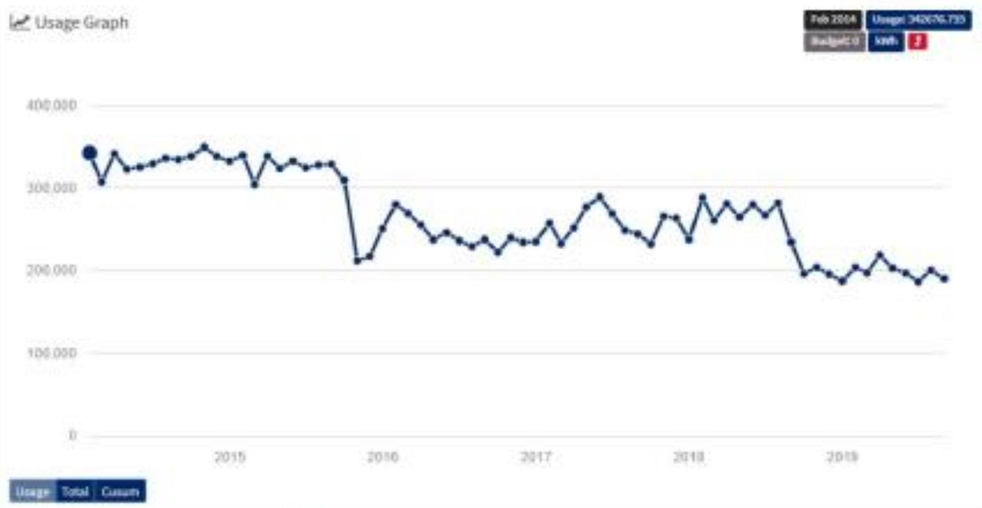

Figure 23: Total Electricity Load Profile over a Period of Five Years after the Implementation of the Lighting Interventions

Figure 24 shows the total electricity consumption 2 months prior and 2 months post the implementation of the HVAC interventions corresponding to the period between 05 July 2019 and the 05 December 2019. Before the interventions were installed, the peaks reached around 250 kWh and the troughs were slightly above 50 kWh. After the implementation of the HVAC energy efficient interventions, the peaks reached a maximum peak of 530.714 kWh and the troughs reached a minimum of 0.546 kWh. The inconsistent spikes in the peaks after the interventions is a result of equipment and system testing and monitoring.

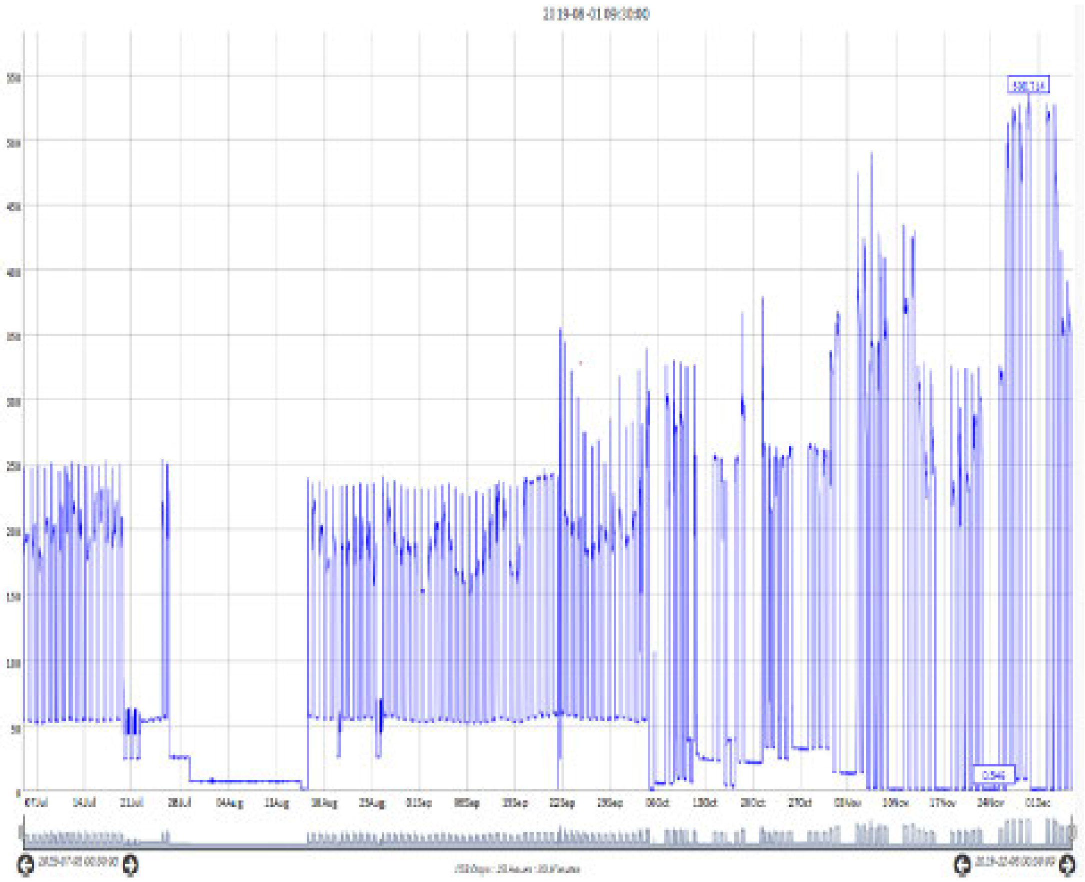

Figure 24: Total Energy Consumption after HVAC Interventions in 2019

Figure 25, generated by PowerWatch™, shows the total building energy consumption in kWh before the installation of ECM, for the period from 01 January 2019 to 28 January 2019. According to PowerWatch™, the total energy consumed was 137 808 kWh. At the beginning of January, the troughs of the graph were around 40 kWh then towards the end of the month the troughs dipped just below 40 kWh. The peaks of the graph are not very consistent during this period, with the highest peak reaching approximately 540 kWh. At this stage energy was still being consumed every day of the week including public holidays and weekends, as indicated by the graph.

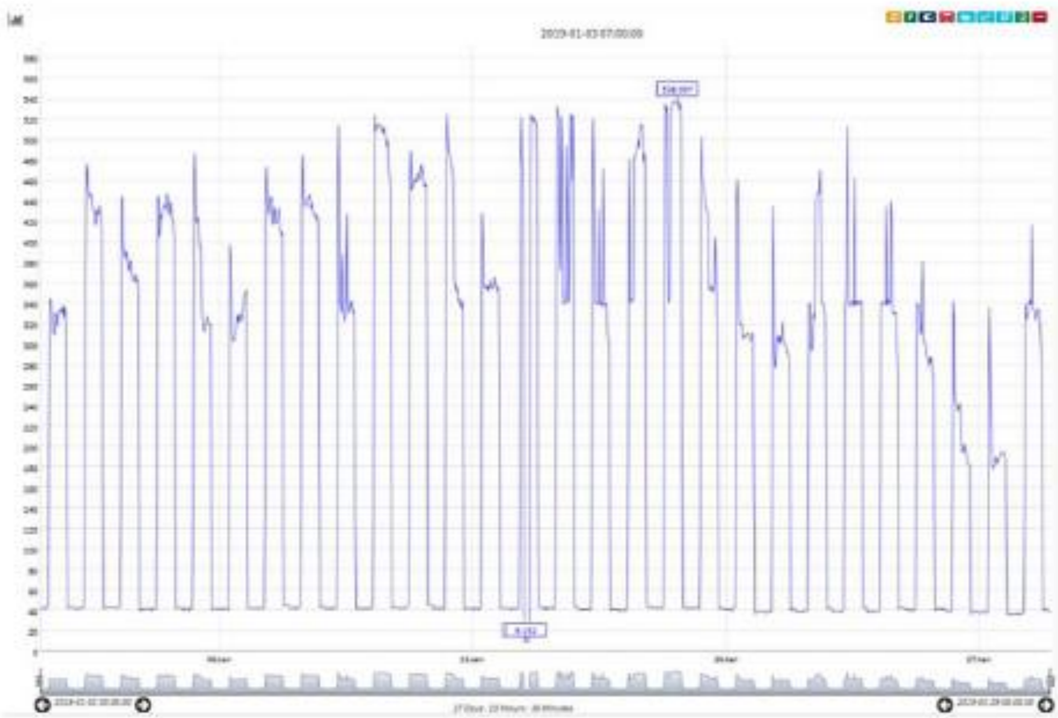

Figure 25: Energy Consumption (in kWh) from 01 January 2019 to 28 January 2019

Figure 26 highlights the various discrepancies in energy consumption for the period between June 2019 and July 2019, which is prior to the HVAC energy efficient interventions. The blue blocks indicate that the HVAC system was not switched off during off-peak periods by the main BMS systems used for the lighting. The green block shows that the lighting control system was working as designed. The HVAC pumps were not yet connected to the existing BMS, causing the night load as highlighted by the orange block in Figure 26.

Figure 27 shows the total energy consumption between 01 January 2020 and 28 January 2020 after the HVAC ECMs had been implemented. According to PowerWatch™, the total energy consumed for this period was 100 286 kWh. The maximum amount of energy consumed according to Figure 27 as slightly under 560 kWh. The troughs of Figure 27 show that 0 kWh of energy was consumed during off-peak periods. The low energy consumption during the beginning of January, where many building occupants are still on annual leave, show that the system regulated itself according to the load required. The 4th and 5th of January was a weekend, and the graph shows that there was no energy consumption. However, from the 6th of January the graph peaks are relatively constant at between 520 kWh and 540 kWh for the rest of the 5 working days, thereafter the graph drops to 0 kWh over the weekend, which shows that the ECM implemented shut the system off completely and the automatic on/off switch functioned according to its programming.

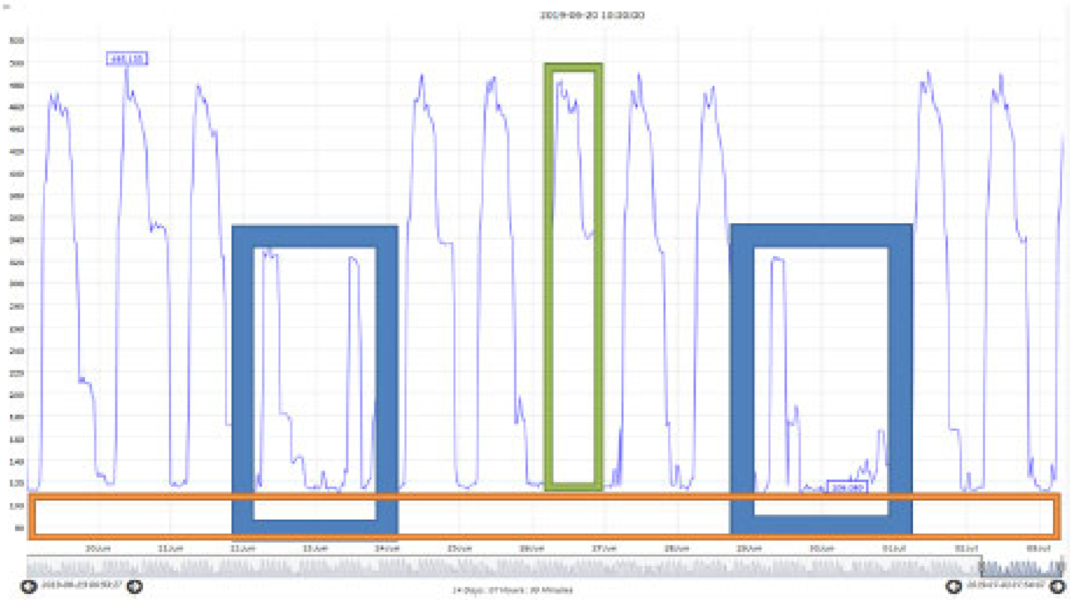

Figure 26: Highlighting the Anomalies in the Graph

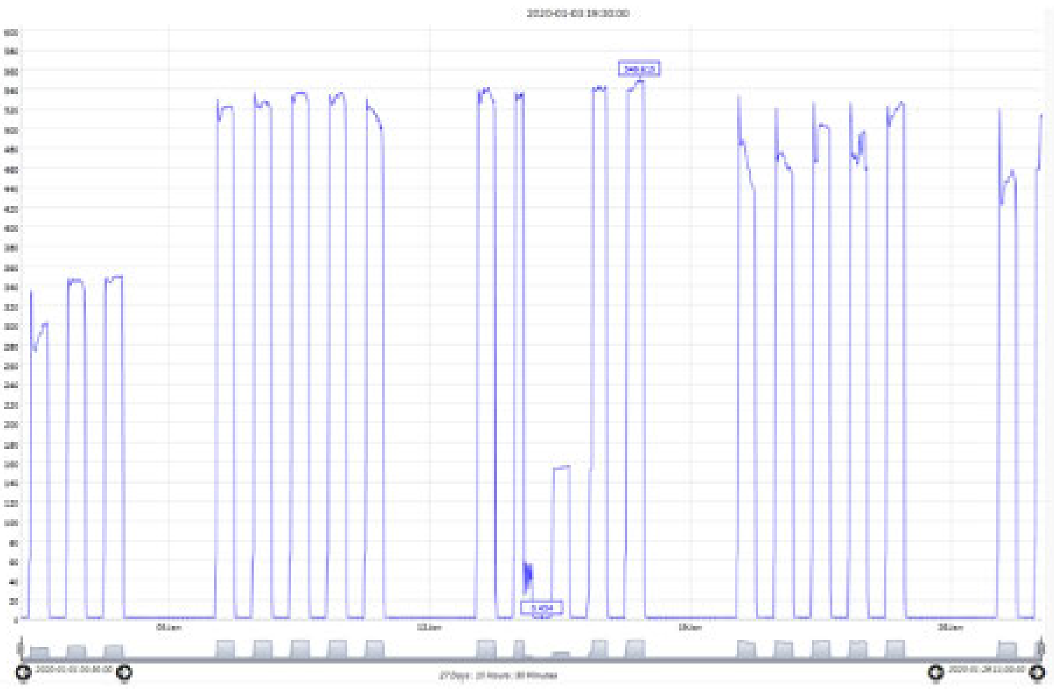

Figure 27: Energy Consumption (in kWh) from 01 January 2020 to 28 January 2020

Using the baseline data for January from Table 2, the energy consumption for that month was calculated to be 589 000 kWh for 31 days. Using the PowerWatch™ software, the total energy consumption for January 2020 was 190 569 kWh, therefore the realised saving was 67.65 %. This energy savings percentage is rather high when compared to other research results; this can be attributed to the fact that the facility's electricity consuming systems were operational daily, which means that the facility management team were not regularly switching off the lights and the HVAC systems according to the usage of the building. Implementing automatic on/off switches cuts down the total electricity usage by 50

%, with the other 17 % representing a reduction due to the control system that regulates the HVAC system according to the use and the lighting occupancy sensors. Another aspect to consider is that the facility had been poorly managed – systems were not serviced on time and they were often left to operate continuously. This had a direct impact on the energy efficiency of the building previously, resulting in high energy consumption.

The EUI of the facility was calculated for the month of January using equation (1). The EUI before ECM retrofits had been implemented indicate that 5.9 kWh of energy was consumed per square area of the facility. This is unreasonably high.

$$\text{EUI before ECM retrofits} = \frac{\text{Total annual energy consumption}}{\text{Total unit of output}} = \frac{589\ 000}{100000} = 5.9\ kWh/m^2$$

The EUI after ECM retrofits had been implemented indicate that 1.9 kWh of energy was consumed per square area of the facility.

$$\text{EUI before ECM retrofits} = \frac{\text{Total annual energy consumption}}{\text{Total unit of output}} = \frac{190569}{100000} = 1.9\ kWh/m^2$$

The energy efficient interventions dramatically reduced the building's energy consumption, thus improving the overall energy efficiency of the building.

4.4 Financial Savings Achieved

The lighting and HVAC interventions reduced the building's total energy consumption, therefore the amount paid for electricity was reduced.

4.4.1 Lighting Savings

The apparent total lighting load was calculated to be 277.395 kVA, therefore the actual lighting load in kW is calculated using equation (2) and assuming the power factor = 1 to be 277.395 kW.

$$Actual\ power\ (kW) = Apparent\ power\ (kVA) \times Power\ Factor \tag{2}$$

A total of an average of 10 hours of electricity consumption was saved per day, therefore the lighting system saved 2 773.95kW per day. Using an electricity tariff of R1.2 per kWh (2011 utility rate), the facility saved R3 328.74 per day and in a year a saving of R1 214 990.10 was achieved.

4.4.2 HVAC Savings

The total estimated HVAC electricity savings per month was 6 095.96 kWh over the weekends and 568 kWh during the week. Therefore, the total electricity savings for the month was (6 095.96 x 4) + (568 x 20) = 35 743.84 kWh. Using an electricity tariff of R1.0624 per kWh (2018 utility rate), the total saving per month was R57 275.93 and R687 311.16 over a year. The total savings achieved per month after the installation of both the HVAC and the lighting energy efficient interventions was R1 902 301.26 per year.

4.5 Prevalent Barriers to Energy Efficiency

It was noted during the energy audit that the facility management team had not provided sufficient support or awareness when it came to managing the total energy consumption of the building, therefore the facility was consuming more energy that it should have. The staff and building occupants did not actively participate in energy conservation activities. The maintenance team were not regularly servicing the electricity consuming system to ensure that all components operated optimally. These factors play an important role in ensuring that the building operation is energy efficient. The lack of enthusiasm and commitment from the facility management team was a major barrier during the operation and maintenance of the ECM retrofits.

Lack of funds, another barrier to energy efficiency, prevented the installation of more advanced energy efficient systems, therefore simple and cost-effective retrofits were implemented. These retrofits have improved the energy efficiency of the facility, however, with the availability of funds other energy efficient measures could be sought such as the option of installing photovoltaic (PV) panels or other sources of renewable energy. South Africa, being a Third World country, lacks the resources to implement advanced energy efficient technology and control systems in public facilities because there are only a few services providers who can implement the advanced technological energy efficient measures and are the only ones that can service and maintain those systems. Knowing that, these companies then charge exorbitant prices for service and maintenance causing the ECM to become less financially feasible. Also, the parts for such advanced systems are not easily available in the country (in some cases they need to be imported) and are more costly.

5. CONCLUSIONS

This case study quantified the implementation of ECM and the improvement of energy efficiency of the facility. ECM retrofits saved an average of 398 431 kWh of electrical energy per month amounting to a 67 % improvement in energy efficiency. The ECM retrofits improved the EUI of the building to 1.9 kWh/m^2. The total financial savings achieved was R1 902 301.26 per year. Barriers to energy efficiency were identified during the planning stages and during the operation of the building. Some of the barriers were related to lack of information and enthusiasm to participate in improving the energy efficiency of the building, lack of resources, and the lack of funds to improve energy efficiency.

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CHAPTER 7: CONCLUSION AND FUTURE RECOMMENDATIONS

This chapter provides concluding comments related to achievement of the aim and objectives of this research.

7.1. Conclusion

The aim of this research was to evaluate energy efficiency in a public building and identify the drivers and barriers to energy efficiency to improve energy management practices and ensure that electrical and mechanical systems are optimally energy efficient. The aim was achieved by accomplishing the following objectives: firstly, identify energy losses in public facilities and studying energy consumption patterns in the facility used in the experimental case study; secondly, identify suitable energy efficiency measures that can be implemented in public facilities without affecting service delivery; thirdly, review barriers and drivers to energy efficiency to gather information on these factors and how they affect energy efficiency, thus finding suitable solutions to enhance the impact of energy efficiency; and fourthly, evaluate the energy conservation retrofits implemented to determine the effectiveness of cost-effective energy conservation measures and the long-term financial feasibility of it. The following paragraphs provide the concluding comments for each chapter.

Chapter 2 reviewed factors affecting energy efficiency in commercial buildings, providing a holistic approach to energy efficiency in commercial buildings. This chapter concludes that energy consumption can be improved and reduced by using energy efficient technology, implementing energy efficient design techniques for systems design, and incorporating energy conservation measures where possible. Energy management is another important factor that affects energy consumption. Effective energy management of a commercial building involves operation and maintenance of electro-mechanical equipment, and continuously improving energy consumption by monitoring the building’s energy consumption. Government regulations, building policies and other regulatory documents also play an important role in encouraging the implementation of energy efficiency as well as monitoring and improving energy consumption.

One of the major energy consuming systems in a commercial building is the HVAC system. Chapter 3 reviewed how energy efficiency can be improved in HVAC systems. The conclusion is that energy efficiency in HVAC systems must be implemented from the design stage, where the designer selects energy efficient technology and utilises it in such a manner that energy efficiency of the system is optimised.

Lighting and MELs consume the second highest amount of electrical energy in a commercial building. Chapter 4 reviewed energy efficiency of lighting systems and MELS. The energy efficiency of lighting systems and MELs can be improved by the use of energy efficient light bulbs, occupancy sensors, day/night switches and other novel technology. The review concluded that smart control systems are becoming more popular within commercial buildings and intelligent lighting systems are gaining popularity in research.

Energy efficiency is ultimately affected by factors that enhance the impact of energy efficiency or by factors that retard energy efficiency outcome. Chapter 5 reviewed the drivers and barriers to energy efficiency prevalent in public commercial buildings. It is concluded that drivers and barriers can be found in the various stages of a building's life cycle and in some cases, decisions made at the inception stages affect the energy consumption during the operation of the facility. Drivers and barriers during the operation stage was the focus and it was found that energy management, government and social dynamics play an important role in optimising energy efficiency of a commercial building.

Chapter 6, the experimental chapter, concludes that ECM retrofits saved an average of 398 431 kWh of electrical energy per month amounting to a 67 % improvement in energy efficiency. The ECM retrofits reduced the EUI of the building to 1.9 kWh/m^2. The ECM implemented were relatively cost effective and produced a dramatic improvement in the consumption of electrical energy. The most prominent barrier identified was the lack of energy management of the facility which stemmed from poor resources and knowledge pool. Building occupants were not encouraged to get involved with energy conservation practices, resulting in behavioural barriers to energy efficiency.

7.2. Research contributions

This dissertation explored energy efficient practices and technology implemented in commercial buildings. The following research contributions have been made:

1. The major energy consumer in a commercial facility is the heating, ventilation and air conditioning system, followed by lighting and miscellaneous electrical loads. In the HVAC system, the compressor accounts for most of the energy in the system.
2. It was found that the major barrier to energy efficiency in the commercial building was human behaviour. Human behaviour influences the energy consumption patterns and it also affects the maintenance and servicing of energy intensive systems.

3. The greatest factor driving energy efficiency is financial savings that can be made. From my research, it is common for commercial building owners and investors to be focused on the financial savings that can be made from energy efficient measures.
4. The older commercial buildings in South Africa are highly energy intensive for 2 primary reasons among other contributing factors; 1. The design of the facility and 2. Poor facility management. The energy consumption of these commercial buildings can be improved by simply retrofitting the building with occupancy sensors, day night switches for outdoor lights, variable speed drives (VSD's) or variable frequency drives (VFD's) and the use of switches to switch on/off the HVAC system as part of a building management system (BMS) have shown that a commercial building can reduce its overall energy consumption. It was found that these retrofits are inexpensive to purchase and easy to install (and replace when necessary) yet these measures had a big impact on the amount of energy saved.

7.3. Future recommendations

To improve research results from energy efficiency in commercial buildings the following research topics should be considered:

1. Evaluating the energy efficiency of lighting systems using smart control systems or intelligent control systems.
2. Looking into various design techniques and strategies to improve the energy efficiency of HVAC systems by means of a smart control.

Investigate the effectiveness of using photovoltaic panels to run lighting and HVAC systems and how this reduces reliance on electricity from the grid.

APPENDIX A: EDITING CERTIFICATES

This appendix contains the editing certificates by a professional editor.

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I confirm that I have edited these chapters and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homoeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years and supervised many master's degree dissertations during that period.

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I confirm that I have edited this article and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homeopathy at Technikon Natal in 1999 (now the Durban University of Technology). During my 13 years as a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology I supervised numerous Master's degree dissertations.

Dr Richard Steele
09 August 2019
per email

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EDITING CERTIFICATE

Re: **Amina Ismail**
Journal article: **ENERGY OPTIMIZATION TECHNOLOGIES AND STRATEGIES FOR CENTRIFUGAL WATER-COOLED CHILLER SYSTEM IN COMMERCIAL BUILDINGS – A REVIEW**

I confirm that I have edited this article and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homoeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years and supervised many Master's degree dissertations during that period.

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EDITING CERTIFICATE

Re: **Amina Ismail**
Journal article: **ENERGY EFFICIENCY OPPORTUNITIES FOR LIGHTING SYSTEMS AND MISCELLANEOUS ELECTRICAL LOADS IN COMMERCIAL BUILDINGS – A REVIEW**

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Dr Richard Steele
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EDITING CERTIFICATE

Re: **Amina Ismail**
Journal article: **POTENTIAL BARRIERS AND DRIVERS TO ENERGY EFFICIENCY IN COMMERCIAL BUILDINGS**

I confirm that I have edited this article and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homoeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years and supervised many Master's degree dissertations during that period.

Dr Richard Steele
10 January 2020
per email

APPENDIX B: PUBLICATION ACCEPTANCE AND CERTIFICATES

This appendix contains acceptance letters and publication certificates for all publications in this thesis.

IAEME Publication

(Publishers of High Quality Peer Reviewed Refereed Scientific, Engineering & Technology, Medicine and Management International Journals)

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INTERNATIONAL JOURNAL OF MECHANICAL ENGINEERING & TECHNOLOGY (IJMET)

www.iaeme.com/ijmet/index.asp

Paper ID: IJMET_10_11_021 **Date: 06-December-2019**

Certificate of Publication

This is to certify that the research paper entitled "REVIEW OF FACTORS AFFECTING ENERGY EFFICIENCY IN COMMERCIAL BUILDINGS" authored by "Amina Ismail and Freddie Inambao" had been reviewed by the Editorial Board and published in "International Journal of Mechanical Engineering & Technology (IJMET), Volume 10, Issue 11, November 2019, pp. 232-244; ISSN Print: 0976-6340 and ISSN Online: 0976-6359; Journal Impact Factor (2019): 10.6879 Calculated by GISI (www.jifactor.com)".

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Chief Editor

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Paper Id: IJMPERDJUN202127

Date: 05/11/2021

Certificate of Publication

This is to certify that the research paper entitled " A REVIEW OF THE ENERGY FLOW THROUGH A CENTRIFUGAL WATER-COOLED CHILLERS AIR CONDITIONING SYSTEM " authored by " AMINA ISMAIL & FREDDIE INAMBAO " had been reviewed by the board and published in " INTERNATIONAL JOURNAL OF MECHANICAL AND PRODUCTION ENGINEERING RESEARCH AND DEVELOPMENT (IJMPERD); ISSN (ONLINE): 2249-8001; ISSN (PRINT): 2249-6890; IMPACT FACTOR(JCC) (2020): 9.6246; INDEX COPERNICUS VALUE (ICV) - (2016): 60.6; NAAS RATING: 3.11; VOL - 11, ISSUE - 3; EDITION: JUN-2021 "

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Certificate of Publication

This is to certify that the research paper entitled " AIR CONDITIONING SYSTEM DESIGN AND STRATEGIES FOR IMPROVING ENERGY EFFICIENCY - A REVIEW " authored by " AMINA ISMAIL & FREDDIE INAMBAO " had been reviewed by the board and published in " INTERNATIONAL JOURNAL OF MECHANICAL AND PRODUCTION ENGINEERING RESEARCH AND DEVELOPMENT (IJMPERD); ISSN (ONLINE): 2249-8001; ISSN (PRINT): 2249-6890; IMPACT FACTOR(JCC) (2020): 9.6246; INDEX COPERNICUS VALUE (ICV) - (2016): 60.6; NAAS RATING: 3.11; VOL - 11, ISSUE - 3; EDITION: JUN-2021 "

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Paper Id: IJMPERDAPR202110

Date: 03/08/2021

Certificate of Publication

*This is to certify that the research paper entitled " ENERGY EFFICIENCY OPPORTUNITIES FOR LIGHTING SYSTEMS AND MISCELLANEOUS ELECTRICAL LOADS IN COMMERCIAL BUILDINGS - A REVIEW " authored by " AMINA ISMAIL & *FREDDIE INAMBAO " had been reviewed by the board and published in " INTERNATIONAL JOURNAL OF MECHANICAL AND PRODUCTION ENGINEERING RESEARCH AND DEVELOPMENT (IJMPERD); ISSN (ONLINE): 2249-8001; ISSN (PRINT): 2249-6890; IMPACT FACTOR(JCC) (2020): 9.6246; INDEX COPERNICUS VALUE (ICV) - (2016): 60.6; NAAS RATING: 3.11; VOL - 11, ISSUE - 2; EDITION: APR - 2021 "*

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Paper Id: IJMPERDAPR202114

Date: 03/10/2021

Certificate of Publication

This is to certify that the research paper entitled " POTENTIAL BARRIERS AND DRIVERS TO ENERGY EFFICIENCY IN COMMERCIAL BUILDINGS " authored by " AMINA ISMAIL & FREDDIE L. INAMBAO " had been reviewed by the board and published in " INTERNATIONAL JOURNAL OF MECHANICAL AND PRODUCTION ENGINEERING RESEARCH AND DEVELOPMENT (IJMPERD) (IJMPERD); ISSN (ONLINE): 2249-8001; ISSN (PRINT): 2249-6890; IMPACT FACTOR(JCC) (2020): 9.6246; INDEX COPERNICUS VALUE (ICV) - (2016): 60.6; NAAS RATING: 3.11; VOL - 11, ISSUE - 2; EDITION: APR202114 "

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Paper Id: IJMPERDAUG202122

Date: 07/14/2021

Certificate of Publication

This is to certify that the research paper entitled " IMPLEMENTING ENERGY CONSERVATION MEASURES: A CASE STUDY ON RETROFITTING A COMMERCIAL BUILDING IN SOUTH AFRICA " authored by " AMINA ISMAIL & FREDDIE INAMBAO " had been reviewed by the board and published in " INTERNATIONAL JOURNAL OF MECHANICAL AND PRODUCTION ENGINEERING RESEARCH AND DEVELOPMENT (IJMPERD); ISSN (ONLINE): 2249-8001; ISSN (PRINT): 2249-6890; IMPACT FACTOR(JCC) (2020): 9.6246; INDEX COPERNICUS VALUE (ICV) - (2016): 60.6; NAAS RATING: 3.11; VOL - 11, ISSUE - 4; EDITION: AUG - 2021 "

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