A Study of Residential District Cooling System in Hyderabad, India

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by

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CERTIFICATE

It is certified that the work contained in this thesis, titled "A Study of Residential District Cooling System in Hyderabad, India" by Madhan Kumar K, has been carried out under my supervision and is not submitted elsewhere for a degree.

Date	Adviser: Prof. Vishal Garg

To the future

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Abstract

Over the years, the energy consumed by buildings has been on a steady rise, accounting for approximately 30% of global final energy consumption. Among various appliances that consume energy in buildings, air conditioning is a major contributor. With the growing demand for space cooling in the country, it is an excellent opportunity to implement meaningful and resourceful interventions for the future of cooling technologies. The District Cooling System (DCS) with water cooled chillers is an energy-saving technology that offers a significant advantage over individual split air conditioning systems. The load profile plays a vital role in the efficient design and operation of DCS. The assessment of cooling loads to determine an appropriate system sizing can have significant economic and environmental benefits. However, much of the existing research on DCS has focused on theoretical calculations rather than real-world data.

In this study, we considered 387 flats in Hyderabad, which have a DCS connection for chilled water supply. Annual operational data spanning 12 months across different seasons were selected to assess the residents' requirement for the cooling demand. In order to better facilitate the operation of the residential DCS, load diversity and system performance were analyzed for different seasons in the year. After analyzing cooling data of flats and electricity data of DCS, this research provides the load profile for various seasons throughout the year.

The daily average thermal usage per flat during summer, monsoon and winter was 26.4 kWh_{th}, 9.4 kWh_{th}, and 4.7 kWh_{th} respectively. The hourly average probability of a flat using Air Conditioning (AC) during summer, monsoon, and winter was 0.35, 0.17 and 0.10. The AC usage of common places during summer, monsoon, and winter was 2.3%, 3.4% and 2.8% of overall AC usage respectively. The maximum hourly thermal load in summer, monsoon and winter was 1492 kW_{th}, 556 kW_{th} and 429 kW_{th}. The daily average electrical usage by the DCS during summer, monsoon, and winter was 4.96 MWh_{e}, 3.1 MWh_{e}, and 2.49 MWh_{e}, respectively. During summer, monsoon, and winter pumps and auxiliary equipment contribute around 45%, 54% and 41% of the total consumption of DCS respectively. The mean daily thermal consumption of a flat during peak month was 34 kWh_{th}. The

average daily energy consumption of DCS during peak month was 15.3 kWh_e per flat. The daily average COP during the peak month was 2.2. This also includes pumps and auxiliary.

The peak thermal energy demand was 1492 kW_{th}, which was effectively managed using a single chiller. Compared to the installed capacities, the actual peak demand represented 10.4% of the total indoor unit capacity and 94.3% of the primary chiller capacity. A simulation model was prepared based on the analysis of the actual measured data. The tuning has been done on schedules for cooling load profile to match the actual measured load profile. This calibrated model was then used for the simulation of residential thermal load in Delhi. It shows a cooling load reduction of 37% during April.

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List of Abbreviations

ASHRAE	American Society for Heating Refrigerating and Air-conditioning Engineers
HVAC	Heating Ventilation and Air Conditioning
ICAP	India Cooling Action Plan
ISHRAE	Indian Society of Heating, Refrigerating and Air-conditioning Engineers
AC	Air Conditioning
COP	Coefficient of Performance
kWh_{th}	Thermal kilowatt-hour
kWh_e	Electrical kilowatt-hour
DCS	District Cooling System
AHU	Air Handling Unit
TES	Thermal Energy Storage
LHS	Latent Heat Storage
VFD	Variable Frequency Drive
TR	Ton of refrigeration
RH	Relative Humidity
HTF	Heat Transfer Fluid

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Chapter 1

1. Introduction

1.1. Motivation and background

Rapid urbanization has led to a surge in urban populations, posing increased risks and detrimental environmental effects. In 2021-2022, the residential apartment market sales have increased by 41% across the top 8 cities in India [1]. Due to fewer green spaces and water bodies, the built environment in cities is getting warmer and making people vulnerable to rising temperatures. In response, demand for space cooling in the building has been viewed not only as a luxury but also as a critical element in promoting health, well-being, and productivity. Apart from fans and air coolers in India, room air conditioners have a 7-9% penetration in the residential sector, which will significantly increase over the next decade [2]. This heightened cooling demand necessitates cleaner, more energy-efficient technologies and environmentally friendly cooling solutions. According to India Cooling Action Program (ICAP) reports, per capita energy consumed for space cooling in India stands at 69 kWh_e compared to the world average of 272 kWh_e [2]. With the growing demand for space cooling in the country, it is an excellent opportunity to implement meaningful and resourceful interventions for the future of cooling technologies.

Generally, space cooling in hot regions is characterized by large seasonal and daily variations, which puts a heavy demand on the electricity grid. The cooling load for most of the flats is met through window units, split air conditioning or evaporative air coolers. These systems are mostly predefined sizes catering to common markets. Unfortunately, these systems contribute to negative environmental impacts by releasing greenhouse gases and excess heat. They also affect the aesthetics of the building and create a noisy environment while running. In contrast, central air conditioning like

District Cooling Systems (DCS) uses environment-friendly refrigerants and water-cooled chillers to reduce environmental impacts. This type of air conditioning provides reliable service and can be equipped with energy-efficient equipment to reduce electricity consumption.

Demand load evaluation and management have assumed greater importance because user patterns significantly influence system effectiveness. Studies have shown that compared to traditional cooling systems in residential buildings, District Cooling Systems (DCS) offer significant benefits in terms of reducing peak demand and operational costs [3], [4]. The energy efficiency and suitability of centralized AC systems in residential buildings are highly dependent on the load pattern and load ratio [5]. It's worth noting that due to the dispersed nature of residential structures, larger pumps may be necessary to supply cooling to scattered zones, which can result in lower energy efficiency due to the dispersion of cooling loads [6]. Accurately simulating building energy consumption relies heavily on occupancy schedules, which can impact the internal heat gains from occupants, as well as the operational status of building equipment and personal devices that occupants control, such as air conditioning, lighting, and windows [60], [61]. It's important to note that inaccurate occupancy input can significantly affect energy consumption simulation, especially in a community with numerous households.

1.2. Problem statement

The problem statement of this thesis is to evaluate the performance of residential district cooling systems with a focus on understanding the load diversity, load profile, and seasonal variations. Through onsite measurement, we develop the building energy model to simulate and evaluate the cooling load profile for residential buildings.

1.3. Contributions of the thesis

This study comprises of the following contributions in DCS:

1. Analyzed the load pattern for cooling in flats of apartment buildings during different seasons.

2. Quantifies the electricity consumption patterns of district cooling system (DCS) across various seasons.

3. Analyses the peak summer AC usage and electricity consumption of DCS.

4. Identifies the load diversity of residential district cooling system.

5. A simulation model was created based on the actual DCS and the summer month cooling profile for the flats was created through the AC usage analysis.

1.4. Thesis organization

This thesis is organized into six chapters. Following are the description of the chapters:

Chapter 1 gives a background of the study. The problem statement is defined, and contributions are listed.

Chapter 2 provides a literature review on district cooling systems, thermal energy storage and load management. Research gaps were identified and presented in the thesis.

Chapter 3 illustrates the physical description of the apartment building considered for this thesis. It also describes the details of the district cooling system in the building.

Chapter 4 illustrates seasonal AC consumption patterns of flats and common areas and identify various other factors affecting the usage patterns.

Chapter 5 analyses the electrical energy consumption of district cooling system for summer, monsoon, and winter.

Chapter 6 presents the evaluation of peak summer month analysis of thermal and electrical consumption of DCS and the load diversity.

Chapter 7 presents the building energy model of residential district cooling system in DesignBuilder and the simulated cooling load profile of a summer month.

Chapter 8 consists of a summary and conclusions of this research work and possible future work suggestions.

Chapter 2

2. Literature review

2.1. Load profile and peak load

Recent advancements in dynamic simulation tools for energy consumption in residential buildings have revealed that the behavior of occupants has a profound impact on building performance. In order to achieve more precise results, it is crucial to input realistic occupant-related schedules, including occupancy and appliance use schedules, into the simulation of building thermal loads. Neglecting to do so could result in substantial discrepancies from real-world measurements [7]. Chow [8] and Gang [9] conducted a study analyzing the system performance of various building types - such as offices, schools, and hotels - for cooling load prediction based on predicted loads and different schedules.

Unlike a single residential building, a district consists of numerous households with varying thermal demands, resulting in significant spatial and temporal load diversity. Weissmann et al. [10] have demonstrated the impact of load diversity on central supply peak load using load profiles from two buildings. Fonseca and Schlueter [11] have emphasized the importance of comprehending spatial and temporal load diversity in district systems to determine equipment sizing and control strategy application. Furthermore, Brounen et al. [12] have examined 305,001 dwellings in 2008-2009 and found a wide variation in household consumption. Previous studies have concentrated on load diversity based on building type, orientation, and envelope performance [10], [11], [13]. However, occupant behavior could potentially be another crucial factor influencing load diversity among buildings.

The sizing of HVAC systems heavily relies on peak loads, which is why much of the research on building aggregation has focused on peak load variation. For instance, Zhu et al. [14] conducted an analysis of peak load and annual demand changes across various building scales using EnergyPlus simulation results [15]. Gouveia and Seixas [16] on the other hand, looked into the differences in daily electricity consumption among households and obtained ten typical residential electricity consumption patterns by using clustering. Xu et al. [17] analyzed building electricity consumption data and found that the uncertainty of aggregated load profiles decreased as the number of households within a larger group increased. Kristensen et al. [18] concluded from data experiments that building scale increase gradually reduce energy consumption prediction uncertainty. Richardson et al. [19] showed how the value and uncertainty of peak load decrease as the number of households within residential buildings increases.

The load profile plays a critical role in the effective design and operation of DCS. By accurately sizing the system and assessing cooling load, DCS can offer both economic and environmental benefits. A recent study analyzed actual hourly cooling and electricity usage data from the Hong Kong Polytechnic University campus [20]. Using a simulation model, the study evaluated the energy efficiency of DCS and individual cooling systems under various operating modes. The results indicate that depending on the control technique employed, the payback period can range from 6.4 to 10.4 years.

2.2. District cooling system

ASHRAE defines DCS as “a concept of providing and distributing, from a central plant, cooling energy to a surrounding area (district) of tenants or clients (residences, commercial businesses, or institutional sites) [21].” The concept behind District Cooling System (DCS) technology is to enhance the efficiency of air conditioning systems by centralizing them. DCS is an energy-saving solution that outperforms individual split air conditioning systems. It operates as a centralized cooling system that supplies refrigerant fluid (often water) through a distributed network to fulfill the cooling needs of multiple buildings. Figure 2.1 depicts the schematic of the District Cooling project [22]. It encompasses four main components: a central cooling plant, a heat rejection system, a distributed network, and a terminal system. The central cooling plant's primary responsibility is to generate chilled water to offer cooling services.

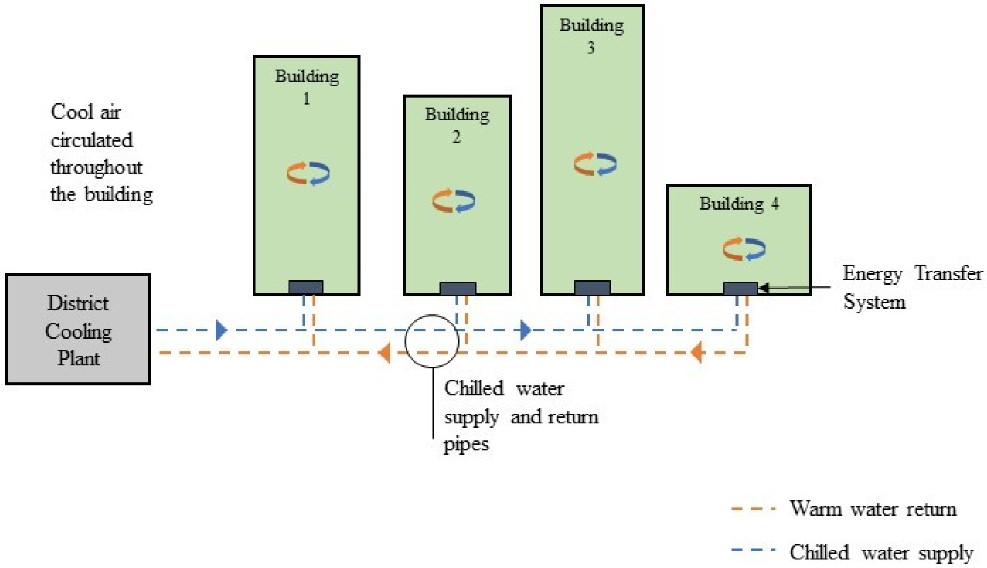

Figure 2.1 District Cooling Project Schematic.

2.2.1. Central cooling plant: chiller

The chiller is a crucial component in a DC system, facilitating the transfer of energy from a lower temperature (chilled water temperature) to a higher temperature sink (typically the surroundings). Chillers fall under two main categories: vapour compression and vapour absorption/adsorption types. Vapour compression chillers rely on an electrically driven mechanical compressor to circulate refrigerant throughout the system and are the most widely used type. Further classifications of these chillers are based on the technologies employed for heat rejection and compression, which are described below.

Classification based on heat rejection: Chillers can be categorized into two main types: air-cooled and water-cooled. Despite their differences in heat dissipation methods, both operate on the same principle. Air-cooled chillers use finned tube heat exchangers to release heat into the air, while water-cooled chillers utilize a shell and tube heat exchanger to expel heat into water. In the case of water-cooled chillers, the condenser water carrying the expelled heat is cooled even further in a cooling tower.

Classification based on compression technologies: When it comes to DC applications, vapour compression chillers can be found with either screw or centrifugal compression technology. Screw chillers utilize rotary screw compressors to cool and compress, while centrifugal chillers rely on centrifugal force to compress the refrigerant [23]. In terms of energy efficiency, centrifugal chillers are typically more efficient when operating at full load, whereas screw chillers tend to excel in part-load efficiency.

Absorption chillers: Absorption chillers and vapour compression chillers differ in the type of input energy used to transfer heat from a low temperature to a high temperature. In the case of absorption chillers, heat is the primary source of energy. After evaporation, the refrigerant is absorbed in a solution and then pumped to a generator using a liquid pump, unlike a vapour compressor. In the generator, heat is used to separate refrigerant vapour from the liquid solution. Refrigerant vapour flows to the condenser, where it expels its latent heat to water from a cooling tower, changing from vapour to liquid phase. Lithium bromide (Li-Br) is the most commonly used absorbent in commercial absorption chillers, with water as the refrigerant.

Adsorption Chillers: Adsorption chillers and absorption chillers differ in the type of substance they use to cool. While absorption chillers use a liquid absorbent, adsorption chillers use a solid sorbate. As a result, adsorption chillers have distinct operational and performance features. To function, adsorption chillers require two beds to be charged and discharged simultaneously and then swapped, making their operation different from absorption chillers.

2.2.2. Heat rejection systems

Heat rejection systems, mostly cooling towers, are essential components of DCS. These towers facilitate heat rejection by allowing air and water to directly interact with each other, resulting in a decrease in water temperature. The design of the cooling tower is dependent on various factors, including the quantity of heat to be expelled, the wet bulb temperature of the surrounding air, and the approach temperature. As part of this process, a minimal amount of water is evaporated, resulting in a reduction in the temperature of the water that is circulating through the tower.

2.2.3. Distribution network

A District Cooling system (DCS) is comprised of a chilled water distribution network situated within the chiller plant, as well as a distributed network piping that connects to the building on the load side. Additionally, there is a condenser water distribution system (in the case of water-cooled systems) that connects the chillers, cooling towers, and condenser water pumps. While various types of pumps can be employed in fluid transfer, centrifugal pumps are the most commonly utilized in

District Cooling applications. The pre-insulated pipe insulation is designed with a maximum temperature loss of 0.5°C in chilled water distribution [22].

2.2.4. Terminal system

Terminal System serves as a vital connection between the DC service and a consumer's AC system, facilitating the transfer of thermal energy from the plant level to buildings or other consumers. Within this system, a revenue-grade flow meter and temperature sensors are employed to accurately calculate cooling energy consumption and demand for billing purposes. Known as a thermal energy meter or BTU meter, this device continuously monitors the temperature of incoming and outgoing chilled water as well as cooling capacity (TR).

2.3. Advantages

District Cooling is a cost-effective solution in certain contexts [24]. For instance, it is particularly beneficial in urban areas where many buildings require cooling. On the other hand, district energy is a more economical choice for buildings with high cooling demand, such as large public buildings, commercial buildings, and densely populated residential areas [25]. Research has shown that district cooling can reduce the reliance on fossil fuels for cooling in buildings [24]. Additionally, district cooling provides many advantages to both building owners and the city. For building owners, it eliminates the need for individual chillers and heat rejection units in each building, thus increasing the amount of rentable space available. Furthermore, district cooling offers several benefits, such as improved cooling quality, space savings, and the absence of sound pollution [26]. Moreover, implementing district cooling can lead to a significant reduction in cost compared to individual cooling systems.

The implementation of district cooling systems is a wise choice for businesses as it alleviates the need for constant chiller operation and maintenance, freeing up resources to concentrate on their primary activities [27]. This move also benefits the city by reducing noise pollution [28] and mitigating the heat island effects caused by heat rejection units. Furthermore, the use of fewer individual chillers leads to a decreased demand for refrigerants, aligning with the goals of the Montreal Protocol and Kigali Amendment. Additionally, opting for larger chillers results in a lower aggregated need for electricity as they can achieve higher efficiencies compared to smaller units typically found in buildings [29].

The thorough examination and assessment determined that DCS exhibits significant potential for energy savings throughout the year. DCS operates efficiently under partial loading, with Variable Frequency Drive (VFD) technology and dual compressor Chillers performing at high efficiency levels. As Chillers constitute a significant proportion of the initial cost, DCS presents a substantial opportunity for cost savings compared to individual cooling systems [30].

2.4. Storage

The role of energy storage is becoming increasingly important as the use of renewable energy sources like wind and solar power continues to rise. These sources are known to fluctuate, making energy storage a crucial component of modern power systems, which require instantaneous consumption of electricity. However, electrical energy storage, such as batteries, can be costly. Thermal storage entails storing cool water on various scales, ranging from daily to seasonal variations. Accumulator tanks are frequently utilized to address daily fluctuations and can assist in reducing system load spikes by redistributing the load, resulting in more consistent production. Moreover, energy storage in buildings has proven beneficial for short-term storage [31].

Numerous materials are utilized for thermal energy storage, each requiring specific thermophysical properties such as a suitable melting point, high latent heat, high specific heat, and high thermal conductivity to cater to various thermal applications. In addition, these materials should ideally possess other characteristics like low supercooling, affordability, easy accessibility, thermal and chemical stability, minimal volume change, non-toxicity, low vapor pressure, congruent melting, and low flammability [32]. TES systems can be classified into three main groups based on the type of material selected for cold storage [33].

- Sensible thermal storage systems
- Latent thermal storage systems
- Chemical thermal storage systems

2.4.1. Sensible thermal storage systems

Sensible thermal energy storage materials store heat energy in their specific heat capacity (Cp). The thermal energy stored by sensible heat can be expressed as

$$Q = m \cdot C_p \cdot \Delta T \qquad (2\text{-}0)$$

where m is the mass (kg),

C_p is the specific heat capacity ($kJ.kg^{-1}.K^{-1}$) and ΔT is the raise in temperature during charging process.

Throughout the energy absorption process, there is no phase change, resulting in an increase in temperature for the material. The quantity of heat stored is directly proportional to the storage material's density, volume, specific heat, and variation in temperature.

Water is a highly versatile substance that can be utilized in active systems as both a heat transfer fluid (HTF) and a TES material. Being readily accessible and non-toxic, as well as non-flammable, it poses no harm to individuals. As such, water is exceptionally well-suited to serve as a thermal energy storage material for a range of applications, including home space heating, cold storage of food products, and hot water supply [33].

Thermal storage materials that are deemed sensible are known for their remarkable thermal stability even at high temperatures, making them the go-to choice for numerous high-temperature applications. Sensible heat storage materials are typically made from low-cost materials, with the exception of liquid metals and thermal oils. While the specific heat of these materials is 50-100 times smaller than that of latent heat, they still possess a sizable thermal energy storage density due to their wide range of operating temperatures and high density.

2.4.2. Latent thermal storage systems

These materials are capable of storing heat through latent heat during a constant temperature process, such as phase change. Solid-liquid phase change is typically used, but solid-solid phase changes have their own advantages, such as no leakage and no need for encapsulation. While liquid-gas phase change has the highest latent heat of phase change [34], the significant change in storage material volume makes it impractical for general use. The thermal energy stored by latent heat can be expressed as

$$Q = m \cdot L \qquad (2\text{-}0)$$

where m is the mass (kg), L is the specific latent heat ($kJ.kg^{-1}$).

Organic materials are a popular choice for TES due to their solid-liquid phase change temperature falling within or near human thermal comfort range. They are also readily available in nature, chemically stable, non-toxic, and non-corrosive. However, they decompose at higher temperatures and have poor thermal conductivity. With latent heat 50-100 times greater than sensible heat, latent heat storage materials offer high energy storage density near the phase change temperature, resulting in compact TES systems. In LHS TES systems, the outlet temperature of the HTF remains steady during discharge. The main drawback of latent heat storage materials, however, is their poor thermal conductivity.

2.4.3. Chemical thermal storage systems

Chemical thermal storage systems utilize reversible reactions that involve heat absorption and release to store thermal energy. They operate at a moderate temperature range of 200°C to 400°C. Chemical thermal energy storage boasts advantages such as the highest thermal energy storage density (per-unit mass and per-unit volume), as well as long-lasting storage with minimal heat loss. However, there are some technical challenges associated with this method, such as sintering and grain growth during charging, which can reduce porosity and hinder the rehydration process during discharge. While chemical thermal energy storage is still in the laboratory stage, further research and experience are needed to refine the technology for commercial applications.

2.5. Operation strategies

As urban populations continue to grow and energy needs rise, it's crucial to ensure demand can be met during peak hours. However, DC systems often face a challenge: the significant distance between energy production and consumption can result in time delays [33]. To address this issue, a combination of increased capacity and flexibility is necessary, with TESs proving to be a fitting solution.

During off-peak hours, stored cooling can be used to partially or completely offset on-peak load, according to research [35]. The objectives of the load shifting can be categorized into three groups: minimizing operating costs including energy and peak demand costs, minimizing peak demand costs, and minimizing energy costs [36]. Developing a load shifting control strategy consists of three essential components: load prediction, cooling charging control, and cooling discharging control [35]. To use thermal energy storage for load shifting control, an additional water loop is required to charge and discharge the storage tank and deliver cooling to the existing chilled water loop. Figure 2.2 illustrates typical cooling charging and discharging processes. During the cooling charging process, cooling produced by the chiller in off-peak periods is directly stored in TES. During on-peak periods, cooling is discharged from TES to partially or completely offset end users' mechanical cooling demand [35].

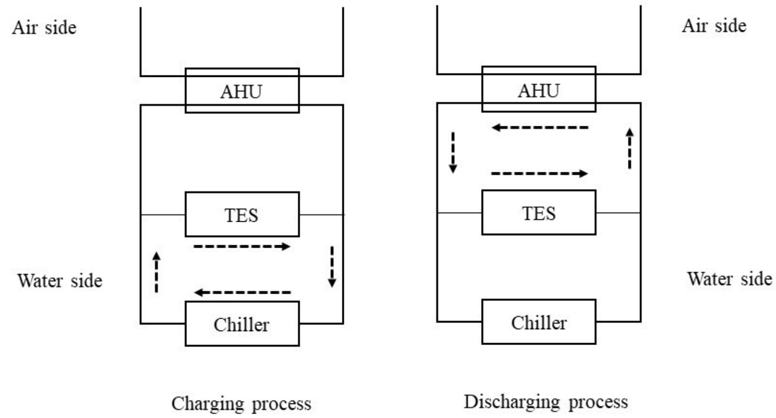

Figure 2.2 Schematic of charging and discharging processes using TES.

The controls that utilize TES for load shifting can be classified into two categories: heuristic control and optimal control. Heuristic control strategies are based on simple heuristic rules and are generally near optimal. These strategies primarily consist of storage capacity-based control and priority-based control. Storage capacity-based control can be divided into full storage control and partial storage control depending on whether the storage system can fully offset the load during peak periods. Priority-based control can be further divided into chiller priority control, storage priority control, and constant proportion control based on which system (chiller or storage) has priority in satisfying the on-peak cooling load. However, since the trade-off between energy increase and peak demand reduction is not considered in these strategies, the final cost savings may not be optimal. On the other hand, optimal control strategies aim to minimize operating costs by considering the trade-off between energy increase and peak demand reduction. The principles of both heuristic and optimal load shifting control using TES are presented in the following sections.

TES systems can be categorized into two types based on their cooling storage capability: full storage and partial storage [37]. In a full storage system as shown in Figure 2.3 a, the stored cooling is sufficient to meet the entire cooling demand during on-peak periods, eliminating the need to turn on the chiller. On the other hand, partial storage systems cannot store enough cooling for on-peak cooling loads, and the chiller needs to be switched on to meet part of the on-peak load as shown in Figure 2.3 b. Peak demand limiting control and load leveling control are two groups of partial storage control. In peak demand limiting control, the chiller operates at a reduced capacity or demand level during on-peak periods, and this strategy requires complex control systems because storage must meet peak demand [37]. Load leveling control typically operates with the chiller running at full capacity for 24 hours, as shown in Figure 2.3 c. Excess cooling is stored when the cooling load is lower than the chiller output, and the additional requirement is discharged from the storage system when the load exceeds the chiller capacity.

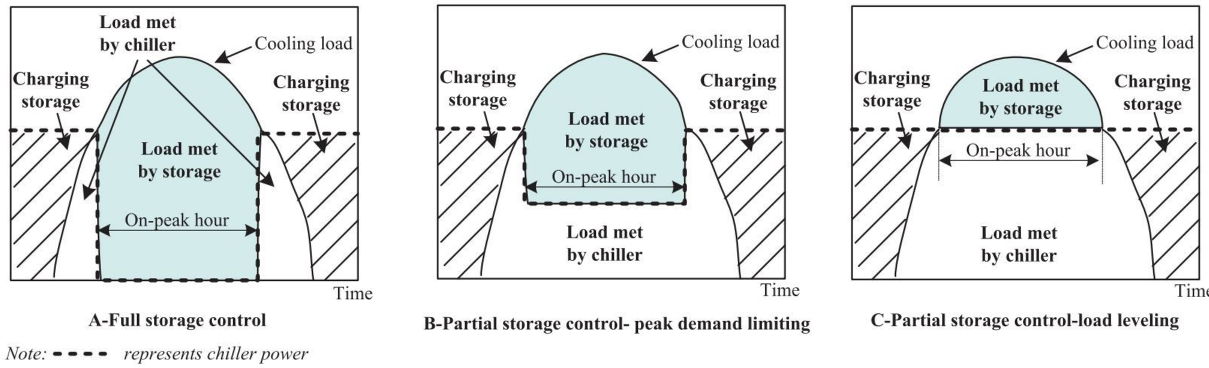

Figure 2.3 Storage capacity-based control strategies [35].

Numerous studies have examined and assessed various load shifting control strategies utilizing thermal energy storage (TES) under different rate structures. The majority of these strategies fall under the heuristic control category. In one case study by Chaichana et al.[38] a simulation of an internal ice-on-coil ice storage system was conducted on a typical office building in Thailand based on the model proposed by Neto and Krarti [39]. The results revealed that under Thailand's electricity tariff rates, the full storage control strategy yielded a monthly savings of up to 55% on cooling electricity costs. Additionally, total energy consumption was reduced by approximately 5%.

In another investigation by Habeebullah [40], on the economic feasibility of implementing ice storage systems in the air-conditioning plant of the Mosque of Makkah, it was discovered that the storage system did not provide any benefits for partial or full storage control strategies due to a fixed electricity rate of 0.07 $/kWh. However, the author recommended the use of a full storage control strategy combined with an incentivized time-structured rate as a means of significantly reducing overall electricity costs.

Yau and Lee [41]. conducted a case study using a typical library building located in a tropical region. They utilized an ice-slurry cooling storage system in their simulation, and the findings revealed that implementing the full storage control strategy resulted in a 24% reduction in overall costs based on the electricity tariff rate of Malaysia. However, it is important to note that the cumulative energy consumption increased by 20% due to the higher chiller energy consumption and longer water pump usage in comparison to the baseline design.

Various studies have explored the effectiveness of heuristic control strategies, including a case study conducted by Sabzali and Rubini [42] on a clinic building. Their research involved analyzing different storage capacity-based control strategies through computational modeling. Results indicated that the full storage control strategy yielded the highest cost reduction for the building in question, but it required a larger chiller and storage system compared to the other partial storage operation strategies. Additionally, the study found that shifting charging periods from 18:00 to 20:00 led to a decrease in total energy usage due to the lower dry bulb temperature.

Many studies [43], [44], [45], [46], [47] have shown that implementing a time-of-use rate structure results in storage-priority strategies outperforming chiller-priority ones. The performance of the storage priority strategy improves as the differentials between on-peak and off-peak energy and demand charges increase compared to the chiller priority strategy.

2.6. Identified gaps

Designing energy-efficient buildings can be a complex process. Traditional computing methods used by building designers may not provide precise estimations of a building's energy performance. In many cases, consultants depend on general guidelines and input from equipment providers to choose and configure building elements and systems. This strategy may not be optimal for developing sizable and intricate buildings and could lead to subpar energy efficiency in the long term.

The energy efficiency and suitability of centralized AC systems in residential buildings are heavily influenced by the load pattern and load ratio. The load profile plays a vital role in the efficient design and operation of DCS. However, much of the existing research on DCS has focused on theoretical calculations rather than real-world data [48], [49]. This can result in discrepancies between theoretical values and actual operating values, as real-world factors such as human behavior often deviate from the intended design usage patterns. In this thesis, we continue to understand the impact of usage pattern on system performance, demand load evaluation and management have become increasingly important.

In the Indian context, there are no studies available related to the residential district cooling system. This thesis aims to address the gap by studying the case of existing residential DCS. Large-scale and long-term studies of AC usage in houses are not available, and this is one of the gaps addressed in this thesis. This thesis aims to examine the load patterns and external factors that contribute to the development and operation of effective residential cooling systems. It is also essential to investigate the load diversity of the system. The annual operating data of the AC usage in flats and the electrical consumption of the DCS will provide valuable insights into the performance of the residential DCS.

Chapter 3

3. Description of the case study

3.1. Introduction

This chapter will provide some background to DCS installed in a residential complex in Hyderabad. This thesis studies the impact of DCS on residential complexes. Therefore, a detailed description of DCS is needed to understand the results. This chapter describes of the building's physical characteristics, district cooling systems, and operation data collected [50], [51]. The initial steps involved collecting detailed information about the DCS equipment involved in the project and how it interacts with the building system.

3.2. Building description

3.2.1. Study area

The residential complex used in the field study is located in Hyderabad (17.3850°N, 78.4867°E), the capital city of Telangana. The city experiences an arid climate, primarily consisting of dry and hot days. Although cooling is needed all year round, the main demand is from March to July. As depicted in Figure 3.1, the May month experiences hot weather with an average maximum temperature of 39.0 °C and an average minimum temperature of 26.2 °C [52]. The precipitation is higher for the four months: June, July, August and September.

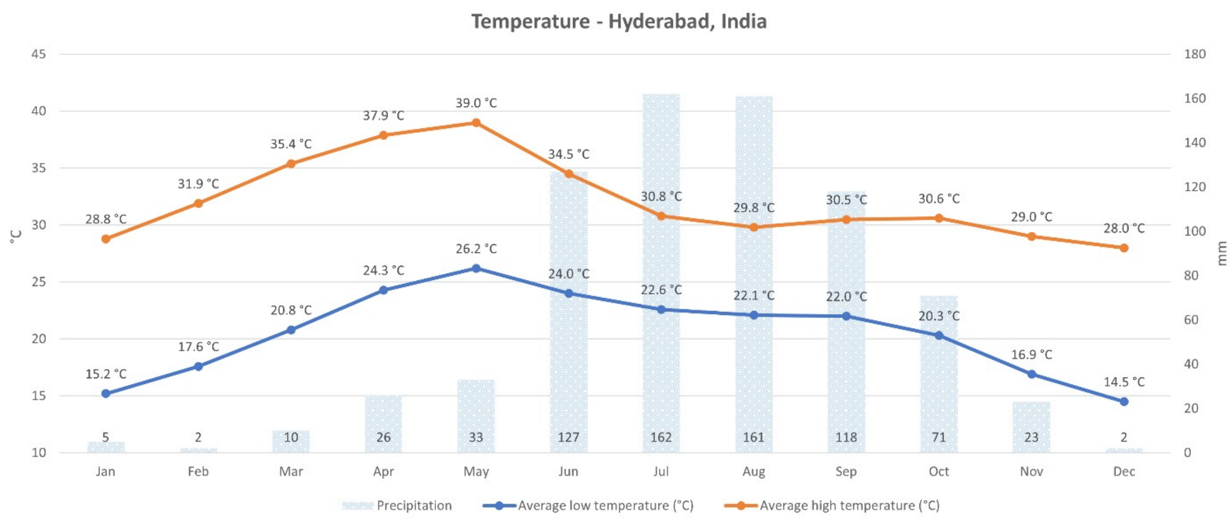

Figure 3.4 Hyderabad weather[52]

3.2.2. Physical description of building

The building as shown in Figure 3.2, is a residential apartment complex located in Madhapur, a commercial area of Hyderabad. The cooling requirements of the entire complex, which featured a built-up area of approximately 1,04,344 m^2 had been met by a centralized air conditioning system since its commenced operations in 2015. The complex comprised five towers, each with 18 floors, and a total of 387 flats. The area of the flats ranges from 180 m^2 to 450 m^2, encompassing a living room, drawing room, kitchen, washroom, dining room, home theatre and three to five bedrooms. Figure 3.3 shows the key plan of the site.

Figure 3.5 Residential apartments

Figure 3.6 Key plan

3.2.3. Residence types

There are five types of flats in the building. Figure 3.4 shows the floor plan of the individual flats. Table 3.1 shows the area and number of flats in the buildings. Type 1 has 3 bedrooms, 1 living/dining, 1 drawing room, 1 home theater, 1 puja and kitchen. Type 2 is similar to Type 1 without a home theater. Type 3 is similar to Type 1 with a servant room attached to it. Type 4 and type 5 have 4 bedrooms, 1 living/dining, 1 drawing, 1 home theater, 1 puja and kitchen. Both type 4 and type 5 differ only by area occupied. All the living space in residence is fully air conditioned through central cooling plant.

Type 1

Type 2

Type 3

Type 4

Type 5

Figure 3.7 Residence layouts

Table 3.1 Number of flats and area.

Flat Type	Flat Area (m^2)	No of flats
Type 1	215	144
Type 2	241	140
Type 3	321	70
Type 4	443	28
Type 5	387	6

3.3. District cooling system

3.3.1. Design considerations

For the cooling load calculations, the considered temperature and relative humidity (RH) were as follows: Summer, T = 41.1 °C, RH = 26%; Monsoon, T = 29.4 °C, RH = 82%; Winter, T = 12.7 °C, RH = 60%. Table 3.2 shows the floor area and load estimation of the towers. Based on the design conditions, the calculated cooling load of the building amounted to approximately 0.13 $kW_{th}/\ m^2$ (0.003 TR/ft^2).

Table 3.2 Floor area and load estimation.

	Floor Area (m^2)	Load estimation (kW_{th})
Tower A	22,182 (2,38,765 ft^2)	2,961 (842 TR)
Tower B	22,182 (2,38,765 ft^2)	2,961 (842 TR)
Tower C	15,616 (1,68,089 ft^2)	1,811 (515 TR)
Tower D	22,182 (2,38,765 ft^2)	2,954 (840 TR)
Tower E	22,182 (2,38,765 ft^2)	2,954 (840 TR)
Total	**1,04,344** (11,23,149 ft^2)	**13,641** (3879 TR)

3.3.2. Central cooling plant

The DCS was situated in the basement of the residential apartment complex. The system was equipped with two water cooled screw chillers, each with a capacity of 1583 kW_{th} (450 TR) - one in operation and the other as standby. Additionally, there was a water-cooled screw brine chiller with a capacity of 1477 kW_{th} (420 TR). Figure 3.5 shows the screw chiller installed at the basement. While screw chiller utilize water as a cooling medium, the brine chiller uses brine solution. The brine system incorporated two plate heat exchangers, each with a capacity of 1583 kW_{th} (450 TR), to facilitate heat exchange with the main chilled water loop. The piping configuration of the screw chiller was parallel, as the peak load generally fell below the full capacity of one chiller. This design also employed a constant primary and variable secondary pump strategy to enhance energy efficiency within the distribution network. Furthermore, two thermal energy storage tanks, each with a capacity of 1500 TR-h, were utilized during periods of low load to enhance chiller efficiency. To accommodate fluid expansion and pressure variations, an expansion tank with a volume of 5500 liters was employed.

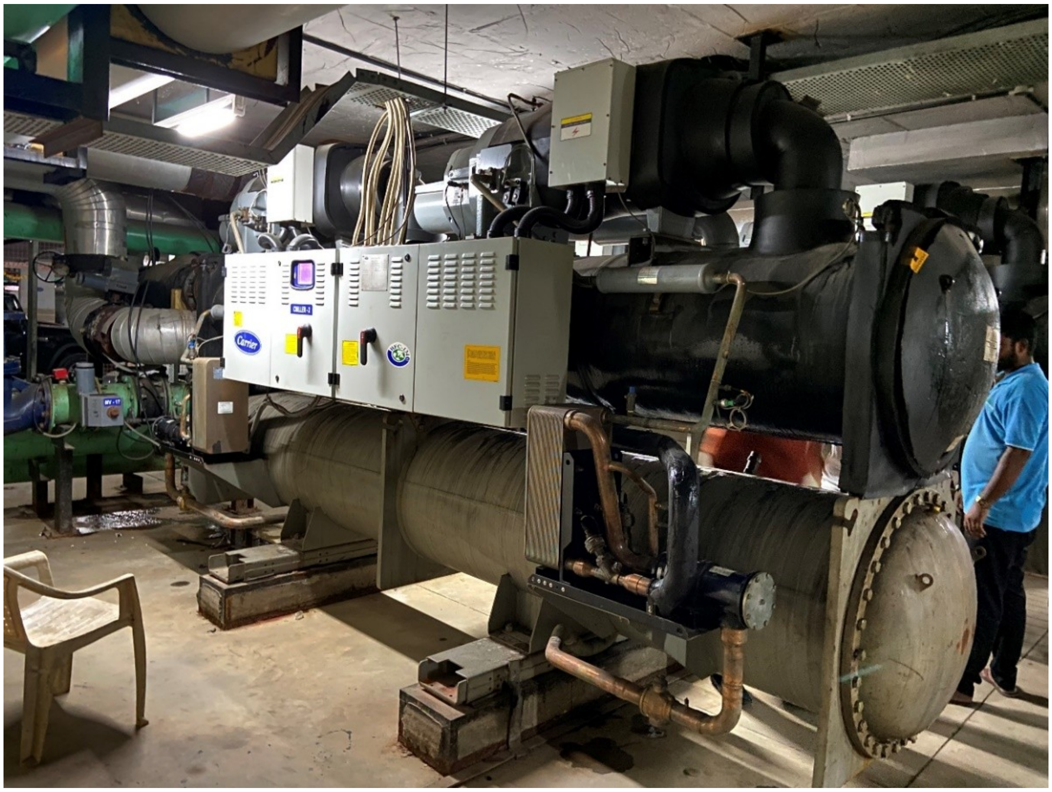

Figure 3.8 Chiller system

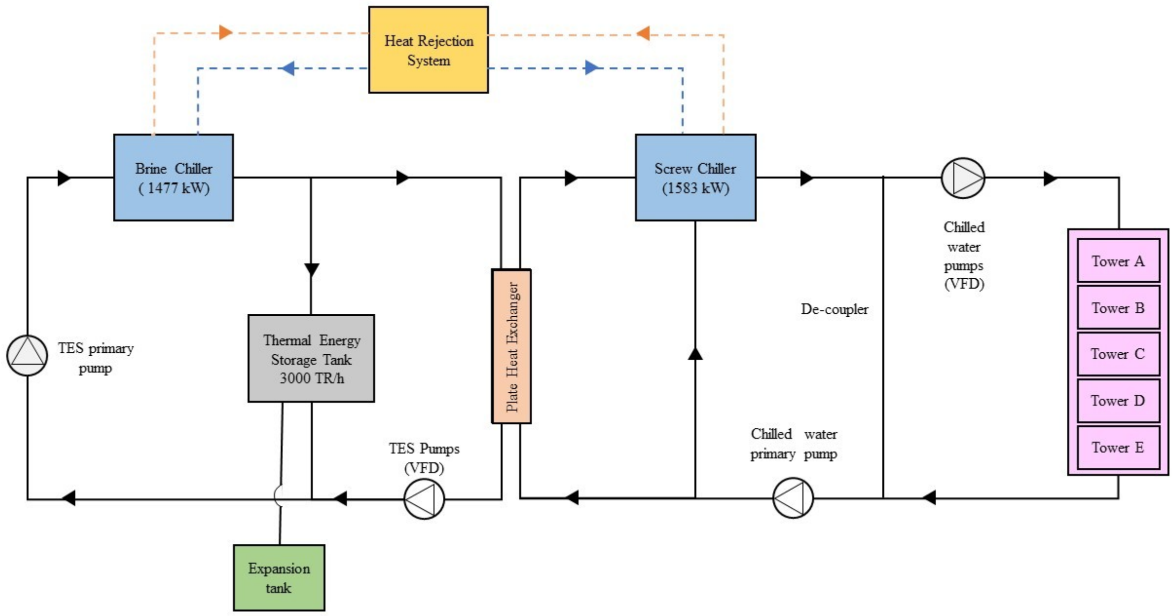

Figure 3.9 Simplified schematic diagram of DCS.

As depicted in the simplified schematic diagram in Figure 3.6, the district cooling system employed a common heat rejection system for both the chillers. The indoor units of the residence have a direct connection with the chilled water system and an indirect connection with the brine chiller system through a heat exchange plate. Depending on the cooling load level, various strategies were adopted to ensure the efficient operation of the chillers. The heat rejection system comprised eight cooling towers utilizing a forced draft design, operating at a constant speed. Among these, two cooling towers have a capacity of 774 kW_{th} (220 TR) each, three cooling towers have a capacity of 528 kW_{th} (150 TR) each and the remaining three cooling towers have a capacity of 440 kW (125 TR) each. The manual operation of these cooling towers is accompanied by continuous monitoring of heat rejection and water chemical levels. Table 3.3 provided the design settings for the DCS. The temperature difference between the supply and the return temperature of condenser water in the chiller system ranges from 2 °C to 6 °C.

Table 3.3 Design settings.

Parameter	Value
Chilled water supply temperature at District Cooling Plant	6 °C
Chilled water supply temperature at the consumer end (°C)	6.5 °C
Chilled water return temperature at the consumer end (°C)	11 °C
Chilled water return temperature at District Cooling Plant (°C)	11.5 °C
Design pressure of the chilled water distribution network (Pa)	4,00,000 Pa
Pressure loss is the chilled water distribution network (Pa)	50,000 Pa

3.3.3. Distributed network

All 387 flats and six common areas are served cooling through a dedicated shaft designed for both the return and supply of chilled water. Figure 3.7 shows the distribution of chilled water from the DCS to the flats. For the circulation of chilled water in the system, two primary pumps with a capacity of 22 kW_e each were employed. Additionally, four secondary pumps were deployed; two pumps with a capacity of 30 kW_e and two pumps with a capacity of 18.5 kW_e, equipped with variable frequency drives to adjust the motor speed according to demand. Five condenser water pumps, each with a capacity of 30 $kW_{e,}$ were used for the circulation of condenser water. Similarly, for the circulation of brine water, two primary pumps with a capacity of 22 kW_e each, were installed, along with four secondary pumps: two pumps with a capacity of 30 kW_e and two pumps with a capacity of 18.5 kW_e.

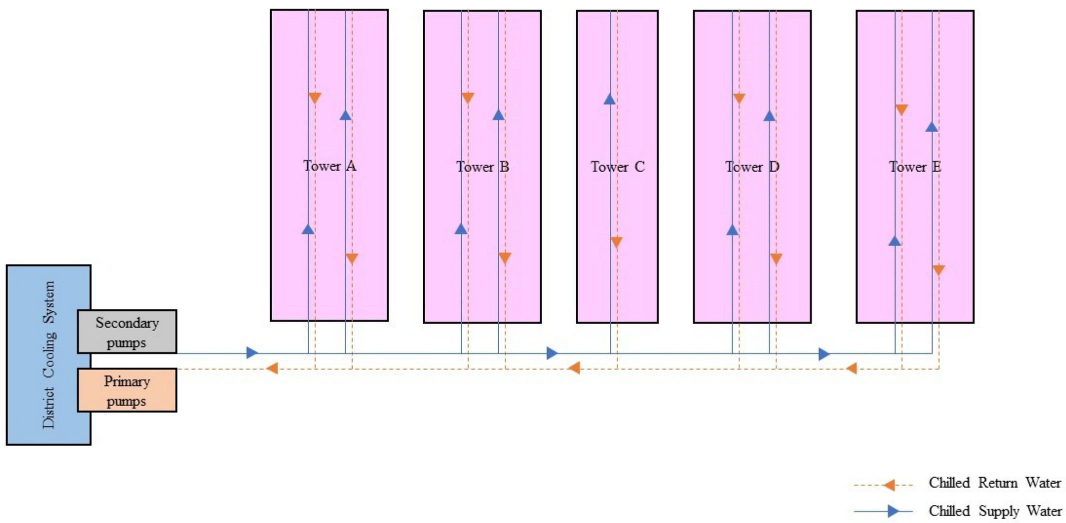

Figure 3.10 Chilled water distribution network.

Figure 3.11 Chilled water supply and return pipes

Nitrile rubber covered with seven mill cloth and white paint was used for insulating the chilled water pipes in the flats. The chilled water header pipeline was insulated using a 75 mm thick Expanded Polystyrene (EPS) pipe section covered with aluminium cladding. Figure 3.8 shows the running chilled water pipes in the shafts. The design temperature drops along the supply and return water in the distribution network were set at 0.5 °C. Nine chilled water shafts facilitated the circulation of chilled water from the plant to each floor.

3.3.4. Terminal system

Figure 3.12 Cassette unit in the living room.

Figure 3.9 shows the view of the living room with cassette unit. The end connection of the DCS is directly connected to each flat with a butterfly valve, thermal energy (BTU) meter and balancing valve. Figure 3.10 shows the BTU meter installed at flats. The thermal energy was measured for every flat separately and the data are stored in the building management system. BTU meter reads the thermal usage of the flat. Apart from regulating the chilled water flow, these valves allowed for disconnection if the residence opted not to use air conditioning. Figure 3.11 illustrates a typical flat A and B with indoor air-cooling units connected to DCS. Each flat was equipped with seven to ten indoor units (cassette/fan coil unit) as per the design.

Figure 3.13 Thermal energy meter.

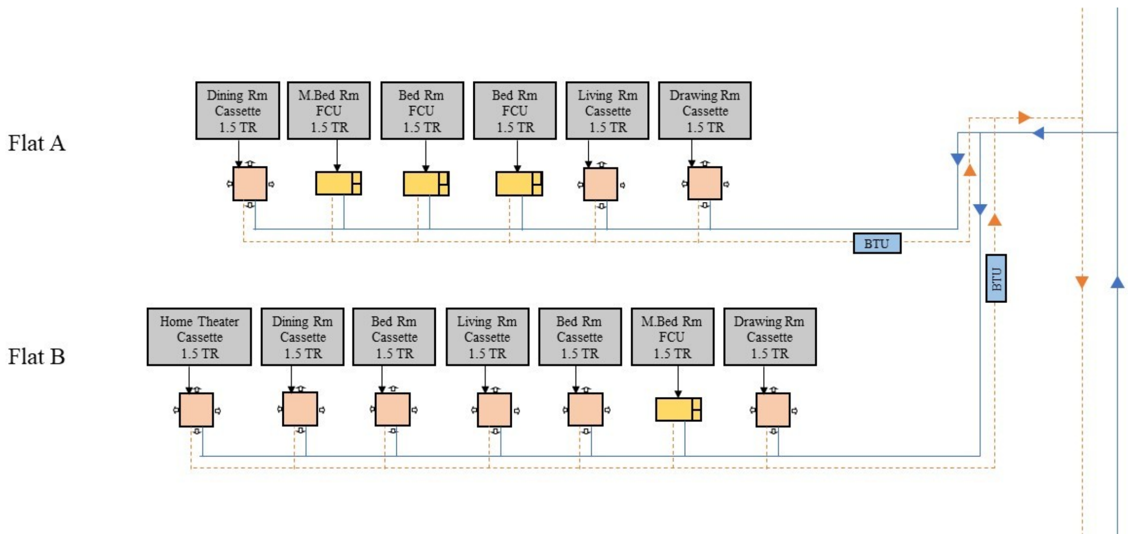

Figure 3.14 Typical flat connection with the DCS.

A summary of the indoor units is presented in Table 3.4. The total number of chilled water Fan Coil Units (FCU) is 829 (1.5 TR - 797, 2 TR - 5, 3 TR - 27), and the total number of chilled water cassette units is 1790 (1.5 TR - 1736, 2 TR- 51, 3 TR - 3). The clubhouse areas featured ceiling-suspended chilled water Air Handling Units (AHU) with a combined capacity of 274 kW (78 TR in total, including 10 TR at multipurpose hall-1, 16 TR at multipurpose hall-2, 16 TR at the gym, 30 TR at the shuttle court and 6 TR at the squash court).

Table 3.4 Indoor units summary.

S No	Location	Cassette			FCU		
		5 kW$_{th}$ (1.5 TR)	7 kW$_{th}$ (2.0 TR)	11 kW$_{th}$ (3.0 TR)	5 kW$_{th}$ (1.5 TR)	7 kW$_{th}$ (2.0 TR)	11 kW$_{th}$ (3.0 TR)
1	Tower A	430	-	-	152	-	-
2	Tower B	374	1	-	206	-	-
3	Tower C	128	50	3	77	5	27
4	Tower D	374	-	-	214	-	-
5	Tower E	430	-	-	148	-	-
Total		**1736**	**51**	**3**	**797**	**5**	**27**

3.4. Monitoring and billing

The monitoring of cooling system usage and electricity usage of the flat was facilitated through a thermal energy meter and a three-phase energy meter, both connected to the building management system and cloud server. The thermal energy was measured from the BTU meter in kWh thermal units and held an accuracy of EC ± (0.5 + $\Delta\Theta$ min/$\Delta\Theta$) %. The electricity meter has an accuracy of class 1 (Default) IEC 61036, CBIP 88 and incorporated options for integrating the BTU meter. The meter transmitted the monitored data to both the server and the building management system within the building. This data was then used to calculate the monthly bills for residents. Electricity data from the district cooling plant was measured collectively for each chiller, pump, and cooling towers. Customers were billed based on the AC consumption recorded by their individual BTU meter, rather than the electricity consumption of the DCS. Figure 3.12 a show the image of the three-phase meter and Figure 3.12 b shows the image of the electricity meter of the pump system.

Figure 3.15 a) Home meter, b) Pump meter

3.5. Data

3.5.1. Data collection

This study used data from 387 flats and six common areas. From the DCS side, chiller data and auxiliary equipment (pumps and cooling towers) data were collected separately. The daily outdoor temperature was collected from the visual crossing website [53]. All data were sourced from the building's Building Management System (BMS) and measured by permanently installed measuring devices. The description of the collected data is given in Table 3.5.

Table 3.5 Description of the data

Type of data	Time period	Data units	Data points	Time interval
AC usage	April 2022 to March 2023 (365 days)	kWh_{th}	13.8 million	15 min
Electricity usage	April 2022 to March 2023 (365 days)	kWh_{e}	0.15 million	15 min

3.5.2. Data processing

The collected data was then cleaned and preprocessed into a readable format suitable for analysis. Microsoft Excel was employed for data viewing and analysis [14]. To protect the privacy of the users' residence IDs were anonymized. Around 2.4% of the data was missing in the collected dataset. To address this, the simple moving average method was applied to interpolate the missing data, using a window of three in the time series [55]. As the values were cumulative, the value was adjusted to match the exact total of the missing data. The year was divided into three parts overlapping with the major seasons: Summer (March to June), Monsoon (July to October), and Winter (November to February). The day was divided into four segments: early morning (12 AM to 6 AM), morning (6 AM to 12 PM), afternoon (12 PM to 6 PM), and night (6 PM to 12 AM).

3.6. Summary

This chapter provides a brief overview of the building and district cooling system, which will be further analyzed based on actual usage data. The study considered flats for typical flats usage patterns without regard to floor area, orientation, or occupancy. It should be noted that the families living in these flats are generally from the upper-middle class, so the findings from the study cannot be extrapolated to the broader population.

Chapter 4

4. Residential AC usage distribution

4.1. Introduction

This chapter analyses AC usage patterns of flats and common areas. It identifies variations in AC usage on a daily and seasonal basis. This chapter further explains the corelation of outdoor temperature and the monthly variations in the AC usage.

4.2. AC usage by all flats

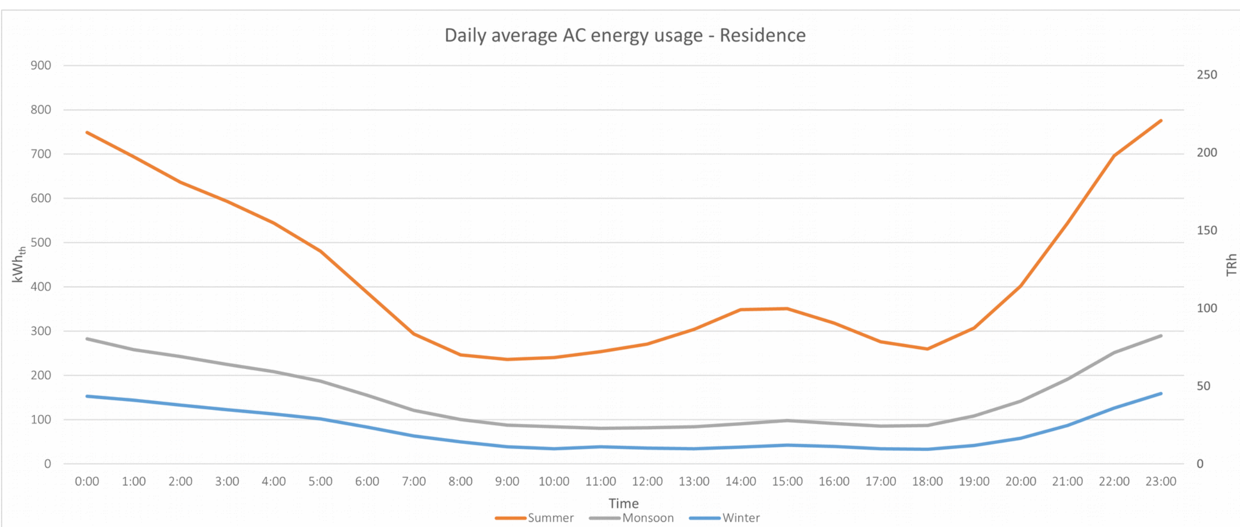

Figure 4.16 Daily average AC usage of flats.

The graph in Figure 4.1 shows the daily average AC usage by all the flats. The total hourly AC load from all the flats during the day was considered for this figure. The hours were averaged for four months to represent the particular season. The daily average thermal usage by the flats during summer, monsoon, and winter was 10,210 kWh_{th}, 3,639 kWh_{th}, and 1,809 kWh_{th} respectively. Table 4.1 represents the hourly average AC usage during the quarter day. The lowest usage occurred during the winter afternoon, and the highest during early summer morning.

Table 4.6 Hourly average thermal load (kW_{th}) of flats.

Time period	Summer	Monsoon	Winter
Early morning	616	234	128
Forenoon	276	105	52
Afternoon	312	89	38
Night	497	179	84

4.3. Probability

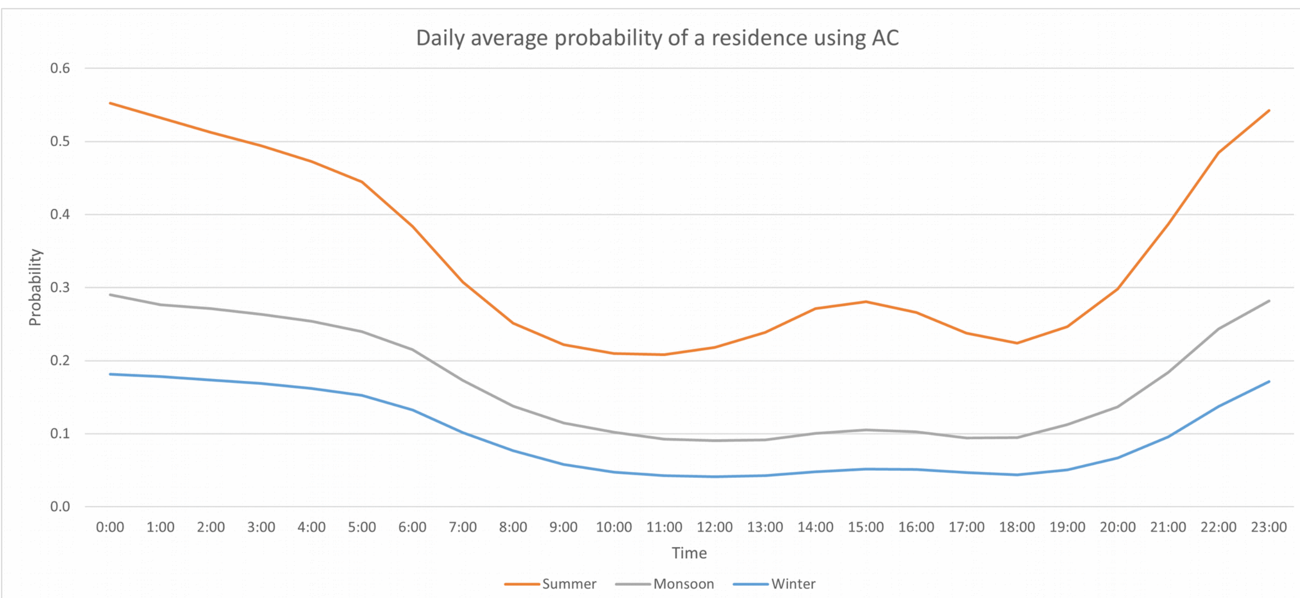

Figure 4.17 Daily average probability of flats using AC.

The graph in Figure 4.2 shows the daily average probability of AC usage by the residents. The hourly probability of flats using AC is calculated by the ratio of the number of days AC is used to the total number of days. Then, the average of each flat's probability is calculated for the particular season. The hourly average probability of a flat using AC during summer, monsoon, and winter was 0.35, 0.17 and 0.10. Table 4.2 represents the hourly average probability of a flat using AC during the respective quarter day. The probability of flats using

AC is lower in the afternoon in all three seasons.

Table 4.7 Hourly usage probability of AC in a typical house.

Time period	Summer	Monsoon	Winter
Early morning	0.50	0.27	0.17
Forenoon	0.26	0.14	0.08
Afternoon	0.25	0.10	0.05
Night	0.36	0.18	0.09

4.4. AC usage per flats (considering all flats)

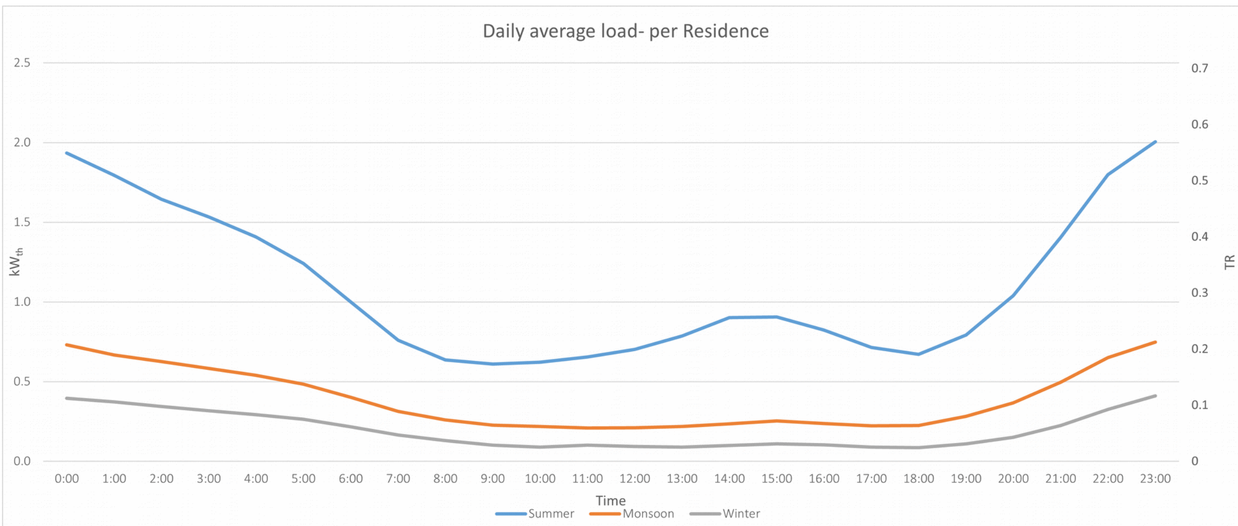

Figure 4.18 Daily average thermal load per flat (all flats).

Figure 4.3 shows the daily average thermal load by a flat (considered all flats). This calculation considers all the flats irrespective of their AC usage at that hour. The hours were averaged for four months to represent the particular season. The daily average thermal usage per flat during summer, monsoon and winter was 26.4 kWh_{th}, 9.4 kWh_{th}, and 4.7 kWh_{th} respectively. Table 4.3 represents the hourly average AC usage per flat (considered all flats) during the quarter day. The daily average AC load per flat (all flats) during summer is 2.8 times more than in monsoon and 5.6 times more than in winter.

Table 4.8 Hourly average thermal load (kW_{th}) of a flat.

Time period	Summer	Monsoon	Winter
Early morning	1.59	0.60	0.33
Forenoon	0.71	0.27	0.13
Afternoon	0.81	0.23	0.10
Night	1.29	0.46	0.22

4.5. AC usage per flat (considering flats using AC)

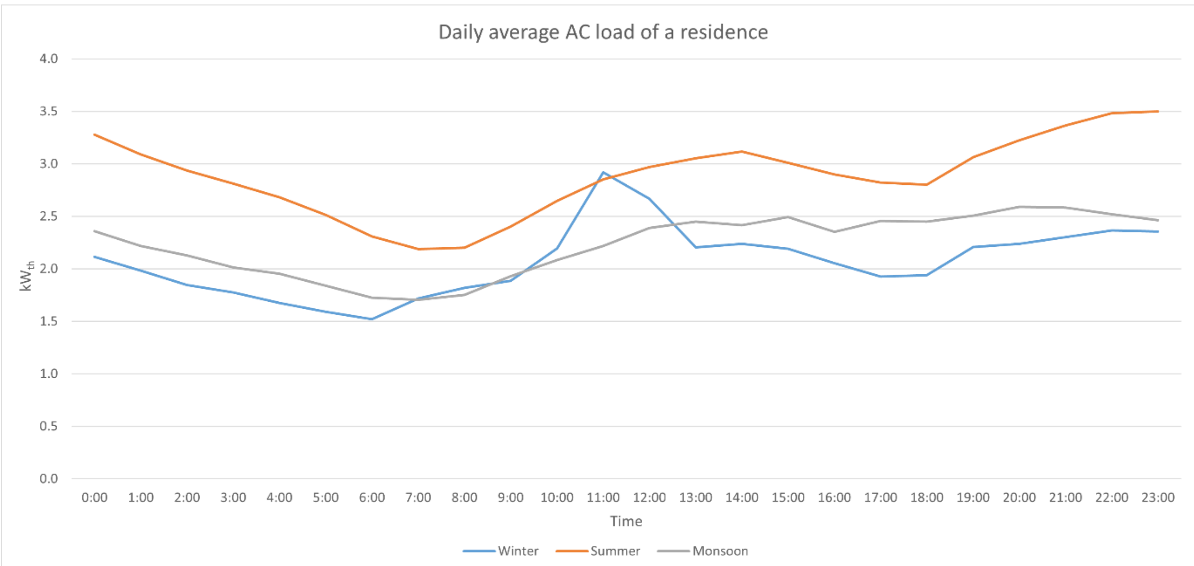

Figure 4.19 Daily average thermal load per flat (flats using AC).

Figure 4.4 shows the daily average thermal load by a flat (considered flats only when AC was used). This calculation considers the flats which use AC during the hour for calculation. The hours were averaged for four months to represent the particular season. In winter, the AC load is higher from 10 AM to 2 PM compared to monsoon. Table 4.4 represents the hourly average AC load per flat (considered flats only when AC was used) during the quarter day. In this table, the AC load during monsoon and winter are almost similar. Table 4.5 shows the daily average AC load per flat (flats using AC) during summer, which is 1.3 times more than in monsoon season and 1.4 times more than in winter.

Table 4.9 Hourly average thermal load (kW_{th}) of a flat.

Time period	Summer	Monsoon	Winter
Early morning	2.9	2.1	1.8
Forenoon	2.4	1.9	2.0
Afternoon	3.0	2.4	2.2
Night	3.2	2.5	2.2

Table 4.10 Average daily energy (kWh_{th}) per flat (flats using AC)

Time period	Summer	Monsoon	Winter
Average daily energy consumption	69.2	53.6	49.7

4.6. Thermal use during weekday & weekend

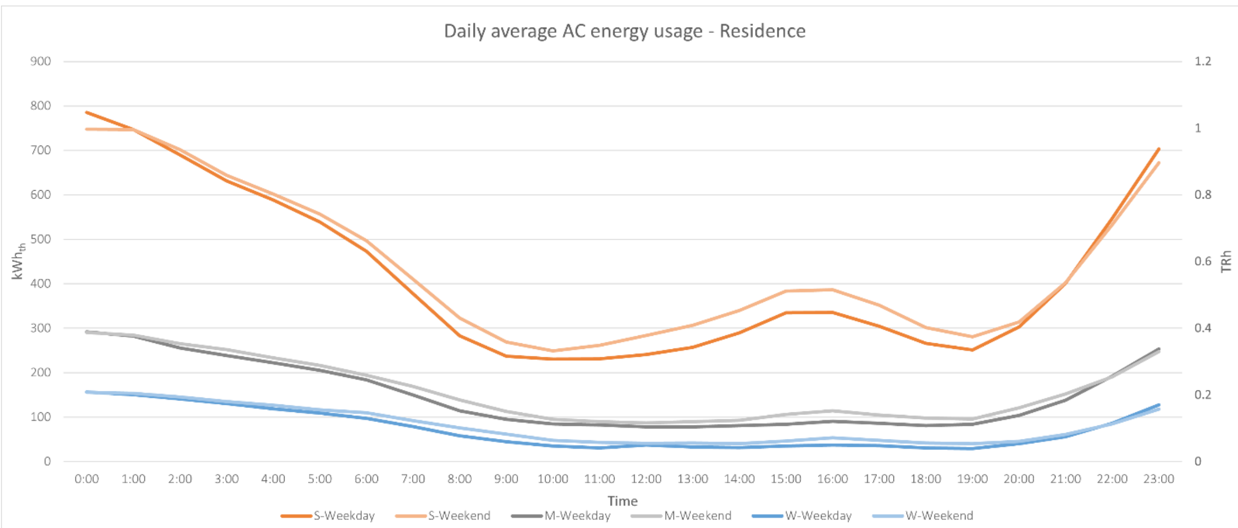

Figure 4.20 Daily average AC usage of flats during weekday and weekend.

Figure 4.5 shows the daily average AC usage by all the residents during weekdays and weekends. This calculation considers Saturday and Sunday as weekends and the remaining days are weekdays. The weekend AC usage during the day is higher compared to the weekdays, but the midnight peak is higher during weekdays. Table 4.6 represents the hourly average AC load of all flats during the quarter day for weekdays and weekends. The table shows that weekend AC usage is higher in all quarters of the day. From Table 4.7, we can see the daily average AC usage during weekdays is slightly higher than at the weekends.

Table 4.11 Hourly average thermal load (kW_{th}) of flats.

Time period	Summer		Monsoon		Winter	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
Early morning	663	667	249	257	134	139
Forenoon	305	335	118	133	57	72
Afternoon	294	342	83	99	35	45
Night	412	417	142	151	62	65

Table 4.12 Average daily energy (kWh_{th}) during weekday and weekend.

	Summer		Monsoon		Winter	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
Average daily energy consumption	10,045	10,563	3,555	3,842	1,732	1,926

4.7. Common areas

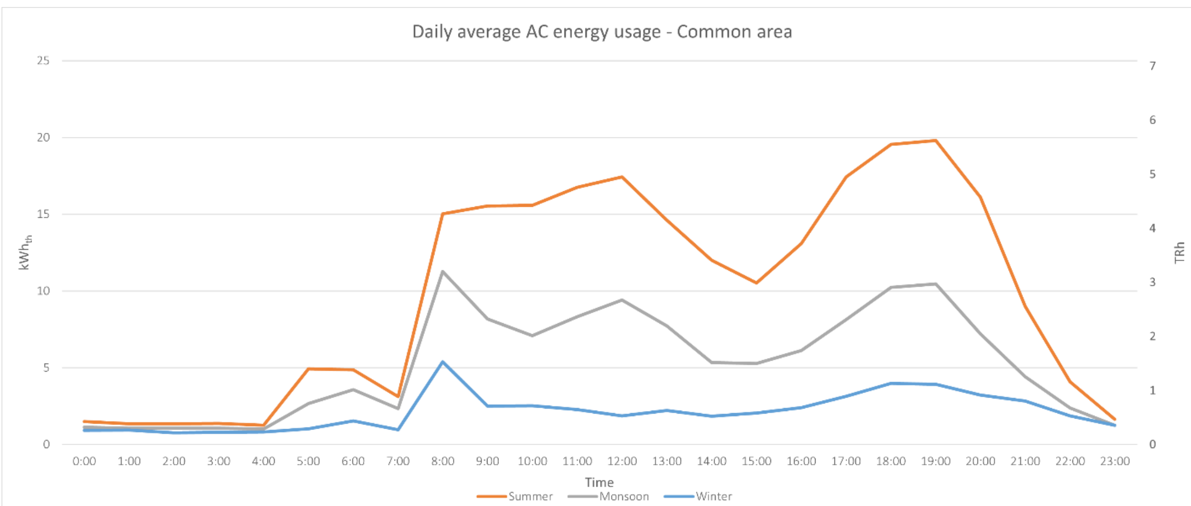

Figure 4.21 Daily average AC usage of common places.

The graph in Figure 4.6 shows the daily average AC usage by the common spaces. The common spaces include a gym, yoga, marketing office, supermarket, indoor court, and multipurpose hall. The average AC usage during the hour of the day by all the common areas is considered for this figure. The daily average thermal usage by the common areas during summer, monsoon, and winter was 238 kWh_{th}, 127 kWh_{th}, and 51 $kWh_{th,}$ respectively. Table 4.8 represents the hourly average AC usage during the quarter day.

Table 4.13 Hourly average thermal load (kW_{th}) of common places.

Time period	Summer	Monsoon	Winter
Early morning	2	1	1

Forenoon	12	7	3
Afternoon	14	7	2
Night	12	6	3

4.8. Overall AC usage

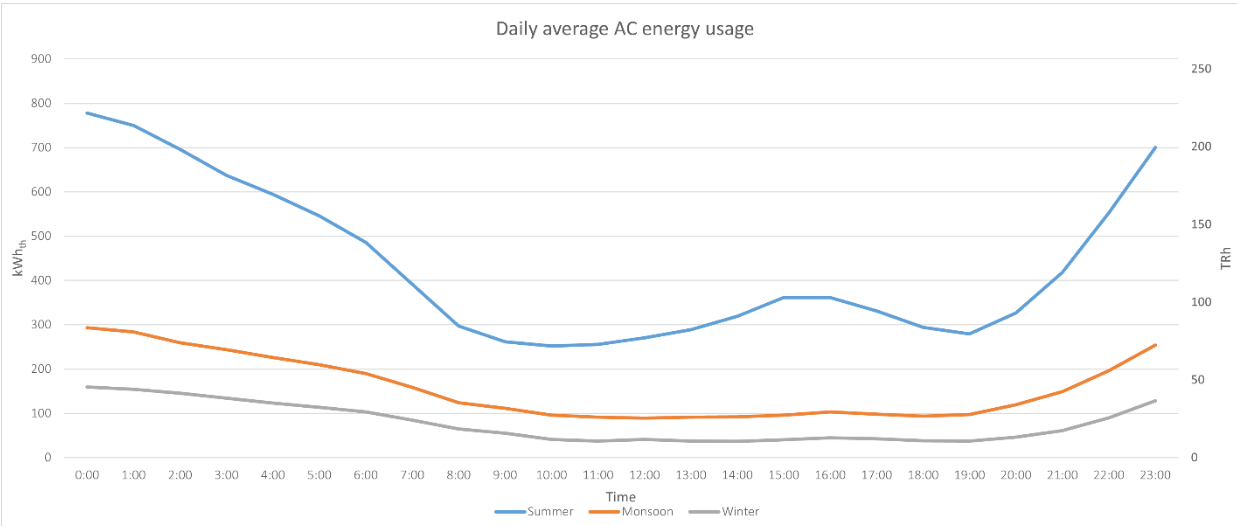

Figure 4.22 Daily average of overall AC usage.

The graph in Figure 4.7 shows the daily average of overall AC usage in the building. This includes both flats and common places. The daily average overall AC usage during summer, monsoon, and winter was 10,449 kWh_{th}, 3,768 kWh_{th}, and 1,859 kWh_{th} respectively. The maximum hourly thermal load in summer, monsoon and winter was 1492 kW_{th}, 556 kW_{th} and 429 kW_{th}. The AC usage of common places during summer, monsoon, and winter was 2.3%, 3.4% and 2.8% of overall AC usage respectively. Table 4.9 represents the hourly average AC usage during the quarter day.

Table 4.14 Hourly average thermal load (kW_{th}) of all users.

Time period	Summer	Monsoon	Winter
Early morning	667	253	138
Forenoon	324	129	64
Afternoon	322	95	40
Night	429	152	67

4.9. Influence of outdoor temperature

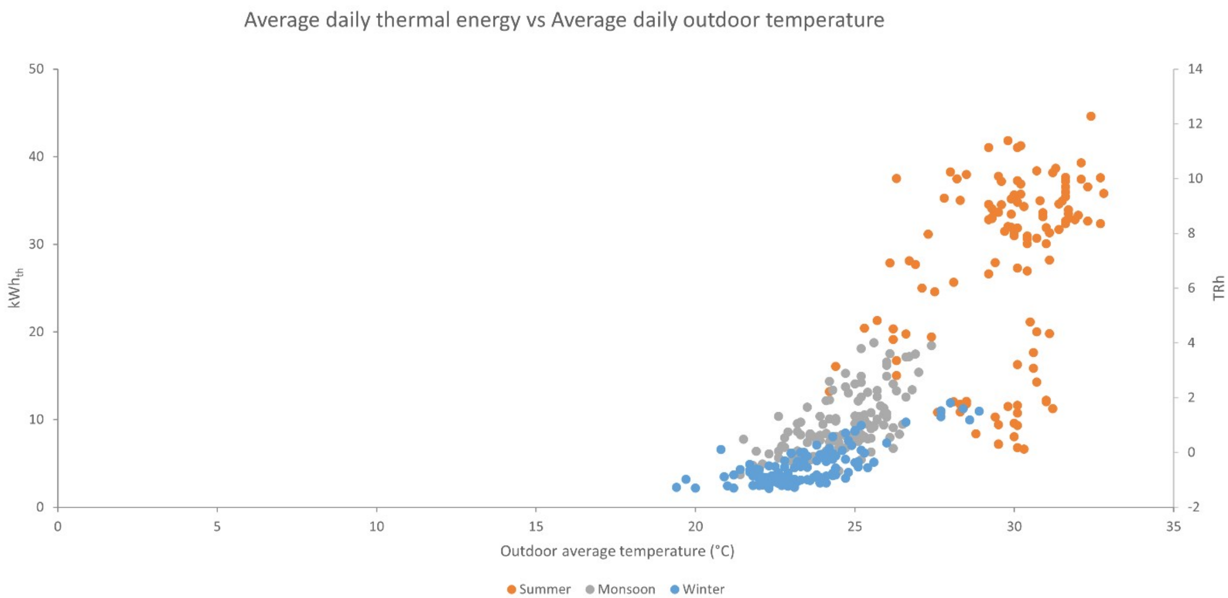

Figure 4.23 Daily average AC usage vs daily average outdoor temperature.

Figure 4.8 reveals the average daily thermal energy as a function of the average outdoor temperature. This calculation uses daily average thermal AC usage per flat (considered all flats). This figure illustrates a clear positive correlation between outdoor temperature and thermal energy. During early summer (march month), the daily thermal load is lower even for higher outdoor average temperatures. The thermal energy consumption by residents is higher in monsoon than in winter, even for the same daily average outdoor temperature.

4.10. Month wise AC usage

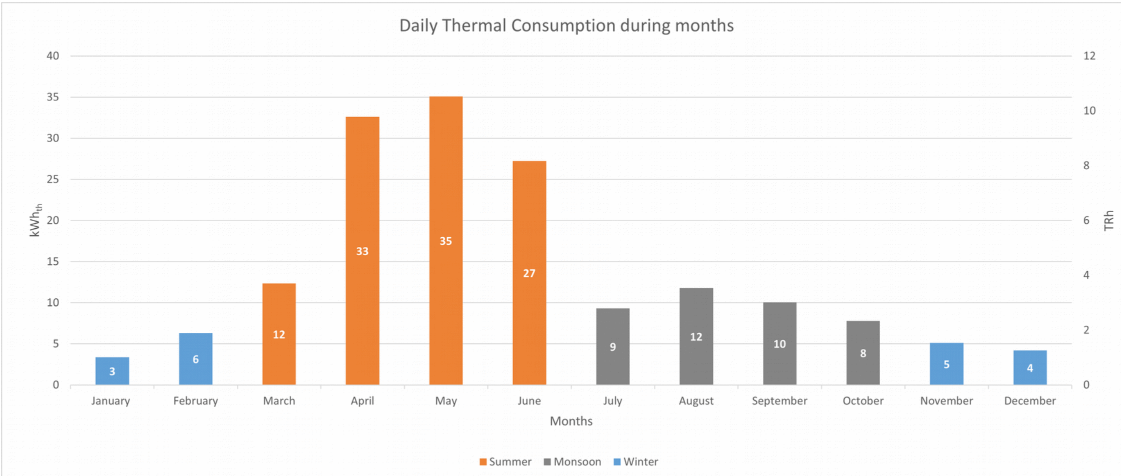

Figure 4.24 Month wise daily AC usage.

The graph in Figure 4.9 shows the daily overall average AC usage per flat during the month. The AC usage includes both flats and common places. The months from January and March are from the year 2023, and the remaining months are from 2022. March 2023 was chosen for summer instead of March 2022 since it has a lot of missing data. Even though the outdoor temperature is high in March, the thermal consumption is still low compared to the other summer months.

Our study shows the summer AC consumption of a house during summer is 9.1 kWh$_{th}$ during daytime and 17.3 kWh$_{th}$ during nighttime. Similar study conducted by Hisham et al. [59] in Malaysia on 20 households revealed that air conditioning was used for around 5 to 6 hours per day, consuming 0.93 kWh$_e$/day during daytime and 3.43 kWh$_e$/day during nighttime. To meet the high demand for electricity, particularly at night when solar photovoltaic solutions are not feasible, it may be necessary to invest in setting up new power plants. Reducing the use of air conditioning during nighttime will help decrease the strain on the power grid and support decarbonization efforts.

Chapter 5

5. System performance

5.1. Introduction

This chapter analyses the electricity consumption pattern of DCS. It identifies variations in electricity consumption on a daily and seasonal basis. This chapter further explains the influence of thermal storage on energy performance.

5.2. Chiller

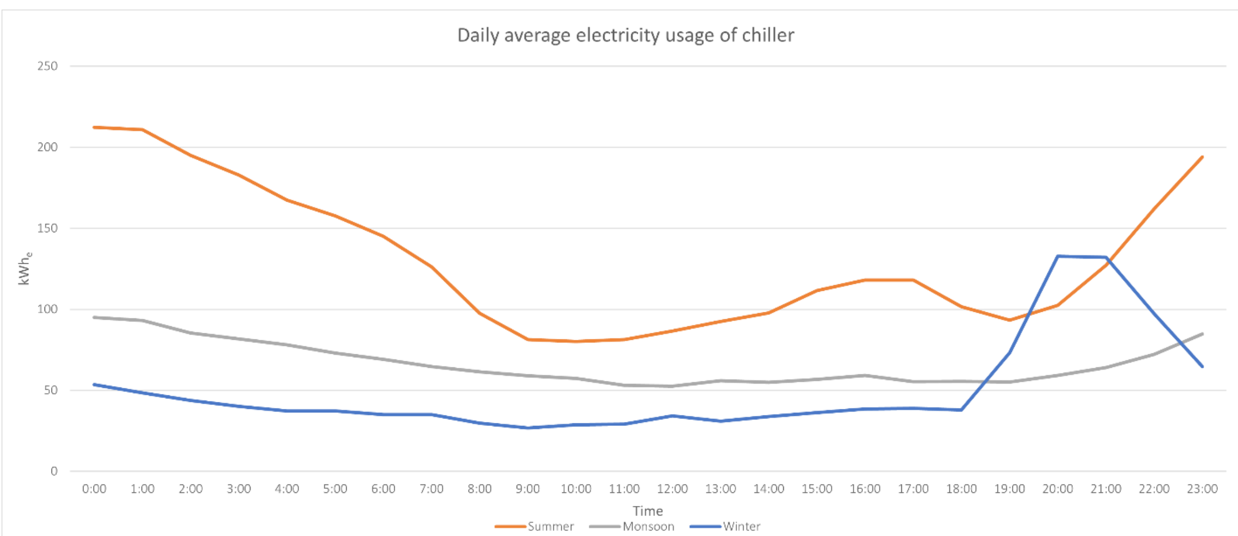

Figure 5.25 Daily average electricity usage of chiller.

The graph in Figure 5.1 shows the daily average electricity usage of the chiller. The average electricity usage during the hour of the day by all the chillers (chiller I & II and brine chiller) is considered. The hours were averaged for four months to represent the particular season. During winter, the thermal storage tank was charged at night and discharged during the remaining period. The daily average electrical usage by the chiller during summer, monsoon, and winter was 3,144 kWh_e, 1,597 kWh_e, and 1,196 kWh_e, respectively. Table 5.1 represents the hourly average electricity usage during the quarter day.

Table 5.15 Hourly average thermal load (kW_e) of chiller.

Time period	Summer	Monsoon	Winter
Early morning	188	84	43
Forenoon	102	61	31
Afternoon	104	56	35
Night	130	65	90

5.3. Chiller operation during winter (Non-TES and TES)

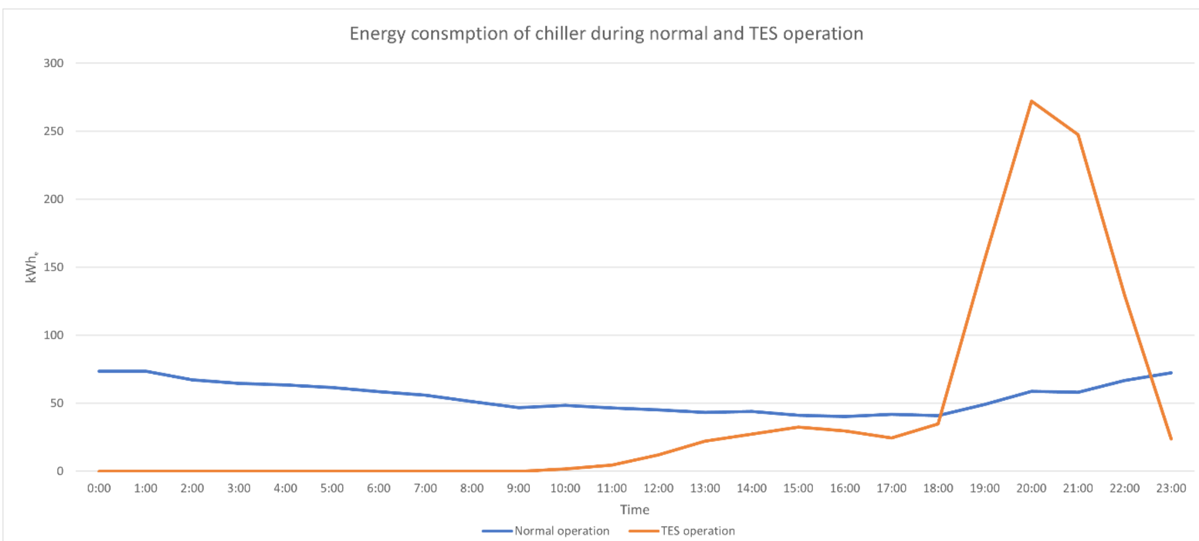

Figure 5.26 Daily average electricity usage of chiller during normal and thermal storage operation.

Ten days were selected for normal operation (Nov 17 to Nov 26) and thermal storage operation (Dec 15 to Dec 24). The graph in Figure 5.2 shows the daily average electricity usage of the chiller. The average electricity usage by all the chillers (chiller I & II and brine chiller) is considered. The hours were averaged for ten days to represent the particular operation. During thermal storage operation, the chiller runs from 7 PM to 10 PM for charging. If the thermal storage runs out before charging, then the chiller starts running to meet the demand. Table 5.2 represents the comparison of normal operation and thermal storage operation. The hourly load mentioned in the table is the average electricity usage of the chiller during the operation time. For the hourly load calculation in thermal storage operation, the chiller load was considered only when the charging happens.

Table 5.16 Comparison of DCS operation with thermal storage and non-storage.

	No of hours chiller operated	Hourly load of chiller during operation (kW_e)	Chiller energy consumption (kWh_e)	Pumps & auxiliary equipment (kWh_e)	Thermal energy delivered (kWh_{th})	COP (considered only chiller)	COP (considered chiller, pumps & auxiliary equipment)
Normal operation	24	53	1315	1438	1610	1.15	0.54
Thermal storage operation	4	212	1018	1221	1236	1.34	0.63

5.4. Pumps & auxiliary equipment

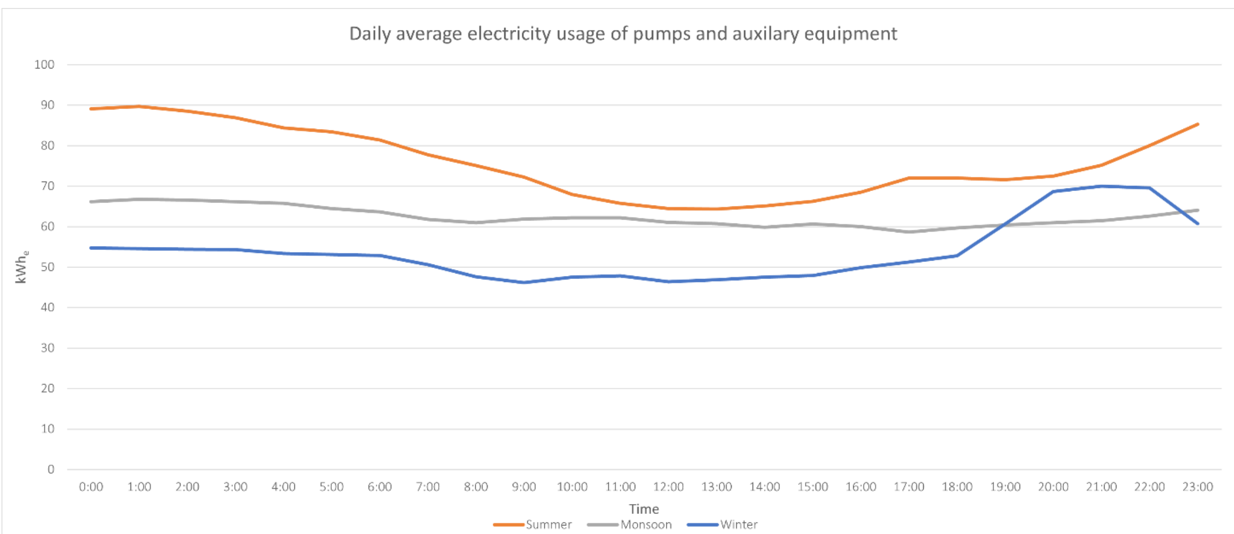

Figure 5.27 Daily average electricity usage of pumps and auxiliary equipment.

The graph in Figure 5.3 shows the daily average electricity usage of the chiller. The average electricity usage during the hour of the day by primary pumps, secondary pumps, condenser pumps, thermal storage pumps and cooling towers. The daily average electrical usage by pumps and auxiliary equipment during summer, monsoon, and winter was 1,820 kWh_e, 1,499 kWh_e, and 1,290 kWh_e, respectively. Pumps and auxiliary equipment contribute around 45%, 54% and 41% of the total consumption of DCS during summer, monsoon, and winter, respectively. Table 5.3 represents the hourly average electricity usage of pumps and auxiliary equipment during the quarter day.

Table 5.17 Hourly average thermal load (kW_e) of pumps and auxiliary equipment

Time period	Summer	Monsoon	Winter
Early morning	87	66	54
Forenoon	73	62	49
Afternoon	67	60	48
Night	76	62	64

5.5. Month wise DCS consumption

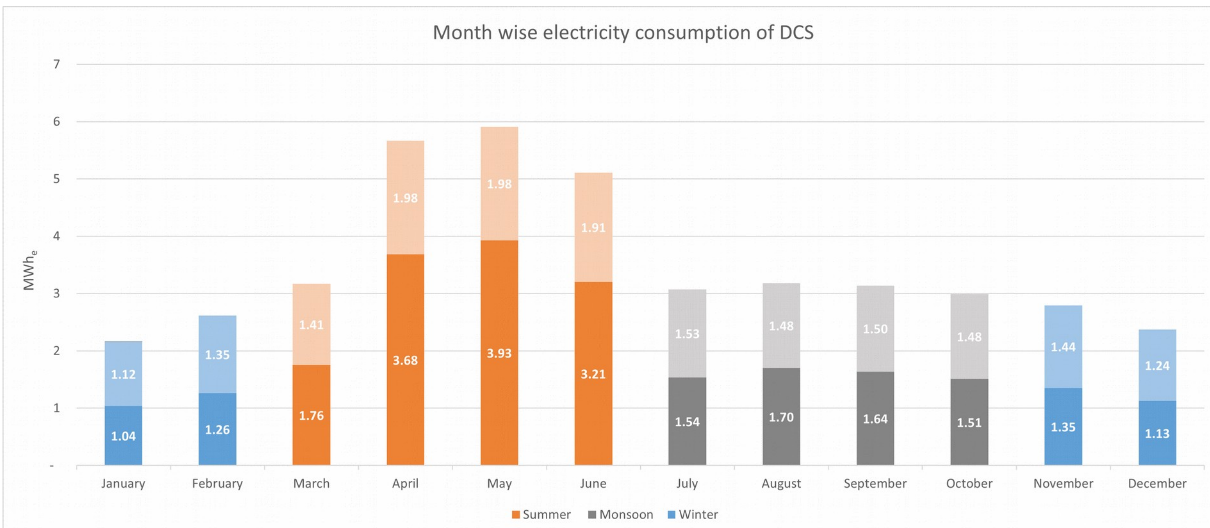

Figure 5.28 Month wise daily electrical usage of DCS.

The graph in Figure 5.4 shows the daily average electrical usage of DCS during the month. This includes chillers, pumps, and auxiliary equipment. The months from January and March are from 2023 and the remaining months are from 2022. March 2023 was chosen for summer instead of March 2022 since it has a lot of missing data. Table 5.4 shows that daily average AC usage on weekdays is slightly higher than on weekends.

Table 5.18 Average daily energy (MWh_e) of DCS.

Time period	Summer	Monsoon	Winter
Average daily energy consumption	4.96	3.10	2.49

Chapter 6

6. Peak month analysis

6.1. Introduction

This chapter analyses the peak month AC usage and electricity consumption pattern of DCS. It identifies day to day variations in load pattern and its performance. This chapter further explains the load diversity of the DCS.

6.2. Daily average temperature

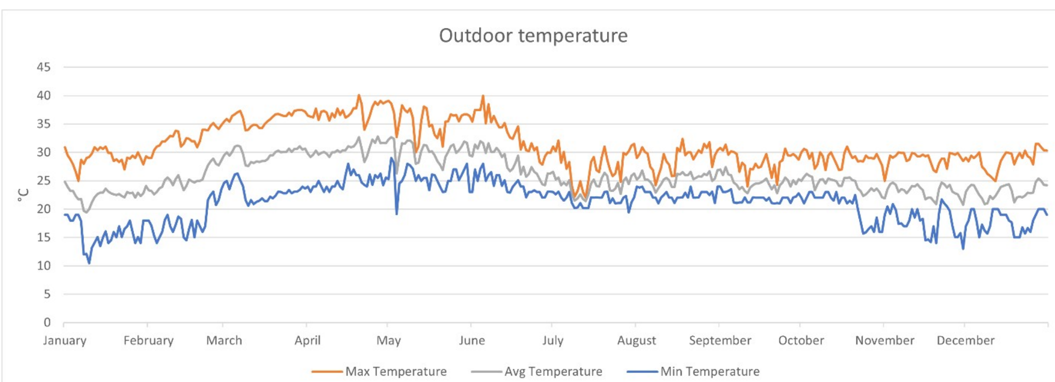

Figure 6.29 Daily average outdoor temperature.

The graph in Figure 6.1 shows the maximum, average and minimum of daily outdoor temperatures. The data for the graph is sourced from the website visual crossing [53]. The temperature during May lies in the upper bound, and the thermal requirement during May is higher than other months. In this chapter, we will analyze the peak month AC usage and electrical usage of

DCS.

6.3. AC usage per flat

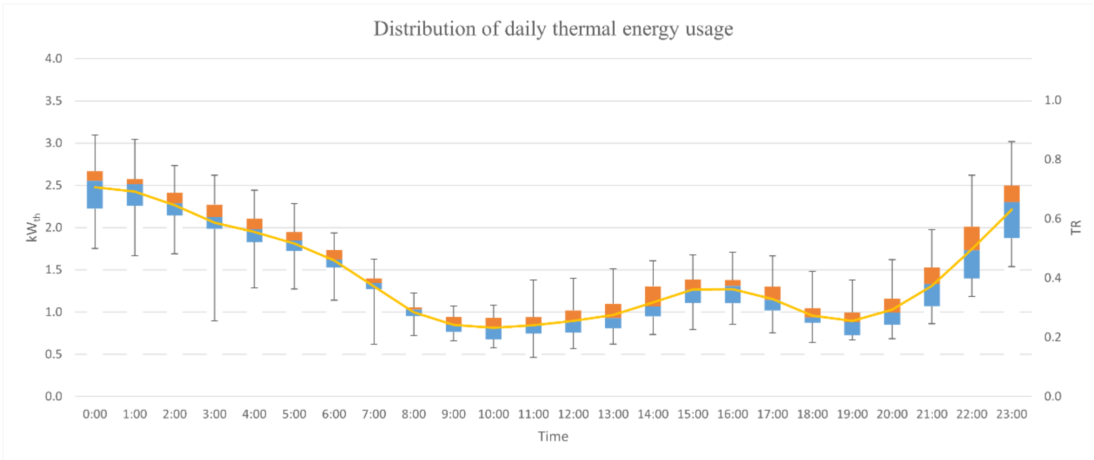

Figure 6.30 Distribution of daily AC usage per flat.

The graph in Figure 6.2 shows the distribution of daily AC usage per flat during peak month. The average daily AC usage per flat was 34.3 kWh_{th}. The average hourly thermal load per flat during the peak month was 1.43 kW_{th} and the maximum thermal load was 3.1 kW_{th}. The average thermal load during different times (average over the month of May) is as follows: early morning (12 am to 6 am) – 2.17 kW_{th}, forenoon (6 am to 12 pm) – 1.07 kW_{th}, afternoon (12 pm to 6 pm) – 1.11 kW_{th} and night (6 pm to 12 am) – 1.36 kW_{th}.

6.4. Overall thermal usage

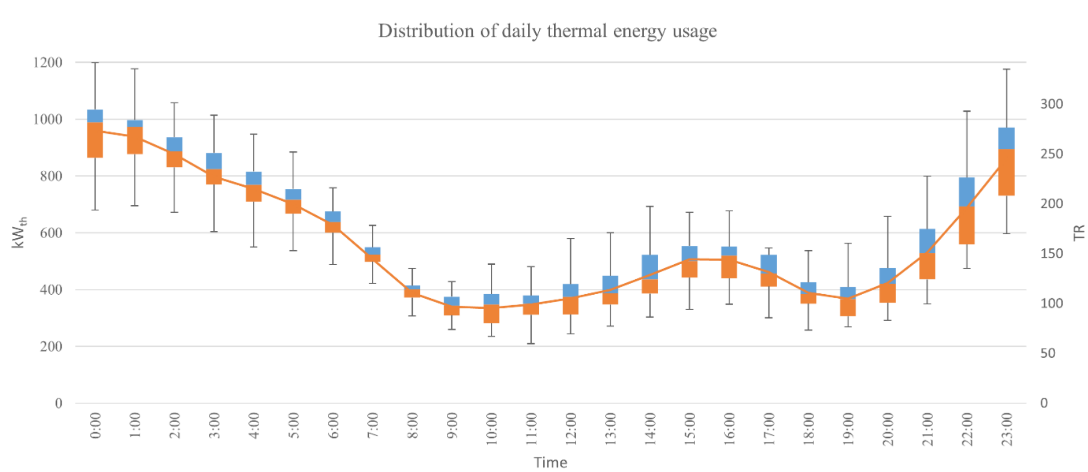

Figure 6.31 Distribution of daily AC usage.

The graph in Figure 6.3 shows the distribution of daily overall thermal usage. This includes both the flats and common areas. The average daily overall thermal consumption was 13,565 kWh_{th}. The average hourly thermal load during the month was 565 kW_{th} and the maximum hourly thermal load was 1199 kW_{th}. The average thermal load during different times (average over May) is as follows: early morning - 840 kW_{th}, forenoon - 426 kW_{th}, afternoon - 450 kW_{th} and night - 545 kW_{th}. The interquartile range is small during the day and high during the night.

6.5. Electrical usage of DCS

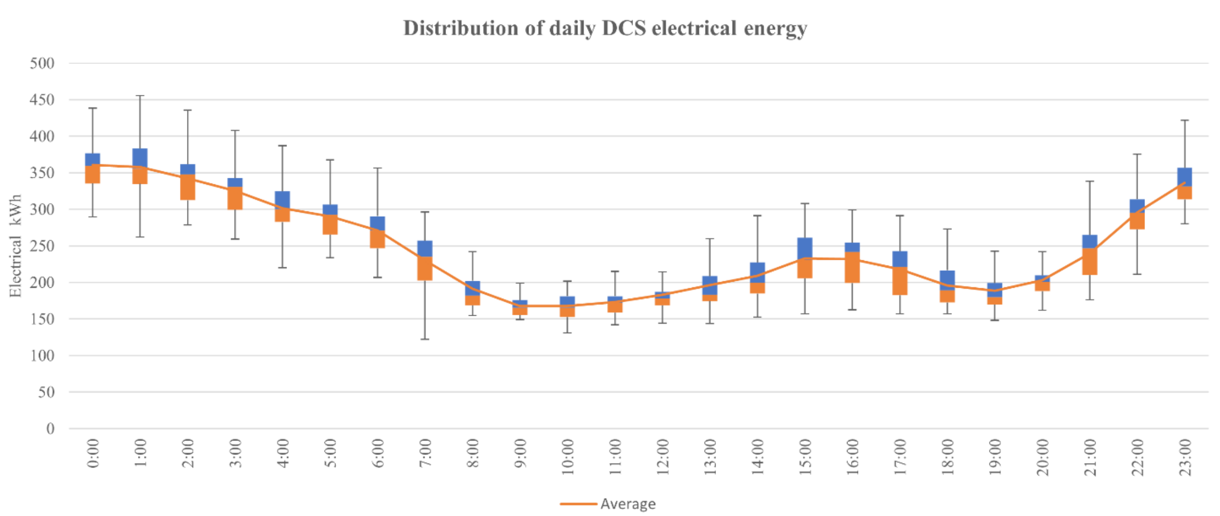

Figure 6.32 Distribution of overall daily DCS electricity usage.

The graph in Figure 6.4 shows the distribution of daily electricity usage of DCS. This includes chillers, pumps, and auxiliary equipment. The average daily electricity consumption of DCS was 5,910 kWh_e with a single active chiller meeting the load. This indicated that for the apartment of 387 flats, the average daily energy consumption of DCS was 15.3 kWh_e per residence. The maximum hourly electrical load of the DCS was 481 kW_e. The average electrical load of DCS during different times (average over the month of May) is as follows: early morning - 330 kW_e, forenoon - 200 kW_e, afternoon - 212 kW_e and night - 243 kW_e.

6.6. Coefficient of Performance (COP)

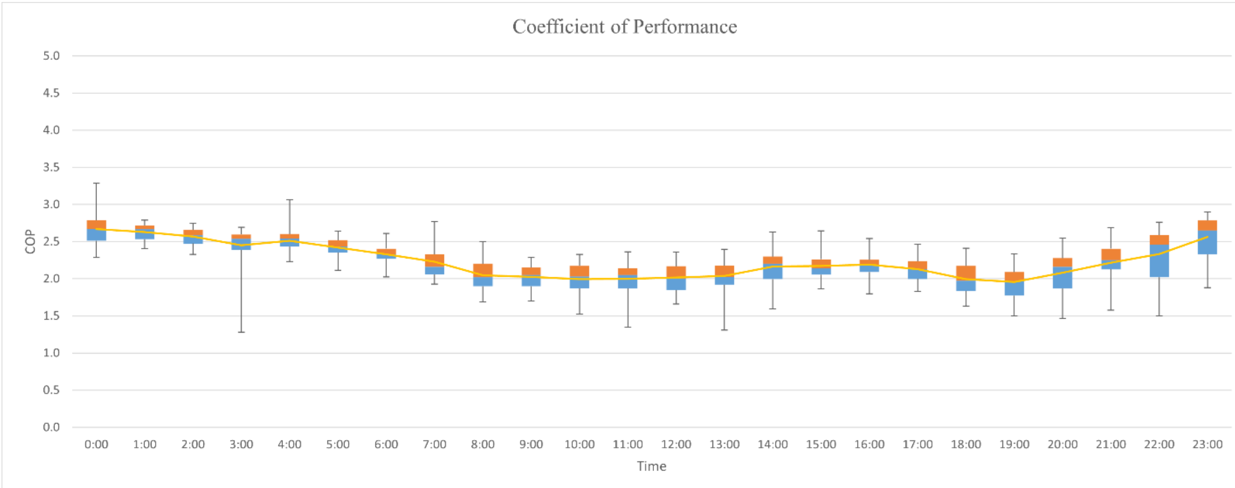

Figure 6.33 Distribution of daily COP.

The graph in Figure 6.5 shows the daily COP. This was calculated from the ratio of overall thermal energy consumed (flats and common areas) and the electricity usage by the DCS (both chillers and auxiliary equipment). The daily average COP during the peak month was 2.2. The average COP during different times (average over the month of May) is as follows: early morning - 2.54, forenoon - 2.1, afternoon - 2.12 and night – 2.19.

6.7. AC usage distribution (Peak month) per day

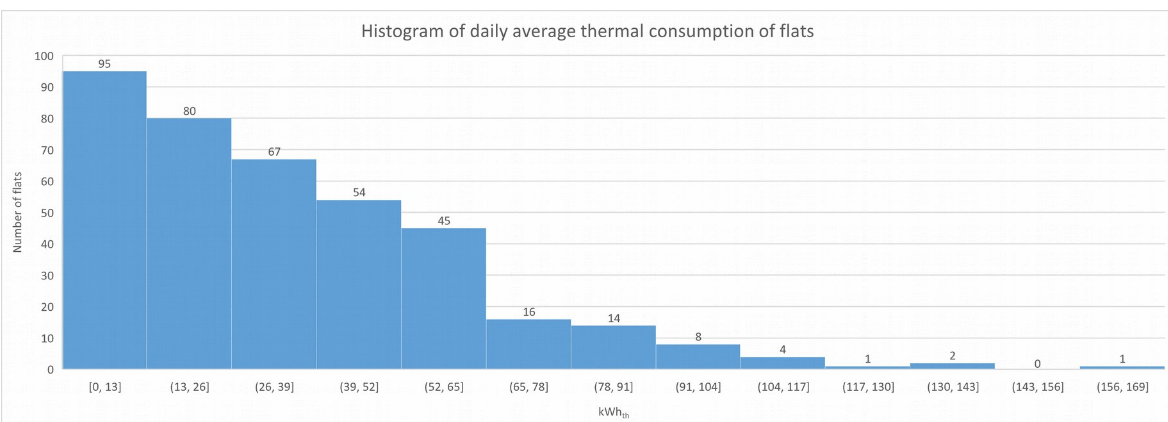

Figure 6.34 Histogram of daily thermal consumption of flats.

The graph in Figure 6.6 shows the distribution of the daily average thermal consumption of flats.

The x-axis represents the interval of daily thermal energy consumed in peak month, and the y-axis displays the total number of flats. The mean daily thermal consumption of a flat during peak month was 34 kWh_{th}. The distribution of monthly AC consumption of flats higher than the mean value is sparser than flats with lower AC consumption. The interquartile distribution of the monthly AC consumption of the flats ranges between 13 kWh_{th} to 51 kWh_{th}.

6.8. Load diversity

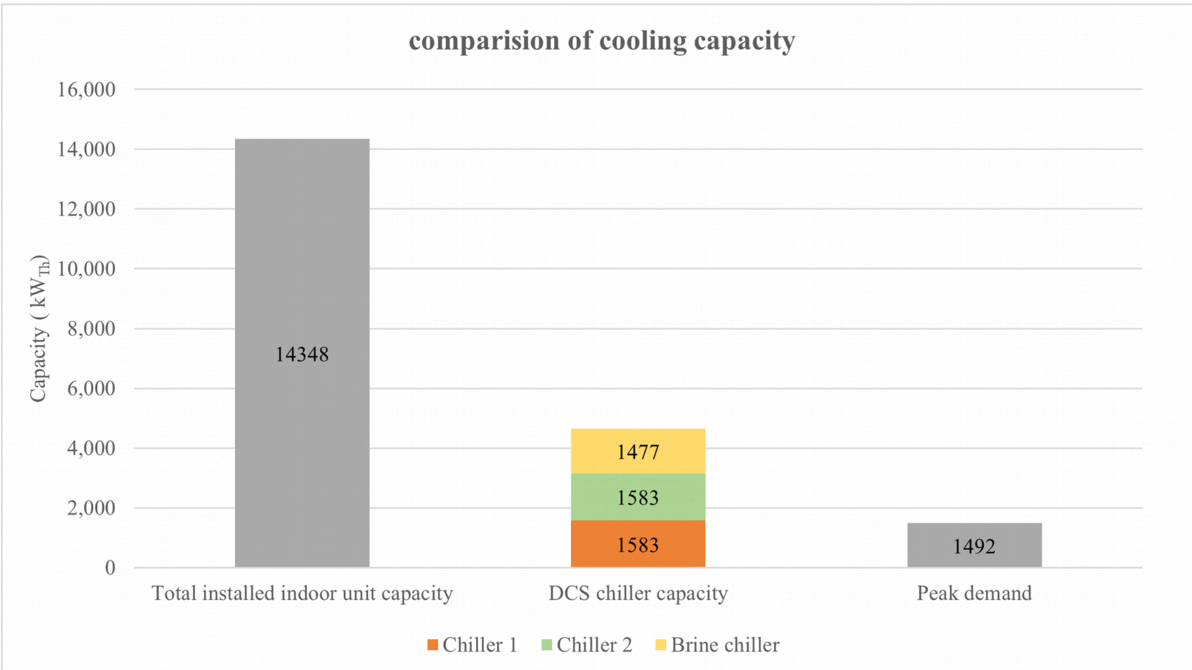

Figure 6.35 Comparison of installed cooling system and peak demand.

Figure 6.7 compares the total installed indoor cooling units, total chiller capacity and peak cooling load. The total installed indoor cooling unit capacity of the buildings was 14,348 kW_{th} (4079.5 TR), comprising 14073 kW_{th} (4001.5 TR) from residential units and 274 kW_{th} (78 TR) in common spaces. The total installed chiller capacity of the DCS was 4642 kW_{th} (1320 TR), comprising three individual chillers. The primary chiller was a 1583 kW_{th} (450 TR) screw chiller, supported by a standby chiller of the same capacity, which operated on a rotating basis. Additionally, a brine chiller with a capacity of 1477 kW_{th} (420 TR) was used to produce chilled brine solution for a thermal storage tank. It is important to note that the thermal energy storage tank (3000 TRh) within the DCS was used only during low-load conditions (especially in winter). Therefore, the tank's thermal capacity was not factored into the total cooling capacity calculation.

The peak thermal energy demand was 1492 kW_{th} (424 TR), which was effectively managed using a single chiller. This overall thermal peak occurred on 1^{st} June. Compared to the installed capacities, the peak demand represented 10.4% of the indoor unit capacity and 94.3% of the primary chiller capacity.

Chapter 7

7. Building simulation model

7.1. Introduction

In this chapter, a simulation model has been developed for a residential district cooling system. The energy simulation model and the parameters used are discussed. This model uses the cooling load profile of the flats, developed based on the operational data of April month.

7.2. Methodology

Building energy modelling is a physics-based technique used in the prediction and analysis of building energy use. In this research work DesignBuilder software (version 7.0.2.006) was used that is based on EnergyPlus. Figure 7.1 shows the methodology used for developing the model. The weather data for simulation was downloaded from the EnergyPlus website [56]. The occupancy schedule was developed from the operational data of the flats. The HVAC component of the simulation model was made similar to the case study building. Tuning was performed on the cooling load schedule to match the cooling load profile of the measured data.

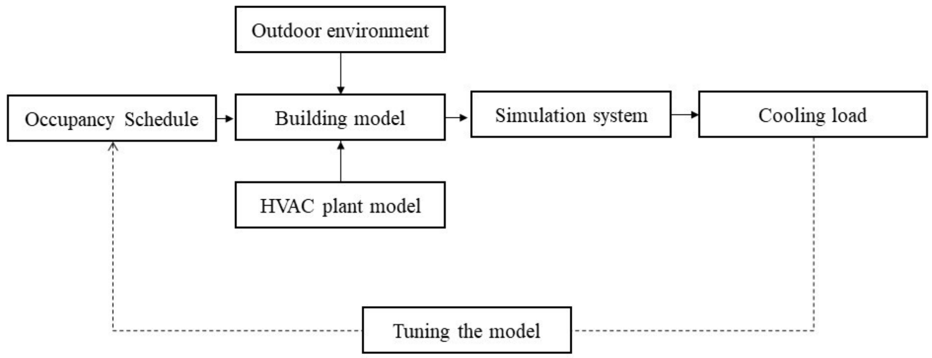

Figure 7.36 Framework for simulating the model.

7.3. Geometry modeling input

The simulation model is a five towered apartment with 18 floors. There are four identical towers A, B, D, and E with the layout-based on Figure 7.2. Tower C layout was based on Figure 7.3. The model consists of 387 flats with five different layouts.

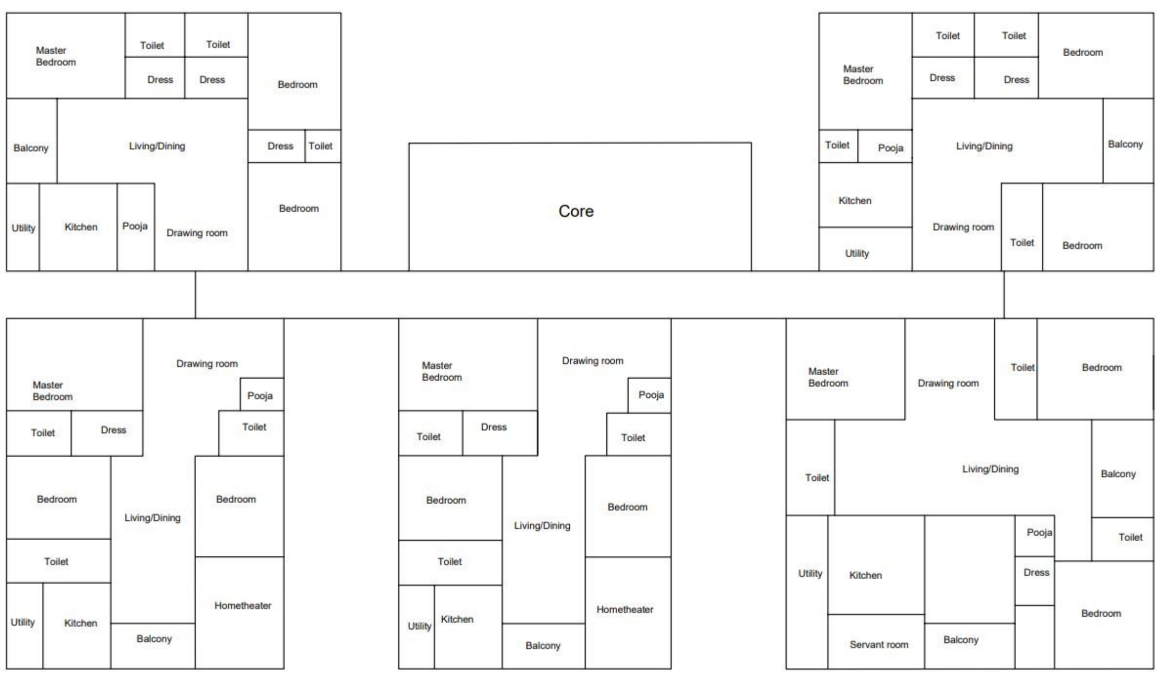

Figure 7.37 Layout of tower B

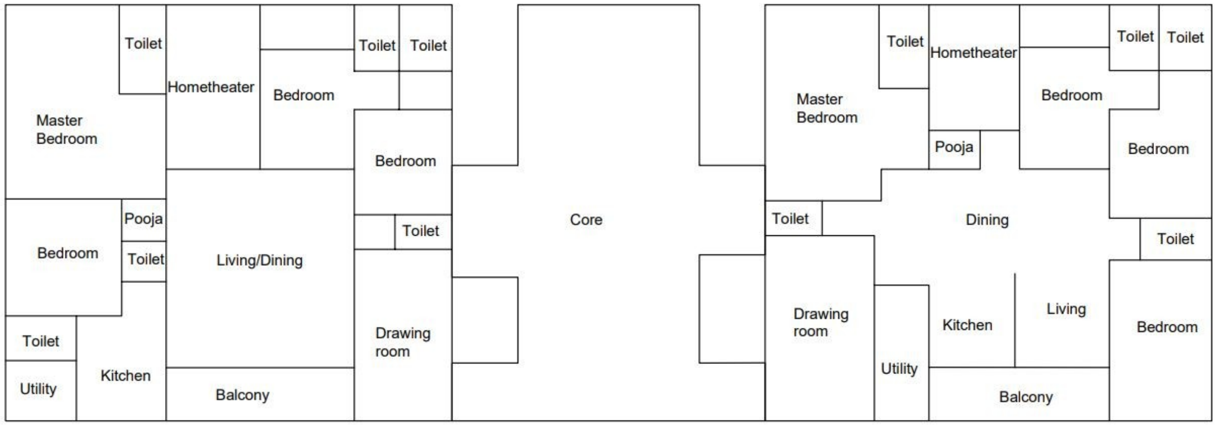

Figure 7.38 Layout of tower C

The zone multiplier method was used to reduce the size of the model [57]. The typical floor was placed at middle level for simulation. The adiabatic component block is added, and the model is shown in Figure 7.4. This method has a greatly reduces the simulation run time with a slight impact on the energy performance accuracy [58]. The envelope characteristics of the building are given in Table 7.1.

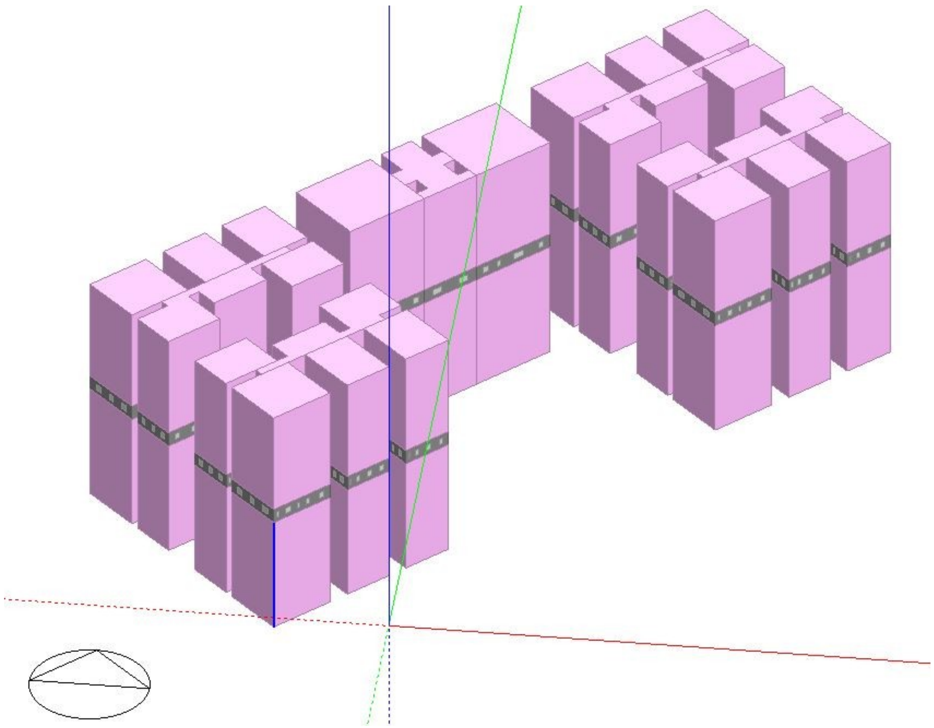

Figure 7.39 DesignBuilder model

Table 7.19 Physical components

Components	Value	Units
Wall U-factor	1.49	$W.m^{-2}.K^{-1}$
Roof U-factor	0.89	$W.m^{-2}.K^{-1}$
Glass U-factor	5.67	$W.m^{-2}.K^{-1}$
Glass SHGC	0.82	
Wall window ratio	15	%

7.4. Building load inputs

The building energy model relies on several components including the operational schedules and setpoints of the building equipment. Table 7.2 provides information on the internal load caused by appliances, lights, and occupancy. This model was created to replicate the summer month (April) cooling load profile by using probability and load of the flat from the earlier analysis.

Table 7.20 Building parameters used in the model.

Parameters	Values	Units
Occupant density	0.019	$People/m^2$
Lighting power density	6	W/m^2

Equipment power density	3	W/m^2
Cooling setpoint	25	°C

7.5. HVAC plant input

This model used the existing HVAC template from DesignBuilder and updated as per the site requirements. The cooling system used in this experiment was Fan Coil Unit (4-Pipe), Water cooled chiller as shown in Figure 7.6.

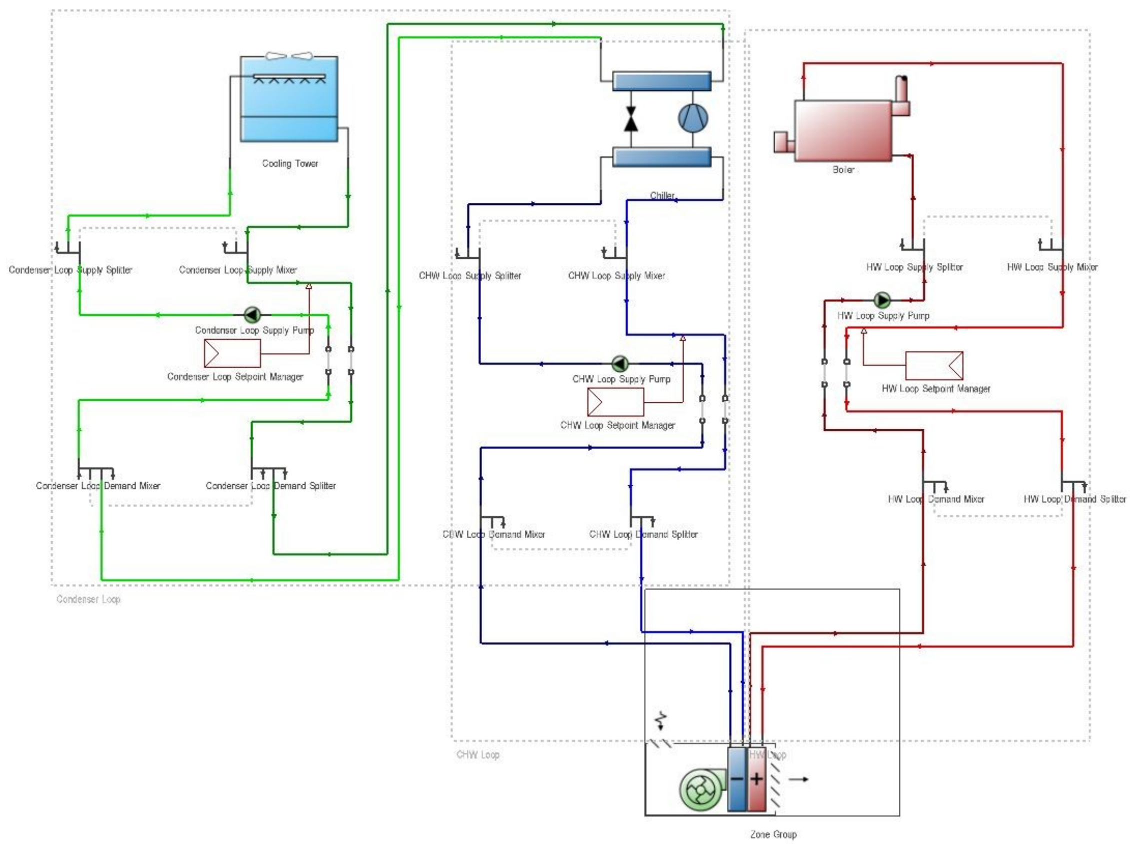

Figure 7.40 HVAC layout.

7.6. Validation of the model

By considering the probability of flats using AC, individual occupancy schedules for the flats were generated as shown in Figure 7.6. For each flat, the schedule for room indoor units varies based on the cooling load intensity. Out of 22 flats, only 14 flats were operating at the peak AC usage on an average day. A total of 14 schedules were created for the flats initially. The model was simulated on an hourly basis to find the cooling load profile of the flats during the summer month (April). The hourly total cooling load profile of the simulated model was compared with the actual cooling load profile of the flats. Figure 7.7 shows the hourly comparison between the cooling load profile of the initial simulated data and the actual data. It shows the total hourly consumption of flats during the time of the day. There is a huge variation in the overall cooling profile.

	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
H1	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
H2	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
H3	5	5	5	5	5	5	5	5	5	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5
H4	5	5	5	5	5	5	5	5	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	5
H5	5	5	5	5	5	5	5	5	0	0	0	5	5	5	5	5	5	5	0	5	5	5	5	5
H6	5	5	5	5	5	5	5	0	0	0	0	0	5	5	5	5	5	5	0	5	5	5	5	5
H7	4	4	4	4	4	4	3	0	0	0	0	0	0	0	4	4	0	0	0	0	4	4	4	4
H8	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5
H9	4	4	4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	4
H10	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5
H11	4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4
H12	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4
H13	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
H14	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4

Figure 7.41 Initial cooling load schedule

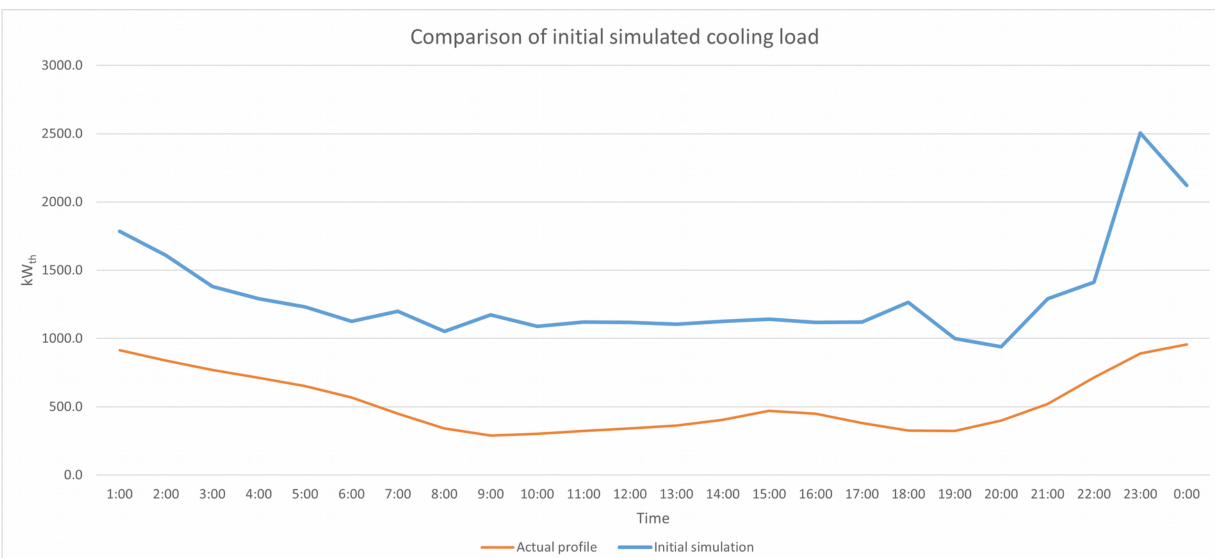

Figure 7.42 Comparison of initial simulated cooling load.

Tuning was performed on the number of operating indoor units and their schedules of each flat.

For tuning, the schedules were rearranged to match the cooling load profile of the actual measured data. Figure 7.8 shows the tuned flatwise cooling schedule along with the number of zones. The final cooling load profile of the simulated model and the actual profile was shown in Figure 7.9. The daily average cooling consumption of the actual operation and simulated model resulted in a consumption of 12,702 kWh_{th} and 13,688 kWh_{th} during the April month. The difference between the average daily cooling load of actual and simulated models was 7.2%.

	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
H1	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
H2	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
H3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1
H4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1
H5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1
H6	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	0	2	2	2	2	2
H7	2	2	2	2	2	2	2	2	0	0	0	0	0	0	2	2	0	0	0	0	2	2	2	2
H8	3	3	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3
H9	3	3	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3
H10	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5
H11	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5
H12	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
H13	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
H14	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
H14a	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H14a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

Figure 7.43 Final cooling load schedule.

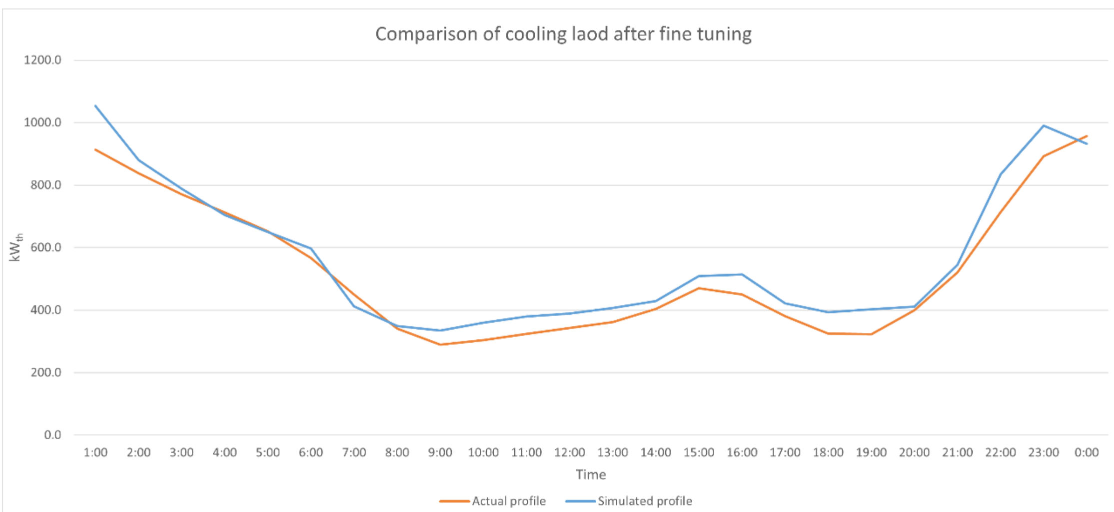

Figure 7.44 Validation of simulated model

The calibrated model was then used to simulate the cooling load of residential buildings in other cities also. The weather file of Delhi was chosen for calculating the cooling load potential of a similar residential building. The daily average cooling load of Delhi was 7,984 kWh_{th}. It shows a reduction of 37% cooling load during the month of April.

8. Conclusions

This study provides insights into the total AC consumption of 387 houses in Hyderabad throughout the year. The ownership and usage of ACs have increased in India, particularly in urban areas, due to the growing middle class and rising incomes. As the number of ACs increases, the demand for electricity is bound to increase. Understanding the characteristics of cooling load demand in building is very important for the better design and operation of air conditioning and energy storage systems. By analyzing the operational data of residential DCS, the cooling load profile of flats and the electrical load profile of DCS were prepared for different seasons in a year.

8.1. Summary

- **Key outcomes of AC usage analysis:** The daily average thermal usage per flat during summer, monsoon and winter was 26.4 kWh_{th}, 9.4 kWh_{th}, and 4.7 kWh_{th} respectively. The hourly average probability of a flat using AC during summer, monsoon, and winter was 0.35, 0.17 and 0.10. Considering only the flats using AC, the daily average AC load per flat during summer is 1.3 times more than in monsoon and 1.4 times more than in winter. The weekend AC usage is higher compared to the weekdays, but the midnight peak is higher during weekdays.

The daily average overall AC usage during summer, monsoon, and winter was 10,449 kWh_{th}, 3,768 kWh_{th}, and 1,859 kWh_{th} respectively. The AC usage of common places during summer, monsoon, and winter was 2.3%, 3.4% and 2.8% of overall AC usage respectively. The maximum hourly thermal load in summer, monsoon and winter was 1492 kW_{th}, 556 kW_{th} and 429 kW_{th}. There is a clear positive correlation between outdoor temperature and thermal energy. The thermal energy consumption by residents is higher in monsoon than in winter even for the same daily average outdoor temperature.

- **Key outcomes of DCS electricity consumption analysis:** The daily average electrical usage by the chiller during summer, monsoon, and winter was 3,144 kWh_e, 1,597 kWh_e, and 1,196 kWh_e, respectively. The chiller efficiency is higher and energy consumption is lower during thermal storage operation compared to normal operation.

The daily average electrical usage by the DCS during summer, monsoon, and winter was 4.96 MWh_e, 3.1 MWh_e, and 2.49 MWh_e, respectively. Pumps and auxiliary equipment contribute around 45%, 54% and 41% of the total consumption of DCS during summer, monsoon, and winter, respectively.

- **Peak month analysis:** The average hourly thermal load per flat during the peak month was 1.43 kW_{th} and the maximum thermal load was 3.1 kW_{th}. The average thermal load during different times (average over the month of May) is as follows: early morning - 2.17 kW_{th}, forenoon - 1.07 kW_{th}, afternoon - 1.11 kW_{th} and night - 1.36 kW_{th}. The mean daily thermal consumption of a flat during peak month was 34 kWh_{th}. The distribution of monthly AC consumption of flats higher than the mean value is sparser than flats with lower AC consumption. The interquartile distribution of the monthly AC consumption of the flats ranges between 13 kWh_{th} (3.7 TRh) to 51 kWh_{th} (14.5 TRh).

The average daily electricity consumption of DCS during peak month was 5,910 kWh_e with a single active chiller meeting the load. This indicated that for the apartment of 387 flats, the average daily energy consumption of DCS was 15.3 kWh_e per flat. The maximum hourly electrical load of the DCS was 481 kW_e. The average electrical load of DCS during different times (average over the month of May) is as follows: early morning - 330 kW_e, forenoon - 200 kW_e, afternoon - 212 kW_e and night - 243 kW_e. The daily average COP during the peak month was 2.2.

- **Significant load diversity among different flats:** The non-coincident cooling load for the design of indoor units was 4080 TR. The installed chiller capacity was sized for coincident cooling load, amounting to 1320 TR. The peak thermal energy demand was 1492 kW_{th} (424 TR), which was effectively managed using a single chiller. Compared to the installed capacities, the actual peak demand represented 10.4% of the total indoor unit capacity and 94.3% of the primary chiller capacity.
- **Simulation model:** Occupancy schedule for the flats was created using the analysis of flat AC usage. Building energy model for the residential DCS was created and simulated to match the actual cooling load profile during a summer month (April). The percentage error between the daily cooling load of actual and simulated is 7%. This calibrated model was then used for the simulation of residential thermal load in Delhi. It shows a cooling load reduction of 37% during April.

8.2. Future scope of work

District cooling requires a strong policy framework for addressing risks and promoting financial and physical viability. It is recommended to update the building codes to support centralize cooling with a possibility of thermal storage to help decarbonizing nighttime residential cooling energy consumption.

There is immense potential for further exploration in this study. By optimizing and evaluating the simulation model, engineers can uncover a range of additional operational strategies. These strategies will prove invaluable in the design and operation of DCS, particularly for residential users.

List of Publications

Following is the list of publications under thesis work.

Conference Publications

1. **Kandasamy, M.K**., Garg, V., Mathur, J., Valluri, S.: A case study of AC usage in residential district cooling system using operational data. Energise (2023).
2. **Kandasamy, M.K**., Garg, V., Mathur, J., Valluri, S., Tejaswini, D. (2024). Assessment of Residential District Cooling System Based on Seasonal Consumption Data. In: Jørgensen, B.N., da Silva, L.C.P., Ma, Z. (eds) Energy Informatics. EI.A 2023. Lecture Notes in Computer Science, vol 14468. Springer, Cham. https://doi.org/10.1007/978-3-031-48652-4_22

References

[1] PropertyPistol, “Residential sales in India’s top 8 cities reached a nine-year high, 2022,” Real Estate Sector Latest News, Updates & Insights - PropertyPistol Blog. Accessed: Sep. 18, 2023. [Online]. Available: https://www.propertypistol.com/blog/residential-sales-in-indias-top-8-cities-reached-a-nine-year-high-2022/

[2] MoEFCC, “India Cooling Action Plan,” *New Delhi: MoEFCC, Government of India. http://www. ozonecell. com/viewsection. jsp*, 2019, [Online]. Available: http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf

[3] Z. X. Jing, X. S. Jiang, Q. H. Wu, W. H. Tang, and B. Hua, “Modelling and optimal operation of a small-scale integrated energy based district heating and cooling system,” *Energy*, vol. 73, pp. 399–415, Aug. 2014, doi: 10.1016/j.energy.2014.06.030.

[4] A. Al-Qattan, A. ElSherbini, and K. Al-Ajmi, “Solid oxide fuel cell application in district cooling,” *Journal of Power Sources*, vol. 257, pp. 21–26, Jul. 2014, doi: 10.1016/j.jpowsour.2014.01.099.

[5] X. Zhou, D. Yan, and X. Shi, “Comparative research on different air conditioning systems for residential buildings,” *Frontiers of Architectural Research*, vol. 6, no. 1, pp. 42–52, Mar. 2017, doi: 10.1016/j.foar.2016.11.004.

[6] G. Deng, D. Yan, and R. Yu, “Case studies: the effect of occupant behaviors on evaluating the adaptability of district cooling system,” presented at the ASim Conference 2012, in ASim Conference, vol. 1. IBPSA-China, Japan, Korea, 2012, pp. 307–314. Accessed: Jan. 18, 2023. [Online]. Available: https://publications.ibpsa.org/conference/paper/?id=asim2012_0147

[7] A. H. Neto and F. A. S. Fiorelli, “Comparison between detailed model simulation and artificial neural network for forecasting building energy consumption,” *Energy and Buildings*, vol. 40, no. 12, pp. 2169–2176, Jan. 2008, doi: 10.1016/j.enbuild.2008.06.013.

[8] T. T. Chow, A. L. S. Chan, and C. L. Song, “Building-mix optimization in district cooling system implementation,” *Applied Energy*, vol. 77, no. 1, pp. 1–13, Jan. 2004, doi: 10.1016/S0306-2619(03)00102-8.

[9] W. Gang, S. Wang, D. Gao, and F. Xiao, “Performance assessment of district cooling systems for a new development district at planning stage,” *Applied Energy*, vol. 140, pp. 33–43, Feb. 2015, doi: 10.1016/j.apenergy.2014.11.014.

[10] C. Weissmann, T. Hong, and C.-A. Graubner, “Analysis of heating load diversity in German residential districts and implications for the application in district heating systems,” *Energy and Buildings*, vol. 139, pp. 302–313, Mar. 2017, doi: 10.1016/j.enbuild.2016.12.096.

[11] J. A. Fonseca and A. Schlueter, “Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts,” *Applied Energy*, vol. 142, pp. 247–265, Mar. 2015, doi: 10.1016/j.apenergy.2014.12.068.

[12] D. Brounen, N. Kok, and J. M. Quigley, “Residential energy use and conservation: Economics and demographics,” *European Economic Review*, vol. 56, no. 5, pp. 931–945, Jul. 2012, doi: 10.1016/j.euroecorev.2012.02.007.

[13] “Energy demand profile generation with detailed time resolution at an urban district scale: A reference building approach and case study - ScienceDirect.” Accessed: Dec. 12, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261917301125

[14] L. Zhu *et al.*, “Uncertainty and sensitivity analysis of cooling and heating loads for building energy planning,” *Journal of Building Engineering*, vol. 45, p. 103440, Jan. 2022, doi:

10.1016/j.jobe.2021.103440.
[15] "EnergyPlus." Accessed: Dec. 08, 2023. [Online]. Available: https://energyplus.net/
[16] J. P. Gouveia and J. Seixas, "Unraveling electricity consumption profiles in households through clusters: Combining smart meters and door-to-door surveys," *Energy and Buildings*, vol. 116, pp. 666–676, Mar. 2016, doi: 10.1016/j.enbuild.2016.01.043.
[17] L. Xu, Y. Pan, M. Lin, and Z. Huang, "Community load leveling for energy configuration optimization: Methodology and a case study," *Sustainable Cities and Society*, vol. 35, pp. 94–106, Nov. 2017, doi: 10.1016/j.scs.2017.07.017.
[18] M. H. Kristensen, R. E. Hedegaard, and S. Petersen, "Hierarchical calibration of archetypes for urban building energy modeling," *Energy and Buildings*, vol. 175, pp. 219–234, Sep. 2018, doi: 10.1016/j.enbuild.2018.07.030.
[19] I. Richardson, M. Thomson, D. Infield, and C. Clifford, "Domestic electricity use: A high-resolution energy demand model," *Energy and Buildings*, vol. 42, no. 10, pp. 1878–1887, Oct. 2010, doi: 10.1016/j.enbuild.2010.05.023.
[20] J. Gao, J. Kang, C. Zhang, and W. Gang, "Energy performance and operation characteristics of distributed energy systems with district cooling systems in subtropical areas under different control strategies," *Energy*, vol. 153, pp. 849–860, Jun. 2018, doi: 10.1016/j.energy.2018.04.098.
[21] S. Tredinnick, G. Phetteplace, and P. B. Kirk, "ASHRAE District Cooling Guide (2nd Edition) and Owner's Guide for Buildings Served by District Cooling (2019) | CIBSE." Accessed: Dec. 13, 2023. [Online]. Available: https://www.cibse.org/knowledge-research/knowledge-portal/ashrae-district-cooling-guide-2nd-edition-and-owner-s-guide-for-buildings-served-by-district-cooling-2019
[22] M. Wypior *et al.*, "District Cooling Guidelines." Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2023.
[23] "Screw Chillers vs. Centrifugal Chillers: What's the Difference? | Insightvity." Accessed: Dec. 13, 2023. [Online]. Available: https://insightvity.com/screw-chillers-vs-centrifugal-chillers-whats-the-difference/
[24] B. Rezaie and M. A. Rosen, "District heating and cooling: Review of technology and potential enhancements," *Applied Energy*, vol. 93, pp. 2–10, May 2012, doi: 10.1016/j.apenergy.2011.04.020.
[25] "Economic Assessment of Rural District Heating by Bio-Steam Supplied by a Paper Mill in Canada - Mariya Marinova, Catherine Beaudry, Abdelaziz Taoussi, Martin Trépanier, Jean Paris, 2008." Accessed: Dec. 12, 2023. [Online]. Available: https://journals.sagepub.com/doi/10.1177/0270467607313953
[26] K. J. Chua, S. K. Chou, W. M. Yang, and J. Yan, "Achieving better energy-efficient air conditioning – A review of technologies and strategies," *Applied Energy*, vol. 104, pp. 87–104, Apr. 2013, doi: 10.1016/j.apenergy.2012.10.037.
[27] S. Werner, "District Heating and Cooling," Elsevier, 2004, pp. 841–848. doi: 10.1016/B0-12-176480-X/00214-X.
[28] M. Calderoni *et al.*, "Sustainable District Cooling Guidelines," May 2019. Accessed: Dec. 13, 2023. [Online]. Available: https://www.semanticscholar.org/paper/Sustainable-District-Cooling-Guidelines-Calderoni-Dourlens-Qaranta/db82aa3dae1e234771aa306361c45f255935697c
[29] *District Cooling Guide*. ASHRAE, 2019.
[30] "DCS Case Study | PDF | Air Conditioning | Refrigeration." Accessed: Dec. 12, 2023. [Online]. Available: https://www.scribd.com/document/321145272/DCS-case-study
[31] J. Kensby, "Smart Energy Grids – Utilization of Space Heating Flexibility," Chalmers University of Technology, 2017. Accessed: Dec. 12, 2023. [Online]. Available: https://research.chalmers.se/en/publication/248875
[32] G. Alva, L. Liu, X. Huang, and G. Fang, "Thermal energy storage materials and systems for solar energy applications," *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 693–706, Feb.

2017, doi: 10.1016/j.rser.2016.10.021.
[33] G. Alva, Y. Lin, and G. Fang, “An overview of thermal energy storage systems,” *Energy*, vol. 144, pp. 341–378, Feb. 2018, doi: 10.1016/j.energy.2017.12.037.
[34] B. Cárdenas and N. León, “High temperature latent heat thermal energy storage: Phase change materials, design considerations and performance enhancement techniques,” *Renewable and Sustainable Energy Reviews*, vol. 27, pp. 724–737, Nov. 2013, doi: 10.1016/j.rser.2013.07.028.
[35] Y. Sun, S. Wang, F. Xiao, and D. Gao, “Peak load shifting control using different cold thermal energy storage facilities in commercial buildings: A review,” *Energy Conversion and Management*, vol. 71, pp. 101–114, Jul. 2013, doi: 10.1016/j.enconman.2013.03.026.
[36] “Load Control Using Building Thermal Mass | J. Sol. Energy Eng. | ASME Digital Collection.” Accessed: Dec. 12, 2023. [Online]. Available: https://asmedigitalcollection.asme.org/solarenergyengineering/article-abstract/125/3/292/463427/Load-Control-Using-Building-Thermal-Mass?redirectedFrom=fulltext
[37] S. M. Hasnain, “Review on sustainable thermal energy storage technologies, Part II: cool thermal storage,” *Energy Conversion and Management*, vol. 39, no. 11, pp. 1139–1153, Aug. 1998, doi: 10.1016/S0196-8904(98)00024-7.
[38] C. Chaichana, W. W. S. Charters, and L. Aye, “An ice thermal storage computer model,” *Applied Thermal Engineering*, vol. 21, no. 17, pp. 1769–1778, Dec. 2001, doi: 10.1016/S1359-4311(01)00046-1.
[39] “Deterministic model for an internal melt ice-on-coil thermal storage tank | Semantic Scholar.” Accessed: Dec. 12, 2023. [Online]. Available: https://www.semanticscholar.org/paper/Deterministic-model-for-an-internal-melt-thermal-Neto-Krarti/890bba3ccb9910c44ddb661540d3e79246024c00
[40] B. A. Habeebullah, “Economic feasibility of thermal energy storage systems,” *Energy and Buildings*, vol. 39, no. 3, pp. 355–363, Mar. 2007, doi: 10.1016/j.enbuild.2006.07.006.
[41] Y. H. Yau and S. K. Lee, “Feasibility study of an ice slurry-cooling coil for HVAC and R systems in a tropical building,” *Applied Energy*, vol. 87, no. 8, pp. 2699–2711, Aug. 2010, doi: 10.1016/j.apenergy.2010.02.025.
[42] M. J. Sebzali and P. A. Rubini, “Analysis of ice cool thermal storage for a clinic building in Kuwait,” *Energy Conversion and Management*, vol. 47, no. 18, pp. 3417–3434, Nov. 2006, doi: 10.1016/j.enconman.2005.12.013.
[43] “A comparison of energy consumption for storage priority and chiller...” Accessed: Dec. 12, 2023. [Online]. Available: https://iifiir.org/en/fridoc/a-comparison-of-energy-consumption-for-storage-priority-and-chiller-13326
[44] G. P. Henze and M. Krarti, “Ice Storage System Controls for the Reduction of Operating Cost and Energy Use,” *Journal of Solar Energy Engineering*, vol. 120, no. 4, pp. 275–281, Nov. 1998, doi: 10.1115/1.2888131.
[45] “Control strategies and energy consumption for ice storage systems...” Accessed: Dec. 12, 2023. [Online]. Available: https://iifiir.org/en/fridoc/control-strategies-and-energy-consumption-for-ice-storage-systems-using-13325
[46] “IMPACT OF OPERATION AND CONTROL STRATEGY ON THE PERFORMANCE OF A THERMAL ENERGY STORAGE SYSTEM | Semantic Scholar.” Accessed: Dec. 12, 2023. [Online]. Available: https://www.semanticscholar.org/paper/IMPACT-OF-OPERATION-AND-CONTROL-STRATEGY-ON-THE-OF-Warren/3baafcb6d54ee685446c259300f5da740f928073
[47] G. P. Henze, M. Krarti, and M. J. Brandemuehl, “A Simulation Environment for the Analysis of Ice Storage Controls,” *HVAC&R Research*, vol. 3, no. 2, pp. 128–148, Apr. 1997, doi: 10.1080/10789669.1997.10391367.
[48] T. T. Chow, W. H. Au, R. Yau, V. Cheng, A. Chan, and K. F. Fong, “Applying district-cooling technology in Hong Kong,” *Applied Energy*, vol. 79, no. 3, pp. 275–289, Nov. 2004, doi: 10.1016/j.apenergy.2004.01.002.

[49] T. Nagota, Y. Shimoda, and M. Mizuno, “Verification of the energy-saving effect of the district heating and cooling system—Simulation of an electric-driven heat pump system,” *Energy and Buildings*, vol. 40, no. 5, pp. 732–741, Jan. 2008, doi: 10.1016/j.enbuild.2007.05.007.
[50] M. K. Kandasamy, V. Garg, J. Mathur, and S. Valluri, “A case study of AC usage in residential district cooling system using operational data,” *Energise. 2023*.
[51] M. K. Kandasamy, V. Garg, J. Mathur, S. Valluri, and D. Tejaswini, “Assessment of Residential District Cooling System Based on Seasonal Consumption Data,” in *Energy Informatics*, vol. 14468, B. N. Jørgensen, L. C. P. Da Silva, and Z. Ma, Eds., in Lecture Notes in Computer Science, vol. 14468. , Cham: Springer Nature Switzerland, 2024, pp. 328–337. doi: 10.1007/978-3-031-48652-4_22.
[52] “Hyderabad, India - Climate & Monthly weather forecast.” Accessed: Apr. 27, 2023. [Online]. Available: https://www.weather-atlas.com/en/india/hyderabad-climate
[53] “Weather Data & Weather API | Visual Crossing.” Accessed: Dec. 12, 2023. [Online]. Available: https://www.visualcrossing.com/
[54] “Microsoft Excel Spreadsheet Software | Microsoft 365.” Accessed: Feb. 25, 2023. [Online]. Available: https://www.microsoft.com/en-us/microsoft-365/excel
[55] D. Radečić, “Time Series From Scratch — Moving Averages (MA) Theory and Implementation,” Medium. Accessed: Dec. 13, 2023. [Online]. Available: https://towardsdatascience.com/time-series-from-scratch-moving-averages-ma-theory-and-implementation-a01b97b60a18
[56] “EnergyPlus.” Accessed: Dec. 26, 2023. [Online]. Available: https://energyplus.net/weather-region/asia_wmo_region_2/IND
[57] “Zone Multiplier.” Accessed: Dec. 10, 2023. [Online]. Available: https://designbuilder.co.uk/helpv7.0/Content/Zone%20Multiplier.htm
[58] V. Garg, J. Mathur, and A. Bhatia, *Building Energy Simulation: A Workbook Using DesignBuilder™*, 2nd ed. CRC Press, 2020. doi: 10.1201/9780429354632.
[59] “Statistical analysis of air-conditioning and total load diversity in typical residential buildings | Hisham | Bulletin of Electrical Engineering and Informatics.” Accessed: Mar. 26, 2024. [Online]. Available: https://beei.org/index.php/EEI/article/view/2299
[60] M. A. Sayegh, “The solar contribution to air conditioning systems for residential buildings,” *Desalination*, vol. 209, no. 1, pp. 171–176, Apr. 2007, doi: 10.1016/j.desal.2007.04.038.
[61] “How to decarbonise your city’s heating and cooling systems.” Accessed: Apr. 23, 2024. [Online]. Available: https://www.c40knowledgehub.org/s/article/How-to-decarbonise-your-city-s-heating-and-cooling-systems?language=en_US