INTEGRATED FRAMEWORK OF DISTRICT COOLING SYSTEM FOR COMMERCIAL BUILDINGS

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In the name of Allah, the Most Gracious and the Most Merciful

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ABSTRACT

Malaysia is situated in the latitude of -6.2 degree and longitude of 106.8 degree with average summer dry and wet bulb temperature of 32.2°C and 32.7°C, thus the use of air conditioning system is crucial to tackle the climate condition. Chilled water air conditioning system is widely used to supply cooling in large capacity for industrial process and commercial buildings. Nevertheless, air conditioner consumes more than 60% of electricity consumption in buildings. District cooling system (DCS) technology comprising of a central chiller plant provides advantage compared to local air conditioning system. DCS has higher efficiency, uses less power for the system to be operated, provides more usable space on buildings, and can be operated with minimum amount of manpower while handling the same amount of cooling load. Additionally, this system can be combined with thermal energy storage and provided lower operational cost. This study developed a new systematic framework and methodology based on pinch analysis for designing DCS integrated with ice thermal storage (ITS). The cooling system cascade analysis (COSCA) is constructed to determine the optimal size of the chiller and ITS. Economic and environmental analysis was performed by calculating the payback period and return on investment using Microsoft Excel Trend function. A sensitivity analysis test was performed by using the Microsoft Excel Table function. However, pinch analysis has a few limitations. To be more holistic, a mathematical model was developed by using the general algebraic modelling system (GAMS) for optimisation of DCS to determine the minimum total energy cost, optimal capacity of DCS equipment and renewable energy (RE) and electricity consumption in order to minimise the economic and environmental effects. The methodology has been demonstrated for commercial building, consisting of 5 main buildings (mall, hotel and cinema) with daily cooling demand requirement of 66,284 refrigerant tonne hour (RTH). The results from the case study revealed that the optimal capacity of the chiller was 3069 refrigerant tonne (RT), ice tank was rated 989 RT, and ice tank capacity was 9894 RTH which showed saving of annual electricity purchase cost to 9% compared to centrifugal system only (without ITS). The programming mathematical model in GAMS revealed that the DCS equipment which were electric chiller and absorption chiller with RE source has been selected to meet the cooling demand requirement with total cost leading up to 72% savings, equivalent to RM 4,846,540 as compared to the baseline. Based on these results, the system designed under the time of use or enhanced time of use tariff scheme was found to give no significant impact. Instead, the system with a RE source is selected. The sensitivity analysis revealed that the capital expenditure and operational expenditure were highly sensitive and affected the system feasibility. This framework could be used as evidence based policy making to determine financial incentive or subsidies to make DCS with RE competitive in the market. In addition, the framework is also beneficial for plant owners and engineers to choose the optimal capacity of DCS equipment, including RE, for efficient operation which accounts for supply and demand sides.

ABSTRAK

Malaysia terletak di latitud -6.2 darjah dan longitud 106.8 darjah dengan purata kering musim panas dan suhu bebuli basah 32.2 ° C dan 32.7 ° C, oleh itu penggunaan sistem penghawa dingin adalah penting untuk menangani keadaan iklim. Sistem penyaman udara air sejuk banyak digunakan untuk membekalkan sistem penyejukan dalam kapasiti besar untuk proses industri dan bangunan komersial. Walaupun begitu, penghawa dingin menggunakan lebih daripada 60% penggunaan elektrik dalam bangunan. Teknologi sistem lingkaran berpusat (DCS) memberikan kelebihan berbanding sistem penyaman udara biasa. DCS berkecekapan tinggi, kurang menggunakan kuasa untuk sistem yang dikendalikan, memberikan ruang yang lebih berguna dalam bangunan, dan dapat dikendalikan dengan jumlah tenaga minimum sambil menangani jumlah beban pendinginan yang sama. Selain itu, sistem ini dapat digabungkan dengan penyimpanan tenaga terma dan memberikan kos operasi yang rendah. Kajian ini membangunkan kerangka dan metodologi bersistematik baharu berdasarkan analisis pinch untuk merekabentuk DCS berintegrasi penyimpanan terma ais (ITS). Analisis penyejukan sistem lata (COSCA) dibina untuk menentukan kapasiti penyejuk dan penyimpanan haba ais (tangki ais) yang optimum. Analisis ekonomi dan persekitaran dilakukan dengan mengira tempoh pembayaran balik dan pulangan pelaburan menggunakan Microsoft Excel Trend. Ujian analisis kepekaan dilakukan menggunakan jadual Microsoft Excel. Namun, analisis pinch mempunyai beberapa batasan. Untuk lebih holistik, model matematik dibangunkan menggunakan sistem pemodelan algebra umum (GAMS) untuk pengoptimuman DCS bagi menentukan jumlah kos tenaga minimum, kapasiti optimum peralatan DCS dan tenaga boleh diperbaharui (RE) dan penggunaan elektrik untuk meminimumkan kesan ekonomi dan persekitaran. Metodologi yang dibangunkan adalah untuk bangunan komersial, terdiri dari 5 bangunan utama (pusat membeli-belah, hotel dan pawagam) dengan keperluan permintaan penyejukan harian sebanyak 66,284 tan jam bahan penyejuk (RTH). Hasil kajian kes menunjukkan bahawa kapasiti optimum penyejuk adalah 3069 tan bahan penyejuk (RT), tangki ais berkadar 989 RT, dan kapasiti tangki ais 9894 RTH menunjukkan penjimatan kos pembelian elektrik tahunan hingga 9% berbanding dengan sistem emparan sahaja (tanpa tangki ais). Model matematik pengaturcaraan dalam GAMS, mendedahkan bahawa peralatan DCS yang merupakan penyejuk elektrik dan penyejuk penyerapan dengan sumber RE dipilih untuk memenuhi keperluan permintaan penyejukan dengan jumlah kos yang menunjukkan penjimatan sehingga 72% yang bernilai RM 4,846,540 berbanding dengan garis dasar. Berdasarkan keputusan ini, sistem di rekabentuk bawah skim tarif masa penggunaan atau peningkatan masa pengunaan tiada perubahan ketara. Sebaliknya, sistem dengan sumber RE dipilih. Analisis kepekaan menunjukkan perbelanjaan modal dan perbelanjaan operasi adalah sangat sensitif dan mempengaruhi kebolehlaksanaan sistem. Rangka kerja ini boleh digunakan sebagai bukti untuk membuat polisi bagi menentukan insentif kewangan atau subsidi agar DCS dengan RE setanding di pasaran. Rangka kerja ini juga bermanfaat bagi pemilik kilang dan jurutera untuk memilih kapasiti peralatan DCS yang optimum, termasuk RE, untuk operasi yang cekap merangkumi bahagian penghasilan dan permintaan.

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LIST OF ABBREVIATIONS

CCHP	-	Combine cooling heating and power system
CHP	-	Combine heat and power
CHWR	-	Chilled water return
CHWS	-	Chilled water supply
CO2	-	Carbon dioxide
COP	-	Coefficient of performance
COSCA	-	Cooling System Cascade Analysis
CWS	-	Chilled water storage
DCP	-	District cooling plant
DCP	-	District cooling plant
DCS	-	District cooling system
DEG	-	Distributed Energy Generation
DoD	-	Depth of discharge
EC	-	Energy Commission
ESCA	-	Electric System Cascade Analysis
GDP	-	Gross domestic product
GHG	-	Greenhouse gasses
HVAC	-	Heating ventilation air conditioning
IAQ	-	Indoor air quality
ITS	-	Ice thermal Storage
MGTC	-	Malaysian Green Technology Corporation
NPV	-	Nett present value
PCM	-	Phase change material
PSE	-	Process System Engineering
PV	-	Photovoltaic

RT	-	Refrigerant tonne
RTH	-	Refrigerant tonne hour
TES	-	Thermal energy storage
WT	-	Wind turbine

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CHAPTER 1

INTRODUCTION

1.1 Research background

Air conditioner is the biggest contributor for commercial building in Malaysian typical energy apportioning. Types of commercial building consist of warehouses, office buildings, or retail (i.e. convenience stores, 'big box' stores, shopping malls, etc.).

In the United States in 2017, commercial buildings consumed 36% of the country's total energy, with approximately 30% wasted due to inefficiencies (Office of EE & RE, 2019). Hence, reducing wasted energy and improving the performance of buildings' consumption is critically important to minimizing energy consumption and the associated environmental impact. Even more, heating and cooling systems are dominant consumers of energy in buildings and offer the potential for a tremendous amount of savings. To realize such savings, one must understand the magnitude of the consumption and associated usage patterns of building equipment and be able to quantify the savings potential of enacting specific actions. However, most building equipment do not use costly submeters to monitor and address performance issues, and on-site auditing can be expensive and insufficient. Consequently, recent "low touch" datadriven approaches have been employed to explore how to quantify and minimize the energy consumption of heating and cooling systems. (Arash Kalilnejad et al, 2020). Various factors influence HVAC (heating, ventilation, and air conditioning) loads such as building type, occupancy, meteorological conditions, equipment efficiency, thermostat setpoints, and building controls. In fact, a thorough analysis of each of these affecting parameters can lead to the identification of specific energy savings opportunities (Arash Kalilnejad et al, 2020). More specifically, a setpoint setback, particularly when used during unoccupied times, can lead to significant energy savings without compromising on comfort. For example, Ghahramani et al. (2016) showed that even a small adjustment in setpoint can lead to up to 30% of energy savings in a building. Capozzoli et al. (2017), studied occupancy patterns to reschedule the HVAC system's operation. For example, they found that an adjustment to the HVAC stop schedule accounting for different occupancy zones resulted in 14% of HVAC savings overall. Several studies also discovered that leaving HVAC systems on during unoccupied hours represents up to 50% of the total energy usage of buildings. This indicates that the energy-efficient operation of M&E equipment could contribute to significant energy savings with less investment. It is important to operate HVAC systems efficiently because they consume almost half the energy used in buildings. (Kwonsik Song et al, 2020).

As shown in Figure 1.1, approximately 57% of the total load for the whole building is for air conditioner, followed by lighting (19%), lift and pump (18%) and 6% for other equipment (S.S. Azis, 2021).

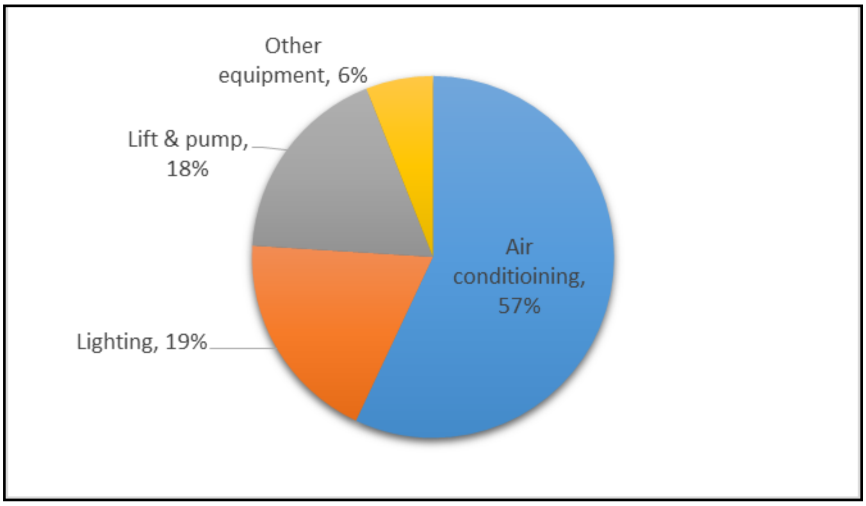

Figure 1.1 Energy Use Estimation in Office Building in Malaysia

Based on the statistics shown, users can optimize and reduce the rate of electricity consumption in a drastic amount. However, the situation will get worse if not maintained properly. This is different from commercial buildings that use a centralized air condition system or district cooling system (DCS) where the rate of energy use of the air conditioning system is lower because it does not require a chiller plant.

Thus, the Dictrict Cooling Plant technology has been introduced to prevent commercial buildings from buying individual chillers. With this method, every bureau in the area can reduce the use of electricity at the largest portion of commercial building in Malaysia approximately 57%, which is used for air conditioner (S. S. Azis, 2021) and indirectly reduces the demand for electricity in the area.

Figure 1.2 shows the sectional distribution of total energy use in Malaysia. Referring to the statistic of energy uses in Malaysia on 2017, transportation consume the highest total energy which is 38.5% (kilo tone of oil equivalent (ktoe)) whereas residential and commercial building in the list with 12.5% which also the fourth largest from the total consumption. Meanwhile, industry, non-energy use and agriculture account for 28.0%, 20.0% and 1.0% respectively from the total amount of 62,489 ktoe per year (EC, 2019).

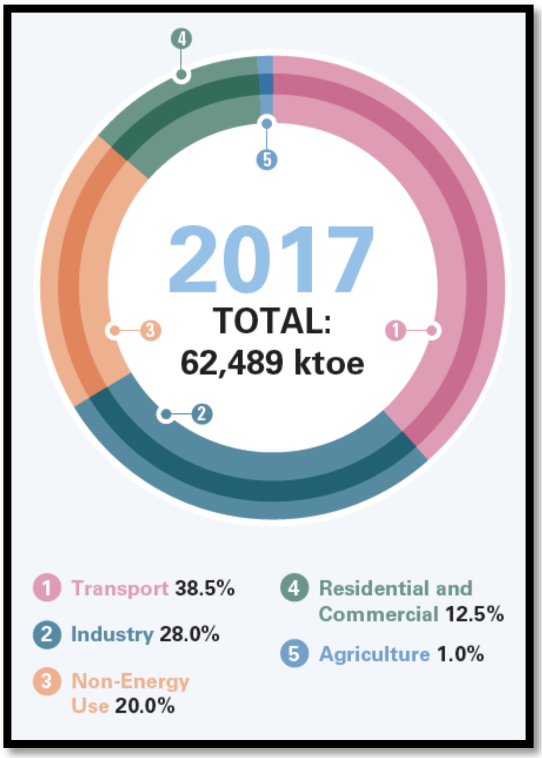

Figure 1.2 Statistic of Energy Uses in Malaysia (EC, 2019)

Figure 1.3 shows Europe statistic of energy usage which the highest percentage of total energy consumption is contributed by buildings (39%), follow by transport (33.1%), industry (25.4%), agriculture (2.2%) and others (0.4%) (Eurostat, Final Energy Consumption, 2015). In this case, the value of 39% energy consumption is contributed by buidings has a high chance of being reduced if the Heating Ventilation Air Conditioning (HVAC) system for the individual building can be optimized.

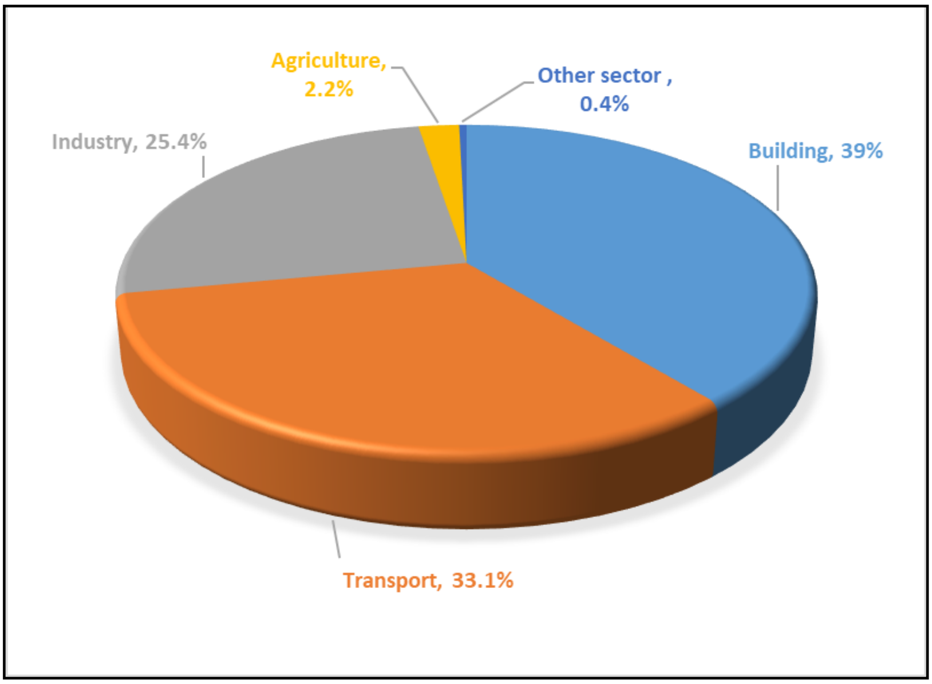

Figure 1.3 Statistic of Energy Uses in Europe Based on Eurostat's Data for 2015

Based on local and global scenario, the percentage value of building energy consumption can be reduced by manipulating the largest Significant Energy User (SEU) of the buildings which is HVAC. Thus, if problem of high energy consumption on the building portion can be solve, it is possible to lower energy consumption in one country and even indirectly reduce the amount of carbon dioxide (CO_2) generated. Referring to Figure 1.1, air conditioning is a major contributor to energy consumption in a building in Malaysia. Therefore, further studies / depths can be extended to address the problem of high energy consumption for this building sector.

Figure 1.4 shows the energy consumption in Malaysia by fuel type for year 2017 whereby electricity is the third highest percentage from the total consumption by 20.2% while petroleum products, natural gas, coal & coke, biodiesel account for 49.4%, 26.9%, 2.9% and 0.6% respectively from the total amount of 62,489 ktoe per year.

Figure 1.4 Energy consumption by Fuel Type (EC, 2019)

Referring to current development status in Malaysia, DCP application technology is very limited. It is only available in certain developing areas such as government building at Putrajaya, Kuala Lumpur Convention Centre (KLCC), Kuala Lumpur International Airports (KLIA), The Curve Mutiara Damansara, and TNB Bangsar where it is only concentrated for a limited radius of area. DCP technology has been established in Malaysia since 1996 (Cofreth, 2016), and the existence of this plant has had a big impact on the reduction of electricity usage for air conditioning in an area or area due to the use of air conditioning is the largest part of a commercial building.

In the present-day, 2017, human beings are looking for new alternatives to green building, green country, green development, which each emphasize on a design that reduces CO_2 emissions resulting from various aspects such as design, operation and waste. Hence various technologies have been designed to meet this requirement. The whole world is trying to generate new technologies and united for this noble goal. In a design of building constructions, the most commonly used electrical energy is air cond. Therefore, the designer should make the best selection to ensure optimum operation. For example, the Malaysian government's administrative centre, federal territory of Putrajaya, does not allow individual chillers to be installed in every building built within the area. Therefore Gas District Cooling (M) Sdn Bhd, Putrajaya is a responsible body for producing and providing chilled water to every building in Putrajaya.

With the existing district cooling plant (DCP), the design and operation of the district cooling plant itself can again be adopted in many ways, such as trigeneration, cogeneration, DCP with seawater or river water, DCP with thermal storage and many more depending on availability. A wide range of technologies including photovoltaic system (PV), wind turbine (WT), combined cooling, heating and power system (CCHP), thermal energy storage (TES) and other renewable energy systems have been employed in various types of buildings.

Compared to the conventional design method, which they refer to load demand as well as conditions or data used at the design stage are certain values. For example, the outdoor weather conditions are usually described using a typical meteorological year (TMY) or a typical design day for the design location (Y.Q. Lu, 2008). This method does not take into account the operational efficiency of the choice of compression driven chiller and ITS and does not take into account the electrical tariff aspect. Electricity consumption in office buildings is about 70-300kWh/m^2 per annum, 10-20 times that of residential buildings (Yang *et al.*, 2008). In the rapidly growing development of present and future years, Green House Gasses (GHG) are produced through activities which release carbon dioxide, methane, nitrous oxide and ozone CFCs (chlorofluorocarbons) where these gases absorb more of the solar radiation that is reflected back from the Earth's surface - trapping heat and keeping it in the atmosphere causes the earth's temperature to rise. CFCs also have been responsible for depleting the ozone layer as they attack and destroy ozone molecules. The root of this problem that causes the release of GHG into earth atmosphere of the earth is due to the industry, commercial building, transportation, agriculture, and uncontainable waste disposal sites.

Malaysia's position on the equator's line has a hot and humid climate coupled with rising world temperatures that cause the majority of residents living in urban areas to use air conditioning to live their daily lives, not to mention being at work especially in commercial buildings of this era. As a matter of fact, the air conditioner is the largest electricity user in a building. Indirectly indicates that commercial building is among the largest users in a given area due to the use of air conditioner for the entire interior of the building except the parking lot. The Commercial Building sector is the third largest consumer of 14.3% of total energy use in Malaysia by sector. The largest part of the building is air conditioning, which is 57% of the total use of the building (S.S. Azis, 2021). Indirectly the impact of this huge energy consumption is on the production of carbon dioxide (CO_2).

Malaysia has taken a commitment to support global emission reduction in the conference of parties (COP 15) under U.N. Climate Change Conference 2009-15th in Copenhagen that Malaysia is adopting an indicator of a voluntary reduction of up to emissions intensity (per unit of Gross Domestic Product (GDP)) by up to 40% by 2020 and 45% by 2030 compared to the levels in 2005, which is emission intensity of GDP in the base year is 0.531 tons CO_2 equivalent per thousand RM (Scientific Malaysian, 2017); (INDC Malaysia, 2015). Based on Figure 1.4, 21.1% in kilo tonne of oil equivalent (ktoe) is used by electricity in Malaysia. The relation between use of energy and the environment shown the quantity of CO_2 emission per kWh. The indicator shown the value of 0.694 kg of CO_2 emitted to the atmosphere for each 1 kWh electricity generated by power plant (Peninsula Malaysia), 0.699 kg CO_2 / kwh for Sarawak and 0.536 kg CO_2 / kWh for Sabah (MGTC, 2020).

1.2 Problem Statement

DCS and thermal energy storage (TES) have high capital expenditure (CAPEX) and operational expenditure (OPEX) which will result in long payback period (PBP) and low return of investment (ROI). Constraints of methods and tools are one of the reasons DCS can not be developed in a country. Pinch analysis method is available for heat integration, power integration, water management, carbon emission reduction (i.e. POPA, ESCA, WPA, GCCA) and etc, but has limited methods for designing cooling integration (i.e. DCP). There is no study to determine the size of ITS and chiller by considering simultaneously design and scheduling to identify the optimal sizing. None of the studies on hourly data to design or size the system, no comparison of cost savings for different types of chiller.

Globally, a study by Hassan Hajaddollahi (2015), and Y. Ruan *et al*., (2016) elaborate about the optimal design for Heating Ventilation Air Conditioning (HVAC) where the demand for the area requires cooling and heating energy and also has a source of supply heat from the heat surplus available in the area. However, the are no study to determine the size of ice thermal storage (ITS), glycol chillers, centrifugal chillers, absorption chiller, which obtains renewable energy (photovoltaic & photothermal) apart from electricity supply from grid by considering simultaneously design and scheduling to identify the optimal sizing in order to reduce electricity consumption using GAMS. Furthermore, there are still no study that determine size of ITS, glycol chillers and centrifugal chillers using a pinch analysis principal (Y. Ruan *et al*., 2016).

In the previous study by W. Gang *et al*., (2016), there are no related studies regarding scheduling factor (for shift peak / off peak electricity tariffs to reduce maximum demand and cost of electricity consumption) to generate chilled water for integration of DCS with ITS. Besides that, the factor to ensure 100% of discharging of solid ice portion contained in ITS is also not considered. Furthermore, there is still no study that combines the combination of chilled water and glycol of compression driven chiller integrate with ITS, using only one (1) fuel source, namely electricity (M.O. Abdullah *et al*., 2013). Therefore, this study is conducted for design DCP integrate with ITS taking into account all the above factors. This study focuses on the type of chiller used for this DCP as the largest consumer of electricity. If the arrangement selection chiller for the operating system is well done, it will have a significant impact on the reduction in the cost of generating chilled water.

Nevertheless, the number of DCP plants in Malaysia is only approximately 17 plants. (Boustead, 2019; GDC, 2018; TNEC, 2019). In 2019, some DCP players in Malaysia include Gas District Cooling, TNB Engineering, Boustead DCP and others where they use trigeneration as well as DCP itself as well as Ice Thermal Storage (ITS) in accordance with the availability of resources and availability. Following are the gaps identified in the current DCP technology in Malaysia:

a. Constraints of local studies on resource and demand in areas particularly in urban centers throughout Malaysia, especially commercial buildings. Therefore, the need to study on optimal design according to avalibility resouces in an area is important for energy and emission reduction.

b. Numerous Research on DCP has been implemented. However, the lack of studies for a region does not provide hourly data to design or size the system, no comparison of cost savings for different types of chiller, no consideration of carbon dioxide (CO2) emissions, no study of chiller performance, assumed value of thermal storage size, etc. Detailed elaboration is described in Table 2.1 in Chapter 2 (Summary of Research Gap).

c. Integration of thermal energy storage with the district cooling system can reduce the operational cost and electricity bill at peak hour. The reduction of operational cost and electricity bill takes the advantages of the lower electricity tariff during the peak hour. The application of the thermal energy storage can save the electricity cost up to 3% with respect to the conventional system without the thermal energy storage (Abdullah *et al.*, 2013). Despite the electricity cost reduction, the installation of thermal energy storage also contributed to an additional capital cost for the heat exchanger and water pumps. The extra cost is 29% higher than the cost of a conventional system which is a drawback for this system. There are constraint due to the oversize, to set the optimal size of chiller and ITS without any tools.

d. There are no disclosure studies on the effect of Time of Use (TOU) and Enhance Time of Use (ETOU) tariff schemes on the use of ITS integrate with DCP. We do not know the effectiveness or feasibility of the ETOU tariff on the integration of DCP with ITS is unknown. (TNB, 2016)

1.3 Research Objective

The main objective of this research is to develop a new systematic framework and methodology based on Pinch Analysis for designing the District Cooling Plant (DCP) or District Cooling System (DCS) integrated with ice thermal storage (ITS). The sub-objectives include performing as following steps / procedure:

a) To develop a new numerical method to determine chiller size and ITS by implementing the integration of DCS equipment for the cooling process of the scenarios including the comparison as follows:
   i. Scenario 1 - Glycol chiller, Variable Speed Drive (VSD) glycol chiller and ITS **(GL)**
   ii. Scenario 2 - Glycol chiller, centrifugal chiller, VSD centrifugal chiller and ITS **(GLC)**
   iii. Scenario 3 - Centrifugal chiller, VSD centrifugal chiller **(C)**
   iv. Comparison between 3 scenarios and perform an economic, environmental and sensitivity analysis based on peak / off peak tariff as well as feasibility study

b) To develop a mathematical model for Optimisation of District Cooling System (DCS) by using General Algebraic Modelling System (GAMS)

1.4 Research Scope

In order to attain the aforementioned objectives, the research scope must include and be divided into the following:

a) Cooling System Cascade Analysis (COSCA)

   i. Obtained desktop data and measured data of glycol chiller, compression driven chiller, cooling demand and mechanical and electrical (M&E) parameters (eg: RTH, temperature, flowrate, voltage, amperage, power factor, maximum demand (MD) and etc) respectively from DCP, Roof Top level at The Curve, Mutiara Damansara case study as well as local service providers data for the costing
   ii. Develop COSCA technique based on Pinch Analysis
   iii. COSCA framework for Optimal Design of ITS chiller capacity
   iv. Calculate payback period (PBP) and return of investment (ROI) in order to perform an economic and environmental analysis
   v. Comparison between 3 scenario
   vi. Sensitivity Analysis to test a new and comprehensive technique

b) Optimization of District Cooling Plant (DCP)

   i. Obtained desktop data and measured data of glycol chiller, compression driven chiller, cooling demand and mechanical and electrical (M&E) parameters (eg: RTH, temperature, flowrate, voltage, amperage, power factor, maximum demand (MD) and etc) respectively from DCP, Roof Top level at The Curve, Mutiara Damansara case study as well as local service providers data for the costing
   ii. Develop modelling framework for optimal design DCP
   iii. Formulate a mathematical model for Optimal Design of DCP
   iv. Programming mathematical model in General Algebraic Modelling System (GAMS)
   v. Comparison of different tariff scheme between TOU and ETOU
   vi. Result analysis and sensitivity analysis to verify the situation

1.5 Research Contribution

The main contribution of this research is an improved / extent framework based on Pinch and ESCA technique, which calculates the integration of heat and power alone.

a) Contribution 1: Advancement in Process System Engineering (PSE) for optimization of chiller.
    i. A development of another industry district cooling system by extending the original Pinch Analysis method.

b) Contribution 2: Extension for Cooling System Cascade Analysis (COSCA) technique based on Pinch Analysis as well as ESCA technique to sizing chiller and ITS for optimum operation.
    i. A new methodology in designing and optimizing district cooling systems.

c) Contribution 3: Performed sensitivity analysis and economic analysis based on industrial case study.
    i. An economic assessment using Simple Payback Period (SPP) and Return of Investment (ROI).

d) Contribution 4: A new formulation of mathematical model for Optimal Design of District Cooling System (DCS) to solve the costing issue by considering hourly cooling demand, availability of heat and sunlight as well as capex and opex DCS equipments including renewable energy (RE).
    i. A new optimisation model of DCS to minimize the total energy cost in Ringgit Malaysia (RM) by using General Algebraic Modelling System (GAMS).

    ii. A useful percentage value can be used to propose/advise Malaysian government for consideration for subsidy of DCS equipment in order make a feasible market of DCS integrating with ITS and RE in Malaysia.

This research has contributed to several publication and copyrights as listed in Table 1.1.

Table 1.1 Publications and Copyrights

No.	Year	Item
Indexed Publications		
1	2020	Muhammad Ikhwan Zamhuri, Haslenda Hashim, Ho Wai Shin, 2020. Optimal Design of Integrated Chiller Capacity with Ice Thermal Storage for Commercial Buildings through Cooling System Cascade Analysis. International Journal of Innovative Technology and Exploring Engineering. 2278-3075, Volume-10 Issue-2, December 2020. (Scopus Indexed)
2	2018	Wen Hui Liu, Haslenda Hashim, Jeng Shiun Lim, Chin Siong Ho, Jiri Jaromir Klemes, Muhammad Ikhwan Zamhuri, Wai Shin Ho, 2018. Techno-economic assessment of different cooling system for office buildings in tropical large city considering on-site biogas utilization. Journal of Cleaner Production 184 (2018) 774-787. (Scopus Indexed)
Copyright		
1	2019	Optimal Design of Ice Thermal Storage and Chiller Capacity Through Cooling System Cascade Analysis (COSCA) © 2019 Universiti Teknologi Malaysia – All Rights Reserved

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