

Optimal energy management of the ice thermal storage-based air conditioning system for commercial buildings with a solar photovoltaic system

by

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DECLARATION

I, Olumuyiwa Yinus Odufuwa, student number #####, hereby declare that this research project, which is submitted to the Central University of Technology Free State, for the degree Doctor of Engineering in Mechanical Engineering, is my own independent work and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules, and regulations of the Central University of Technology, Free State.

This project has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

O.Y. Odufuwa

Date:

DEDICATION

This thesis is dedicated to the heavenly Father God Almighty, my source of inspiration,
and to my blessed family and friends, for all their support and love.

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I would like to show my appreciation to the following people who gave me their support whenever needed and made it possible to complete the study:

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ABSTRACT

Heating, ventilation, and air conditioning (HVAC) systems constitute a substantial portion of the energy demand of the commercial sector; representing 40% of total building energy consumption and 60% of base building energy consumption. Despite this significant consumption, the implementation of energy-efficient strategies is lacking, which is crucial to mitigate associated costs. More studies need to explore effective energy management schemes for HVAC systems, particularly focusing on cooling loads in commercial buildings. Ice thermal energy storage (ITES) systems are often adopted, as one of several options for improving HVAC systems. HVAC-ITES presents opportunities for demand-side management (DSM) and allows cost savings by considering time-of-use (ToU) tariff regions. However, the use of ITES is not without challenges. Problems such as early depletion of stored ice and overcharging still occur in most facilities, which lead to the need for excessive energy to build ice, thereby reducing efficiency gains. Additionally, hybrid energy sources, such as photovoltaic (PV) arrays and solar collectors, which could contribute to further reductions in energy costs, are rare.

In this study, HVAC-ITES, coupled with optimal control, presents opportunities for DSM and allows cost savings by considering ToU tariff regions. This study aimed to address the challenges identified in existing ITES systems, particularly in South Africa. This research emphasises the prediction of HVAC-ITES performance with respect to important variables and parameters using machine learning, optimal control with OPTI-tool applications, and economic analysis to evaluate operational efficiency and to minimise costs related to cooling purposes. The study proposes a comprehensive approach of integrating ITES and hybrid energy systems, using predictive and optimisation tools, and offering advantages presented by ToU tariffs and peak demand management.

The study investigated previous research and existing HVAC-ITES plants and utilised the Performance, Operational, Equipment, and Technology (POET) framework to systematically review HVAC-ITES cooling plants and to highlight potential cost savings through optimal energy usage profile shifts. Secondly, a predictive model was developed using an artificial neural network (ANN) to forecast various configurations for performance and output indicators, such as the storage temperature, coefficient of performance, cooling thermal load, and chiller power consumption. The study focused on

developing an ANN model using a shallow neural net fitting application (nftool) to predict the necessary ITES systems for non-linear input variables. A comprehensive dataset was generated and utilised to build and validate the ANN model, comprising input variables such as dry-bulb temperatures, components' inlet and outlet temperatures, flow rates, and the state of the control valves. The performance metrics associated with forecasting include mean squared errors (MSEs) and regression. These metrics were considered for training, validation, and testing in the prediction and analysis of individual configurations. Thirdly, the cost-saving potential of energy for cooling loads in commercial buildings was analysed using an optimisation control strategy to efficiently manage the ITES operation of a building's HVAC system. ITES is a thermal energy storage system that reduces the cost of energy in HVAC systems by shifting the cooling load from peak and standard periods to the off-peak period, with the aid of stored ice produced when the energy cost is affordable and discharging when the cooling demand is high, particularly at costly tariff rates. Simulations were implemented in the MATLAB optimisation toolbox with the Solving Constrained Integer Programs (SCIP) solver to address mixed-integer programming problems for non-linear optimisation problems. Furthermore, the results from various outcomes were considered to present the monetary benefits of the study.

From the general review, it was clearly seen that the effective utilisation of ITES allows for further advantages in managing off-peak tariffs and consumer demands according to ToU and maximum demand. As a result, the conventional system should be optimally controlled to achieve higher accuracy. Moreover, the investigations revealed that better performance may be achieved with optimal control and optimisation tools, such as fuzzy logic, neural networks, closed-loop control, model predictive control, and SCIP. The choice of adopting the non-linear optimisation application SCIP was based on its capabilities. The findings from the POET analyses of energy efficiency activities for HVAC-ITES cooling systems emphasise the potential cost savings through optimal energy usage profile shifts. In addition, the introduction of renewable energy-sourced systems may further enhance cost reductions, with the POET framework projecting a potential 50% reduction in energy costs. Furthermore, from the ANN prediction results, the regression values were observed to range from 0.9 and above, while the MSE depended on the data range. The study demonstrates the application of machine learning to an ITES cooling system, and the resulting model serves as a benchmark to assess the effectiveness of ANN

methodologies in prediction and provides insight into the impacts of parameter variation for ITES cooling systems. The effective utilisation of ITES allows for further advantages in managing off-peak tariffs and consumer demands according to ToU and maximum demand. The optimisation and economic analyses provide evidence on maintaining thermal cost and controlling the state of charge of an HVAC-ITES system. The optimal switching control model achieved approximately 33% energy cost savings during the summer months compared to the current system control (baseline). The ITES system maintained temperatures below 0 °C to meet thermal requirements, and the PV and battery options used to power the pumps accounted for 10% to 15% of the system's overall energy usage. Optimal control of the system to utilise stored energy during peak pricing and high-demand periods significantly reduced dependence on grid energy. The study projects a return on investment within two years for the additional capital required for the controller, solar PV, and battery installations. Over a 20-year period, the estimated energy cost savings are 35%; assuming an inflation rate and annual electricity price increase of 5% and 10% respectively.

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LIST OF ABBREVIATIONS

°C	Degree(s) Celsius
\$	Dollar(s)
\$/Wh	Dollar(s) per watt-hour
AHU	Air handling unit
AI	Artificial intelligence
ANN	Artificial neural network
BIM	Building Information Modelling
c/kW/h	Cents per kilowatt per hour
CO ₂	Carbon dioxide
COP	Coefficient of performance
CPU	Central processing unit
DC	Direct current
DSM	Demand-side management
ELECTRE III	Elimination and Choice Expressing the Reality [framework]
ESEER	European seasonal energy efficiency ratio
FCU	Fan coil unit
GHz	Gigahertz
HTF	Heat transfer fluid
HVAC	Heating, ventilation, and air conditioning
IoT	Internet of Things
ITES	Ice thermal energy storage
K	Kelvin
kg	Kilogram(s)
kPa	Kilopascal
kVA	Kilovolt ampere
kW	Kilowatt(s)
kWe	Kilowatt electric
kWh	Kilowatt hour
kWt	Kilowatt thermal
l	Litre(s)

l/s	Litre(s) per second
LM	Levenberg-Marquardt
m ²	Square metre(s)
m ³	Cubic metre(s)
MILP	Mixed-integer linear programming
MINLP	Mixed-integer non-linear programming
MIP	Mixed-integer programming
mm	Millimetre(s)
MPC	Model predictive control
MSE	Mean squared error
PCM	Phase change materials
POET	Performance, Operational, Equipment, and Technology [framework]
PV	Photovoltaic
PV/T	Photovoltaic thermal
R/Wh	Rand(s) per watt-hour
SCADA	Supervisory Control and Data Acquisition
SCIP	Solving Constrained Integer Programs
SI	<i>Système International</i> / International System of Units
SoC	State of charge
TES	Thermal energy storage
TJ	Terajoule(s)
ToU	Time-of-use
VAV	Variable air volume
VDC	Volts direct current
VRF	Variable refrigerant flow
VSD	Variable speed drive
W	Watt(s)
W/m ²	Watt(s) per square metre
We	Watt-electric
ZAR	South African rand

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Globally, there is currently a high need to sustain and manage the escalating energy demand [1]. One of the solutions to achieve reasonable energy efficiency is using energy management in the industrial, residential, commercial, and transport sectors. Moreover, exploring alternative technologies for power generation and management of electricity use can provide potential solutions for these challenges [2–4].

In most cases, residential consumers manage their energy consumption since they are responsible for the costs of the energy consumed. On the other hand, consumers in a commercial building are not concerned about the costs of energy consumed as they are not responsible for the costs incurred from the energy usage in the building [5,6]. However, commercial buildings require more attention so that the energy costs can be minimised.

Most commercial buildings require heating, ventilation, and air conditioning (HVAC) systems for various purposes. According to ESI-Africa, an HVAC system consumes a high proportion of a building's overall energy cost, which ranges from 30% to 60%. The HVAC cost of overall building energy costs, in a government office building with fewer working hours, is approximately 30%, while hotels consume over 50%. Commercial buildings therefore consume approximately 40% of the overall energy [7,8].

Several approaches have been adopted to reduce the high overall energy costs and inefficiency related to the cooling load on the HVAC system. Techniques such as retrofitting, thermal energy storage (TES), predictive methods, using renewable energy systems, applying programmable operations to controls and thermostats, investing in energy-efficient HVAC equipment, insulating, thermostat adjustment, changing air filters, and educating users on HVAC energy efficiency [9] have allowed reasonable savings on energy consumption. Current HVAC systems adopt chillers, with or without ice thermal energy storage (ITES), as the primary cooling medium. The combination of some of these approaches, particularly with ITES, has assisted in reducing the high overall energy cost attached to an HVAC system [10–12]. Furthermore, improvement of flow rates, working fluid, and heat transfer fluid (HTF) used in an ITES system may further minimise the cost and improve operational efficiency.

Categorically, most energy cost savings are implemented with the effective shifting of the load, which is achievable by considering and understanding the concept of demand-side management (DSM) [13]. In view of the progress made with HVAC systems' energy efficiency improvement, more than 50% of electricity costs result from cooling and approximately 5% of total energy consumption was saved with ITES implemented in HVAC systems [14]. An acceptable level of thermal comfort is furthermore achievable in commercial buildings, in addition to energy savings, using an ITES system [15].

On the contrary, ITES with an HVAC system reduces the coefficient of performance (COP) of the refrigeration system, compared to a conventional system. The coefficient decrease is due to the increase in work input, while the heat transfer to the refrigeration system from its surroundings does not increase relatively [16]. Furthermore, the external melt ice type has COP of ITES ranges between 2.5 and 4.1, while that of the conventional chiller system ranges from 5.0 to 5.9 [17]. Secondly, the higher energy requirement for the cooling load for the ITES and the refrigeration system may lead to additional costs and reduced energy efficiency if the technology is not implemented correctly [18].

Nevertheless, appropriate implementation proved that applying a model predictive control (MPC) as a control solution is efficient for ITES systems control [19]. Research efforts on real-time optimal control of ITES systems have proven to be a huge success [20,21].

Generally, it is essential to consider the various standards available for applying energy management to acquire an energy-efficient system [22]. Furthermore, energy efficiency may be improved by adopting the Performance, Operational, Equipment, and Technology (POET) framework, which has proved to be a practical approach to managing the energy efficiency requirements of commercial buildings [23].

1.2 PROBLEM STATEMENT

HVAC systems consume a high proportion of the overall energy costs per building, which ranges from 30% to 60% [7]. Conventional control strategies, such as chiller priority control, storage priority control, and constant proportion control, which are currently adopted in ITES operations, are not operated to match the corresponding variation in demand and disturbances (i.e., climatic conditions). Wrongful adoption may result in poor operational efficiency, particularly when considering the time-of-use (ToU) tariff [24].

The challenge with chiller priority control is that ITES should be utilised further to ensure maximum demand decreases. Furthermore, the storage priority control encounters unexpected demand charges when there is insufficient cooling supply at maximum discharge, without optimal switching control based on the forecasted load requirements. Lastly, in the case of constant proportion control, it is usually difficult to achieve coordination between varying load conditions and the cooling supply [25].

One of the main disadvantages of these strategies arises from the failure to implement appropriate system performance prediction and optimisation in the optimal energy control and management of the ITES in the HVAC system, concerning the demand and costs. The conventional control strategies are not multi-objective, as they mainly focus on supplying the variable demand. At the same time, the energy cost minimisation at the maximum potential efficiency of a chiller with ITES is not achieved. Furthermore, these strategies do not include prediction and accommodation of disturbances arising from ambient conditions and the variation in building cooling loads, power input to the chiller, refrigeration COP, and the state of the ice stored in the ice storage tank.

Moreover, the lack of implementation of the proper energy efficiency strategies based on validated results, by utilising optimisation tools for effectively managing the system's operation, has been noted. Switching control was mainly observed for cases subjected to varying intervals, such as 15-minute, hourly, daily, monthly, and seasonal pricing periods, considering regions of the ToU tariff and maximum demand. The continuous operation of these systems, during the costly peak and standard regions of the ToU tariff structure, substantially increases energy costs. In addition, the research gap identified from the literature review indicated that most previous studies should have considered using renewable energy systems, such as solar photovoltaic (PV), to minimise the energy costs of HVAC systems in the long run.

The main research problem identified for this study revolves around various key sub-problems:

- Sub-problem 1: One primary concern is the lack of efficient models for renewable energy systems that are tailored to the specific climate conditions of South Africa. This challenge is further complicated in areas with abundant solar energy due to the need for models that can efficiently harness and manage this resource. This absence

leads to inaccurate depictions of how these systems operate in reality, which undermines the credibility of economic studies on their feasibility.

- Sub-problem 2: There is a pressing need for further research to accurately forecast the performance metrics and features of HVAC systems that are connected to ITES, utilising advanced methods such as machine learning and soft computing. This strategy aims to streamline testing procedures and feasibility evaluations to reduce time and expenses.
- Sub-problem 3: The shortage of precise models for pre-testing optimal control algorithms on existing systems poses a significant challenge. In most commercial buildings, the absence of these models forces the direct implementation of optimal control algorithms on real-world systems, which can potentially lead to increased costs and operational disruptions. Moreover, unfavourable repayment periods or breakeven points often surface when conducting economic evaluations on large-scale energy efficiency renovation projects. While employing optimal control methods could improve such projects' economic viability, there is a notable gap in the research regarding their subsequent financial implications. In addition, dealing with optimisation issues linked to ToU pricing and peak demand fees requires substantial computational power because of the wide range of input factors covering an entire year. Streamlining and verifying models with actual historical data are essential to guarantee precise evaluations of economic viability.

1.3 OBJECTIVES

The study aimed to develop models that increase the operational efficiency of ITES for HVAC systems for commercial buildings using optimal control techniques to minimise energy costs and to improve equipment efficiency.

The objectives of the study are as follows:

- To identify gaps in the operational control and energy management of ITES and HVAC systems, through a literature review and investigations, based on the POET framework.

- To develop a predictive model using artificial neural network (ANN) architecture to train, validate, and test data samples. The model aimed to reduce the time and cost required for experiments.
- To develop an optimal energy management model for an HVAC and ITES system supplied by grid/PV/battery, where the thermal energy supply is either from stored ice in ITES or directly from the chiller.
- To conduct techno-economic analyses of the proposed optimally controlled ITES and HVAC system, with and without PV and battery.

1.4 RESEARCH METHODOLOGY

The following stepwise interdisciplinary approach was implemented in the study to achieve optimal utilisation and operation of ITES with an HVAC system:

- Literature review: A thorough review of literature on the performance, operation, equipment, and technology related to HVAC systems with ITES and renewable energy was conducted. This review included the types of operation of cooling plants with control strategies, the type of energy storage used for retrofitting to save costs, and the artificial intelligence techniques applied to HVAC systems, with ITES and renewable energy for performance analyses and variable prediction.
- System variables identification: The first model considered the ANN architecture to predict performance variables of HVAC and ITES configurations, based on mathematical and thermos-physical energy balance. The inputs and target variables concerning the output required were identified. The second model comprised an HVAC and ITES that are supplied by a grid/PV/battery system. Furthermore, an optimal energy management model was formulated and implemented to minimise total energy expenses. Furthermore, the second model identified independent, control, and state variables that were crucial for their development. An economic analysis of the results was also conducted. The optimisation model (second model) considered the optimal control and economic analysis.

- Data collection (input variables) and case study:
 - ITES storage capacity, chiller capacity, the size of the building, the temperature at the inlet and outlet of entities that made up the system, and meteorological data were collected for the Mediclinic Morningside system that utilises the Ice Bank® Thermal Storage Tank, with model number 1190CV2F and serial number 21530. Studies documented in the existing literature had previously corroborated this data.
 - Description of the model: A baseline system configuration is illustrated in Figure 1.1. Power is supplied to the chiller's compressor and returned fluid from the building undergoes a refrigeration process during charging to cool the fluid in the evaporator, while rejecting heat in the evaporative condenser. The cool HTF fluid builds up the ice in the ITES system for building cooling load during discharge. Power is further supplied to the pumps, which circulate the fluid for thermal energy transfer in the system.

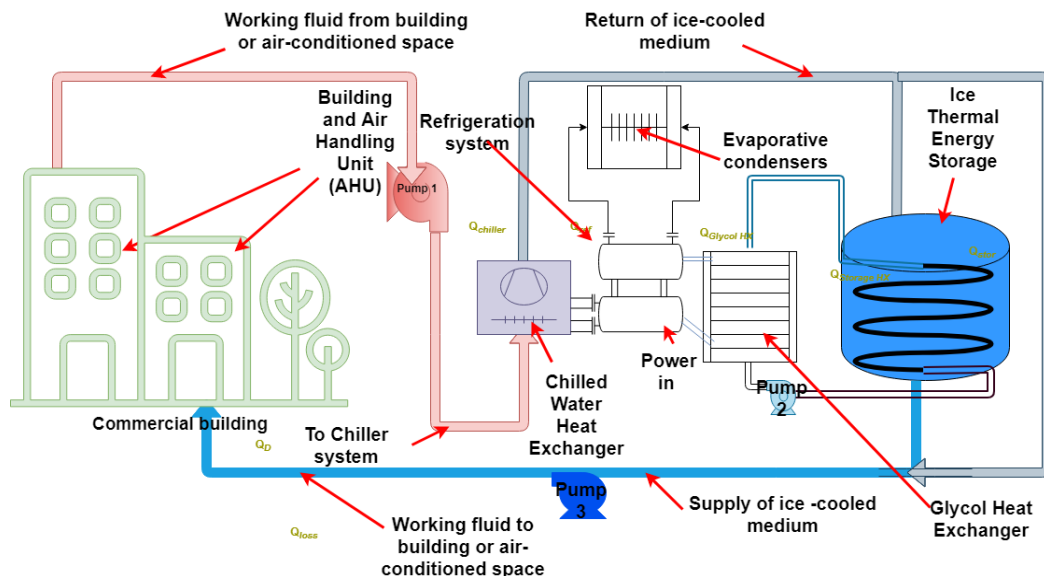


Figure 1.1: Schematic presentation of an HVAC cooling system with ITES [26]

- The proposed approach is shown in Figure 1.2. The processes are the same as the baseline, except that the PV and batteries are included for a supplementary power supply to the pumps, instead of relying solely on the grid.

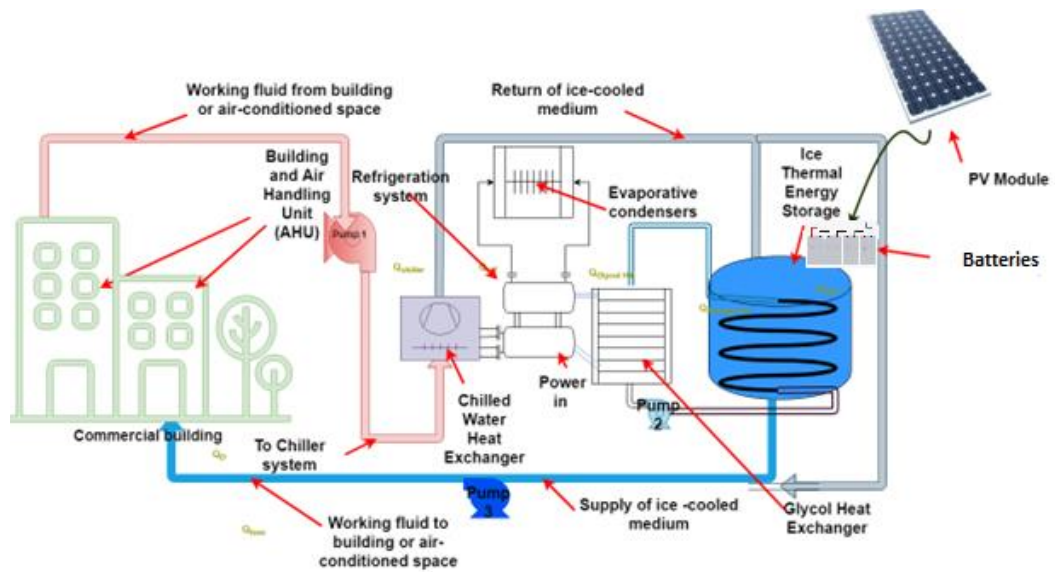


Figure 1.2: Schematic presentation of the HVAC cooling system with ITES, PV, and batteries [26]

- The HVAC and ITES characteristics, including the cost of electricity consumed based on cooling demands.
- The maximum demand charges, as well as the ToU tariff.
- The case study was based on the ITES system in Sandton, Johannesburg, South Africa.
- Model development: The different steps in developing the optimal energy management models for the proposed HVAC-ITES-PV cooling system are shown in Figure 1.3.

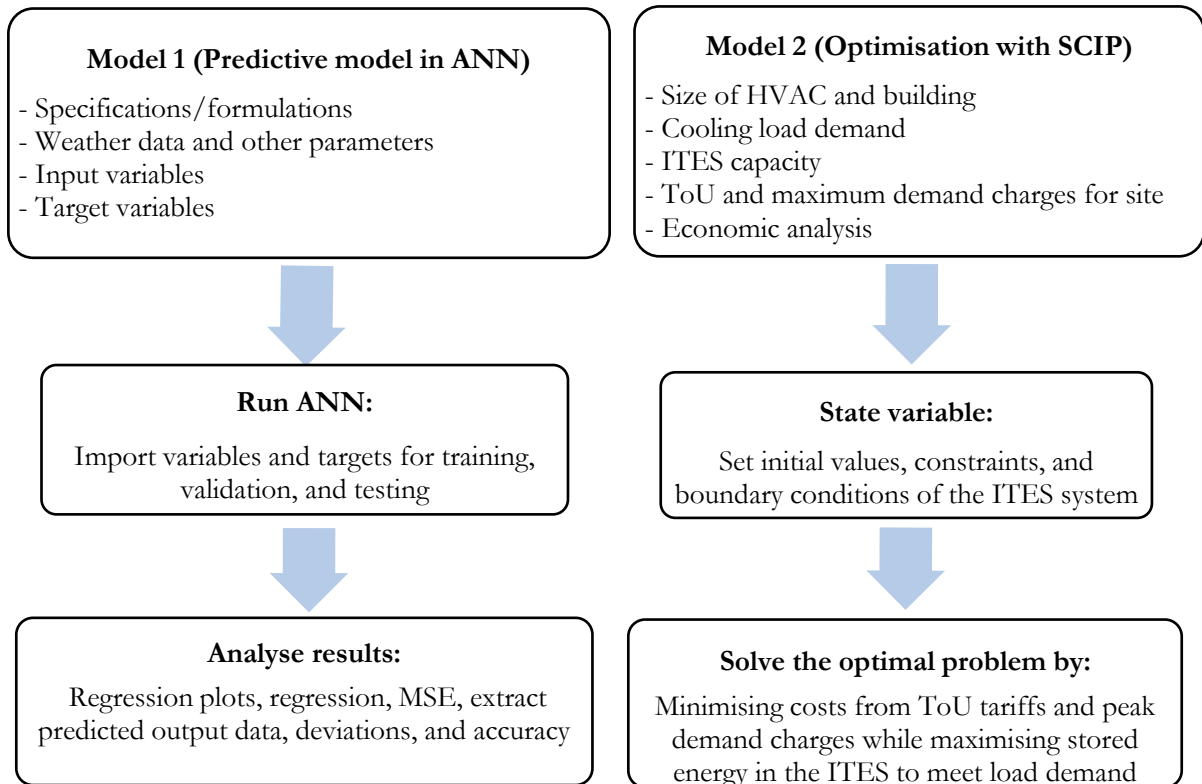


Figure 1.3: Flowchart of methodology and research design

- Formulation from the system using energy balance.
- Simulations were implemented in the MATLAB optimisation toolbox with the Solving Constrained Integer Programs (SCIP) solver, which was selected to address the mixed-integer programming (MIP) problems. It incorporates algorithms such as branch and cut conflict analysis and pre-solving techniques to handle intricate optimisation problems involving continuous and discrete decision variables.
- Simulation results and discussion:
 - HVAC-ITES-PV cooling system ANN prediction performance, considering the storage tank temperature, chiller COP, cooling load, and chiller power input.
 - For the HVAC-ITES-PV-battery cooling system, simulations were conducted to evaluate the effectiveness of the proposed optimal energy management model applied to the charging and discharging of ITES, based on cooling demand. Three main scenarios were simulated and discussed. These are when the HVAC-ITES system is powered solely by the grid with the manufacturer's base

switching (baseline). In the HVAC-ITES system, power is supplied exclusively by the grid, with optimal switching (Proposed Model 1). Lastly, when the HVAC-ITES-PV-battery system's power is supplied by the grid, PV, and battery to the pumps with optimal switching (Proposed Model 2). The simulation results regarding the economic and environmental performance of the building's optimally controlled HVAC-ITES-PV-battery cooling system were further analysed.

- The economic analysis considered the average daily operating costs for each month of the year for a baseline system and the optimally controlled proposed hybrid system. Average monthly savings were calculated to obtain annual savings in energy costs. Thereafter, a lifecycle cost analysis was conducted to determine the total possible savings and breakeven point over a 10- or 20-year project lifecycle.

1.5 CONTRIBUTIONS TO KNOWLEDGE

The study's contributions to existing knowledge are as follows:

Model 1: Application of an ANN model in predicting the performance of the ITES system (Chapter 3):

- This work used non-deterministic and non-linear data capable of predicting performance parameters for HVAC systems with ITES.

Model 2: Optimal energy management of grid-connected PV for an HVAC with ITES system and economic analysis of the results (Chapter 4):

- Energy efficiency and cost reduction: The study presents a novel optimal control model that minimises energy consumption and costs within an ITES system. Intelligently managing the charging and discharging of the ITES, along with using supplementary PV sources and ToU tariff considerations, contributes to substantial energy savings and cost reductions in HVAC systems.
- Comprehensive optimisation technique: Studies related to ITES that focus on power management systems are limited by optimisation algorithms, such as YALMIP, fuzzy logic, and MPC controllers. However, the model in this study adopted the SCIP optimisation technique in the OPTI-master solver, which has the

capabilities of deterministic non-linear optimisation of a system's operation, which minimises the energy costs of the system.

1.6 HYPOTHESES

The study's hypotheses are as follows:

- The ANN model may predict performance parameters in the ITES system. In addition, discrepancies in predicted values may be determined.
- Implementing the optimal energy management model applied to a hybrid HVAC-ITES-PV system may reduce the operation costs and the peak power demand of the cooling system, when compared with the baseline.

1.7 LIMITATIONS

The study was conducted with the following limitations:

- Modelling and simulation focused on healthcare as a case study. However, further types of commercial buildings will be analysed in the future.
- Only the case of ITES system configuration related to CALMAC® model 1190CV2F, serial number 21530, was considered, and not all or various types of HVAC and ITES systems.

1.8 PUBLICATIONS FROM THE STUDY

Conference papers:

- O.Y Odufuwa, K. Kusakana & B. Numbi. 2018. Review on optimal energy management of the ice thermal energy storage for an air conditioning system for commercial buildings. In *Proceedings of the 2018 Open Innovations Conference (OI)*, pp. 286-293.

Journal articles:

- O.Y. Odufuwa, K. Kusakana & B. Numbi. 2020. Optimal energy management of Ice thermal energy storage-based air conditioning system for commercial buildings in real-time – A review based on POET framework. *Journal of Physics: Conference Series*, 1577:012049.

- O.Y Odufuwa, K. Kusakana, B.P. Numbi & L.K. Tartibu. 2024. Optimal energy management of grid-connected PV for HVAC cooling with ice thermal storage system. *Journal of Energy Storage*, 77:109844.
- O.Y. Odufuwa, L.K Tartibu, K. Kusakana, P.A. Hohne & B.P. Numbi. 2024. Application of artificial neural networks in predicting the performance of ice thermal energy storage systems. *Journal of Energy Storage*, 95:112547.

1.9 THESIS LAYOUT

This thesis comprises five chapters, with the main research results being presented in Chapters 3 and 4. The thesis is laid out as follows:

Chapter 1 introduces the background of the study, the motivation for the topic, the problem statement and objectives, the study's methodology and contributions, and the limitations of the research.

Chapter 2 presents a comprehensive literature review of energy management, system efficiency optimisation in ITES-based chillers, and energy management standards and strategies. More specifically, building energy efficiency, based on the POET framework, is applied to an ITES system in a commercial building and is identified and discussed in alignment with energy management.

Chapter 3 analyses and discusses the prediction and validation of the data collected, based on ANN applications applied to HVAC-ITES systems. Meteorological data and Supervisory Control and Data Acquisition (SCADA) readings collected for the hospital are considered for accurate prediction and validation.

Chapter 4 discusses the development of the optimal energy control models of a cooling process with SCIP in MATLAB. The results from the model as applied to HVAC-ITES systems are presented and analysed. The baseline configuration is compared with the optimised system. In addition, a techno-economic analysis of the model is presented.

Chapter 5 concludes the study and highlights recommendations for future research.

CHAPTER 2: REVIEW OF OPTIMAL ENERGY MANAGEMENT OF AN ITES-BASED AIR CONDITIONING SYSTEM FOR COMMERCIAL BUILDINGS AND IMPLEMENTATION OF THE POET FRAMEWORK

2.1 INTRODUCTION

This chapter investigates the existing optimal control strategies of ITES systems in order to obtain the optimal option to manage and adequately satisfy the application requirements. Valuable outcomes were intended to initialise the formulation with capabilities of simple, accurate, and reliable optimal control strategy for an ITES system with frugal means; thus achieving the target purpose of efficient and affordable cooling in buildings without a trade-off on qualities such as, for instance, the comfort of the occupants.

The POET framework is used to review, analyse, and investigate the energy efficiency of a commercial building's cooling system.

The layout of this chapter is as follows: Section 2.2 presents a general overview of HVAC-ITES systems, including control strategies and improvements for ITES systems. Section 2.3 investigates the POET framework. Section 2.4 discusses the outcomes and key findings from the review, and Section 2.5 concludes the chapter.

2.2 GENERAL OVERVIEW

The HVAC of most prominent buildings in South Africa consume approximately 40% of their energy, considering their commercial building average [26]. HVAC's high overall energy cost is mainly reduced by incorporating an ITES system [10].

Earlier researchers developed models on ITES systems for an analytical prediction for different cases of air conditioning systems in residential and commercial buildings [11]. Studies on ITES were conducted using different approaches, including mathematical models, techno-economic analysis, thermo-economic analysis, and other technical analyses [27,28]. ITES analytical models assist in realising the potential of the technology.

Research results have showed that more than 50% of electricity costs are due to cooling and approximately 5% of total energy consumption is saved with ice storage implemented in air conditioning systems in some regions of the world [14]. An acceptable level of thermal comfort is further achievable in commercial buildings, in addition to energy savings, as shown in the investigation carried out by some researchers [29]. Furthermore, there are findings that the COP of air conditioning may be improved by applying a thermal storage system. The working fluid and HTF used in the system may also further influence the performance towards the intended purpose [30]. In addition, the conceptual choice of an ITES model for a specific application is critical and was highlighted in studies by applying a model of resulting solutions for the efficient management of ITES [16]. Research efforts through modelling and analysis have resulted in a new generation of ITES systems, which are currently widely used [20,21].

This study's objective was to investigate existing optimal control strategies of ITES systems to obtain the optimal solution to manage and adequately satisfy the application requirements.

Furthermore, it is essential to sustain and manage the escalating energy demand [1,31]. A solution to achieving reasonable energy efficiency improvement is to implement appropriate and effective energy management in various sectors, such as industrial, residential, commercial, and transport [32].

When comparing the individual consumer behaviour of residential buildings to that of commercial buildings, residential consumers are generally more conservative in order to avoid costly bills. In contrast, most commercial building users consume more energy as the cost incurred will not be settled by the individuals themselves [5,33,34].

According to the Annual Energy Outlook 2019 for American and world energy markets, based on many key assumptions set to operate through to 2050, it was forecasted that the energy consumption for buildings will increase by 0.2% per year, from 2018 to 2050, and this may rise more than the increase in energy efficiency rate at a later stage of the forecast. The forecast further revealed that residential energy consumption will decrease by 0.1% per year by 2050, while commercial energy consumption will rise by 0.5% yearly. Considering electricity consumption, the projection showed that the consumption of purchased electricity will increase by 0.4% and 0.5% per year in the residential and commercial sectors respectively. In addition, total delivered residential energy intensity

(annual delivered energy use per household) will decrease by 22% from 2018 to 2050, due to the faster growth in the number of households over energy use. The decrease results from improved appliance efficiency, on-site electricity generation (e.g., solar PV and other renewables), utility energy efficiency rebates, increasing residential natural gas prices, lower space heating demand based on historical trends, and a continued population shift to warmer regions. On the contrary, commercial electricity intensity (electricity consumption per square foot of commercial floor space) will decline at an average of 0.4% annually, from 2018 to 2050. Lighting accounts for the steepest intensity decline due to improved technology and energy-efficient lighting appliances. However, commercial electricity consumption for space heating, water heating, and ventilation will decline by 29% from 2018 to 2050 due to improved appliance efficiency and a population shift to warmer regions. This population migration causes space cooling intensity to decrease less rapidly, with commercial space cooling electricity consumption remaining flat during the projection period [35].

However, according to an energy report for South Africa, commercial and public sectors comprising financial services, information technology, retail, tourism, services, government, and quasi-government institutions that primarily provide accessible goods and services demand approximately 124 570 TJ of total energy, with electricity consumption of approximately 83%, while coal's contribution accounts for 9% and petroleum 7%. The industrial, agriculture, transport, and residential sectors require 35%, 32%, 1%, and 17% of electricity respectively, which are comparably lower than the commercial sectors [37]. The annual average Eskom prices for electricity in cents per kilowatt hour (c/kWh) has increased tremendously in the past decade (2008 to 2018), with domestic and street lighting increasing from a value of 53.43c/kWh to 118.56c/kWh, and commercial 31.61c/kWh to 111.25c/kWh [38]. Based on the above statistics, effective management of electricity use, across various sectors, will help to reduce the overall energy costs that are currently rising due to increasing electricity prices in the country.

Several approaches have been adopted to reduce the high overall energy costs and low efficiency due to the cooling load on the HVAC system. The approaches include retrofitting, TES, predictive methods using renewable energy systems, applying programmable operation on controls and thermostats, investing in energy-efficient HVAC equipment, insulating, thermostat adjustment, changing air filters, as well as educating users

on HVAC energy efficiency as a priority [9,36–38]. Current HVAC systems adopt chillers with or without ITES as the main cooling medium. Combining some of these approaches, particularly with the incorporation of ITES, has helped to reduce the high overall energy costs related to HVAC systems [10,39,40]. Furthermore, improving the flow rates, working fluid, and HTF used in an ITES system may further influence its performance towards minimising cost and increasing operational efficiency [41,42].

As a result of the issues mentioned above, Section 2.3 applies the POET framework to review, analyse, and investigate the energy efficiency of commercial building cooling systems.

2.2.1 Description and potential of ITES systems

2.2.1.1 Heating, ventilation, and air conditioning (HVAC) systems with ITES

ITES systems have various configurations, ranging from simple to complex types [43]. The cooling system mainly comprises an evaporator, chiller system, and Ice Banks[®]. The evaporator is available mainly in the mechanical room and its function is to absorb heat into the refrigerant and leaving a cool fluid. The chiller system comprises the condensing and evaporating unit that rejects and absorbs heat via the refrigerant and the compressor respectively [17]. The Ice Bank[®] stores the cooling energy charged by the chillers [44,45]. Baltimore Aircoil explained the application of district cooling to reduce peak utility demand in downtown Chicago [46]. A specific configuration is schematically presented in Figure 2.1.

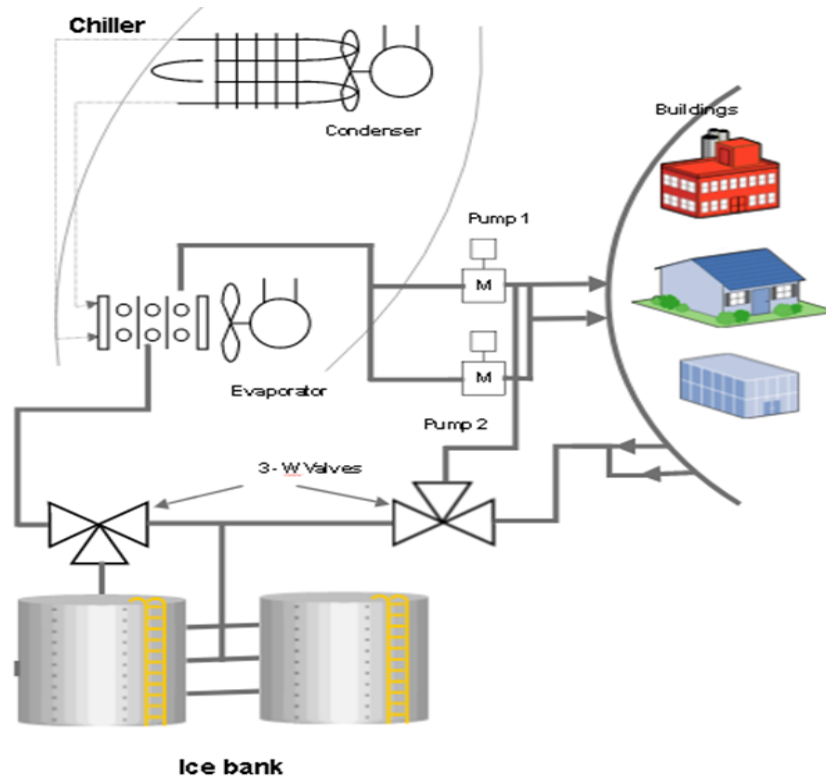


Figure 2.1: The cooling system of an ice thermal storage system [14]

2.2.1.2 ITES potential and limitations

Recent studies have proved the economic feasibility of an ITES system, which, in addition to energy savings, allows a reduction in environmental pollution due to lesser energy consumption generated from fossil fuels, plants, and other unclean power-generation means [48]. In addition, the extra capital cost of an ITES can be recovered relatively fast in fewer years after installation [49]. ITES further widely applies to power and electricity consumption systems [50]. Some models determine the energy requirements of a building, which is useful for management and time shift control of a building's energy consumption, with respect to the occupants' demand at the time of activities [51].

Conversely, it is important to note that TES has limitations depending on the type of system per application. For the system to be viable, the off-peak and the peak periods should further be identified before the intended upgrade of the conventional air conditioning system [52]. Hence, the active thermal storage types could be advantageous over passive types, depending on the application [51]. An active ITES system's advantage over counterparts may be due to the increased storage capabilities and control when compared to passive TES [53]. Another disadvantage that limits the use of ITES is the

additional cost of the conventional system, particularly for the initial installation, which could be compensated for by the energy saved [54].

2.2.2 ITES control strategies and improvements

ITES systems are installed in buildings and their operation relies on pre-specified conventional control strategies aimed at reducing the costs of electricity consumption and maintaining high chiller efficiency with moderated demand, while responding to the occupants' thermal comfort. Conventional control strategies currently use temperature-controlled valves, flow diverters, power switches, and timers to operate the chillers and ITES either alternatively, proportionally, or concurrently, depending on the load requirement, particularly at the temperature set point of the thermal comfort and cooling load storage strategies of the HVAC system [55]. The thermal flow rates are determined by the temperature sensors in the control valve on the HTF in the system, while the flow rates are controlled and remixed to a set temperature through a mixing valve [56]. The control strategy relies on the charge and discharge processes and depending on the type, application, and configurations [57]. An example is an internal-melt-type ITES, under forced circulation, which is used in mines [58]. ITES systems are classified and described as classical, hard, soft, hybrid, and other proposed techniques [59].

Improved ITES systems used in the modern day are the outcome of improving thermal management for thermal systems. The reduction in energy use, performance optimisation, and thermodynamic exergy analysis allow the evolution of enhanced systems, particularly in the performance and efficiency of ITES for respective applications. Moreover, research continues on developing improved heat transfer and insulating materials, storage configurations, and operational strategies for ITES per application [60].

2.2.2.1 Conventional control strategies

The conventional control strategy operates in two major modes, namely partial and full load strategy. The full load strategy involves the ITES system discharging at peak demand, without charging, with a temperature-controlled valve on the water flowing in the coil.

The partial load strategy is based on three common strategies:

- The chiller priority in which the ITES serves as the supplement to the additional day cooling load of the plant's chiller design capacity; the ITES is therefore underutilised as the maximum demand capability of the chiller is limited.
- Storage priority control occurs when the ITES supplies the cooling load during peak periods at a maximum discharge rate requirement; optimised load forecasting is therefore required for variation in demand. The storage priority control may operate at full load if solely used throughout the peak period.
- Constant control is when the chillers and ITES supply cooling load in a constant proportion, but are less effective with seasonal changes.

The first strategy relies on a flow diverter to the ITES tank, which depends on the chiller's cooling load-designated capacity utilising the historical and periodic temperature and energy data. The second strategy is controlled by the switch between the chiller and the ITES when the latter reaches the maximum discharge rate, before the depletion of the support storage level. However, the timer controls determine the engagement of the ITES, depending on peak periods. The third strategy is controlled by releasing cooling energy from the chiller and ITES at a proportion fixed by load variations, using a flow diverter with heat flow remixed to a set temperature through a mixing valve [63]. Figure 2.2 illustrates the categories of the conventional control methods [61,62].

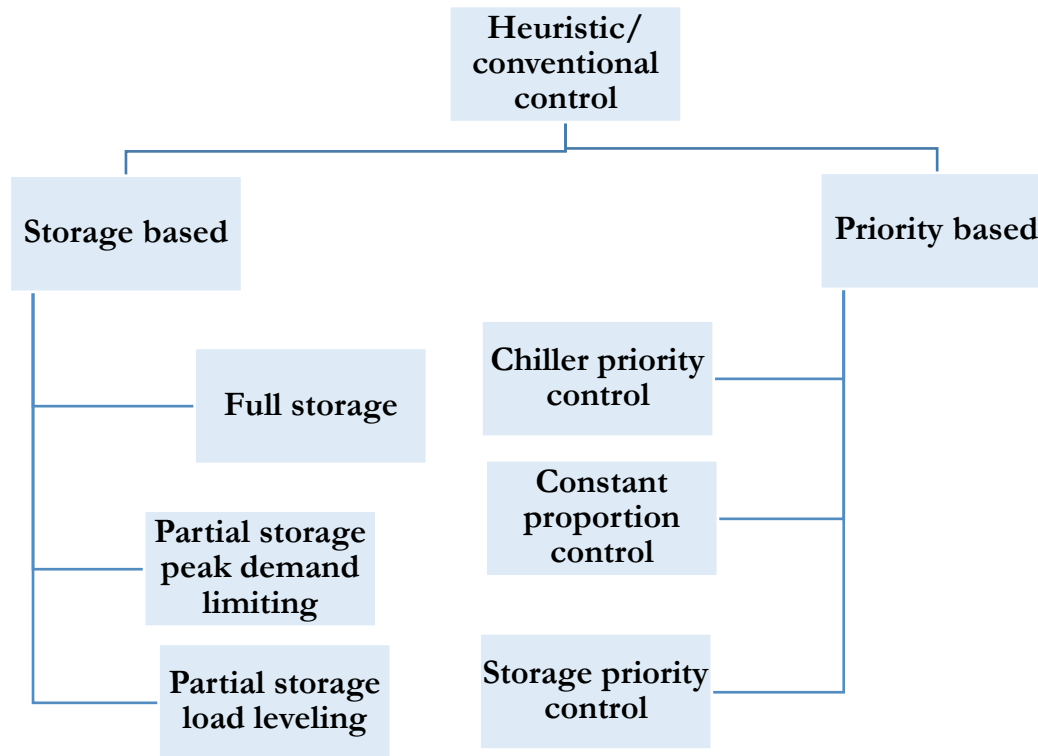


Figure 2.2: The cooling system of an ITES system [14]

2.2.2.2 Optimisation techniques for ITES

Various techniques can be applied; one example is the dimensioning optimisations approach, which provides tools for economic optimisation as implemented by Mousavi et al. [64]. Their study revealed and reviewed various techniques for optimising TES, considering the control strategy under a smart energy system. Choosing the appropriate optimisation technique for the specific purpose is important when analysing a thermal storage system [62]. Some studies categorise the load shifting of a TES in terms of heuristic control and optimal control. Heuristic control is a conventional control, which is either a storage capacity- or priority-based control [62]. On the other hand, metaheuristics or mathematical programming is applicable for optimal control. Current studies on ITES, which are based on dynamic programming and other optimal control approaches, were also considered. Figure 2.3 illustrates the categories of optimal control strategies from previous studies [65].

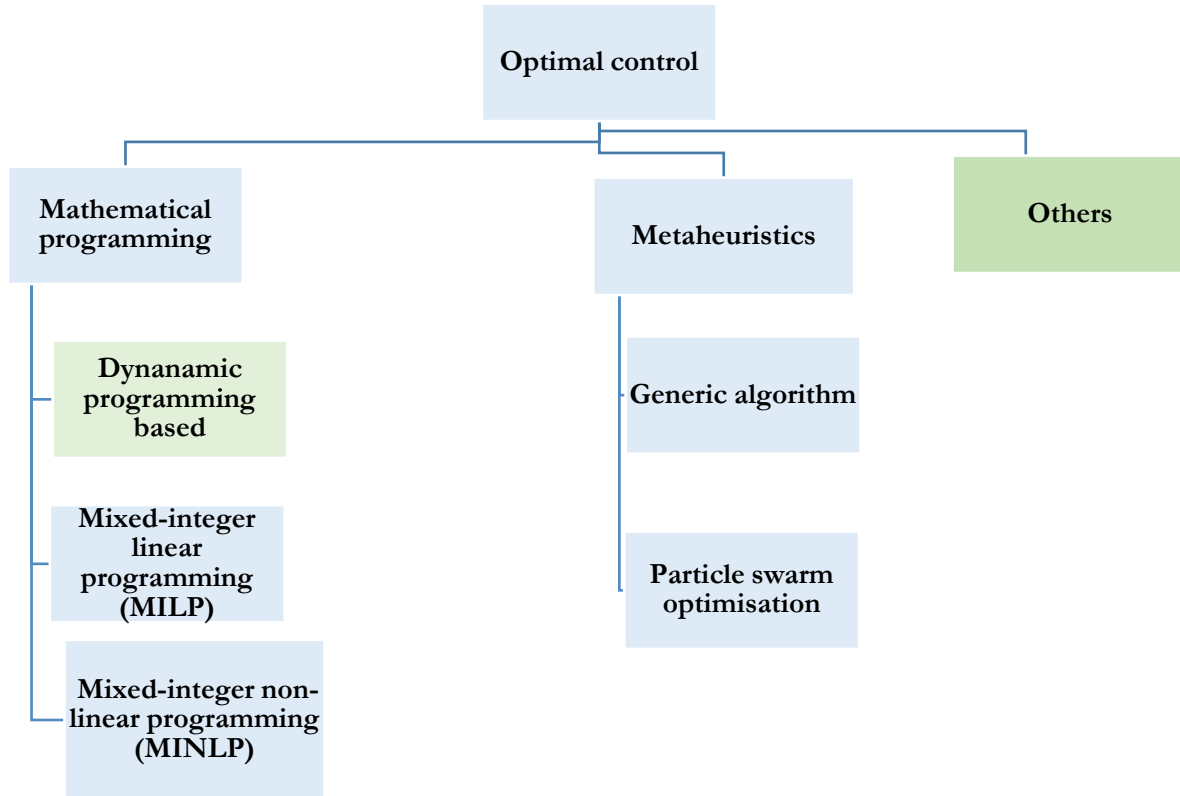


Figure 2.3: Optimal control strategies [14]

2.2.2.3 Real-time optimisations

Real-time control and optimisation tools can be implemented through fuzzy logic, neural networks, closed loops, and MPC. Intelligent control in optimising HVAC systems shows useful output, particularly with developments in computational processing in modelling and simulation. It is therefore possible to optimise an HVAC system in real time [66]. It was found in a study that the integration of MATLAB and Energy Plus in an MPC environment resulted in potential energy savings of up to 54%, compared to the base case [67]. The main challenges were the inaccuracy of the results, which were due to slow simulation speed and thermal historical management. Another study adopted static and dynamic optimisation on the real-time market signals for university campus needs [68]. Although there were drawbacks, it still achieved approximately 16.5% energy savings. Furthermore, a paper presented strategies for building-wide optimisation in real-time environments. It was found that physical interactions among carbon dioxide (CO_2), temperature, pressure, humidity, and occupancy provided significant flexibility to achieve substantial energy savings beyond 50%, without sacrificing air quality and comfort [69].

2.2.3 Other possibilities to improve ITES for cost savings and efficiency

Real-time simulation and optimisation are applicable to load shifting and other improvements that could be achieved from the reconfiguration of the HVAC with an ITES system. Considering various HTF and working fluid substances in the system, the metallurgical components of the units, such as the chillers, pipes, Ice Banks®, and other physical units of the overall systems, should be substituted.

Comparisons of different phase change materials (PCM) provide knowledge of the advantages and disadvantages of specific choices [70,78]. Experimentally, the fastest charging tests have achieved the lowest energy consumption [71].

2.3 ENERGY MANAGEMENT FRAMEWORK APPLICATION AND IMPLEMENTATION

Energy management framework analyses are targeted at improving the lifecycle and energy efficiency and minimising thermal and electrical demands and lifecycle costs. Various energy management frameworks have been adopted to improve sustainability, energy efficiency, cost savings on electricity, and thermal comfort for several cases of energy management. Some energy frameworks and sets of technologies and software such as Building Information Modelling (BIM), Elimination and Choice Expressing the Reality (ELECTRE III), and the Internet of Things (IoT) recorded success in achieving their purposes [79].

BIM and ELECTRE III are frameworks that are applicable to building structures, to enhance net zero energy building and to improve the structural component design. The POET framework covers all major energy management activities and identifies further efficiency-improvement opportunities [80]. Lightweight framing techniques, such as Tas Software by Environmental Design Solutions Limited, allow the potential to reduce building overheating during daylight. Users' favourable thermal comfort in buildings was thus achieved [81–83]. The manufacturing execution system incorporates standards for energy data exchange, online energy data analysis, performance measurement, and energy usage display to increase energy efficiency and to diagnose failures [84]. The IoT supports energy management by providing awareness of improved energy management practices at various production levels through the integration of real-time energy data and monitoring

[84,86]. The POET framework covers all major energy management activities and identifies further efficiency-improvement opportunities [78].

The POET framework has proved reliable and effective in analysing various energy management issues, from building energy systems to further energy management practices. Opportunities for energy saving can be realised by adopting the POET framework; for instance, in energy-consuming processes such as energy audit methods and procedures for wastewater treatment processes [87]. The POET framework also conforms to the International Performance Measurement and Verification Protocol® framework [88].

Energy management frameworks are considered important for accomplishing a sustainable management programme for a project. The assessment of an energy management programme should include the following principles:

- Accuracy of the project value;
- Considering factors that affect the accuracy with minimal use of estimated values and judgements;
- Completeness in measurement and quantification of significant effects;
- Conservativeness by utilising reasonable procedures to achieve targets and due consideration to the level of confidence in the estimation, consistency, and compatibility of performance indices comparing the type or methods of the project;
- Levels of professionals;
- Duration of time and evolution or adoption of new project initiatives;
- Transparency of the data, methodology, parameters, software, and assumptions for quality assurance;
- Relevance and compatibility by considering the determining factors based on current and relevant data and information;
- Socio-economic and environmental impact; and
- Technological and engineering support to ensure the reliability and sustainability of the project [89–92].

The POET framework encompasses all the principles and factors required to achieve savings and to realise the potential for improvement in the overall energy efficiency of ITES use in commercial buildings. The POET framework has been adopted for various

cases, from energy audits in buildings to energy process management with reasonable outcomes. A few of these studies are highlighted in this section. MPC was applied to optimise the energy efficiency of mineral processing, pumping systems (reduced operational energy cost by 37%), and plant maintenance based on the POET framework [93,94]. Another study applied the POET framework to cooling systems in a mine, which realised average electrical energy savings of 33.3% for all sites, without adversely affecting mine cooling requirements [95,96]. Another study demonstrated the effectiveness of operation control approaches in improving the energy efficiency of industrial processes, for the time and physical coordination of the operational efficiency of the POET framework [97]. The POET framework was also applied to the conveyor belt of a coal-conveying system in a coal-fired power plant. The optimal scheduling of this system resulted in the achievement of significant savings in both energy costs ($\sim 29\%$ to 33.5%) and energy consumption ($\sim 7\%$ to 20%) [98]. The POET perspective was applied to the cruise control of heavy haul trains to illustrate the feasibility and the potential of a control engineering approach to energy efficiency and DSM [99]. The POET framework was also applied to improve the energy efficiency of a commercial building, with a saving of R7.5 million [78].

2.3.1 ITES energy efficiency initiatives based on the POET framework

Based on the energy efficiency improvement guidelines, a building's energy efficiency may be increased. These improvement guidelines may involve the conceptual, active, technical, and engineering levels. These levels may each be categorised to represent the performance, operation, equipment, and technological efficiency of the cooling system in a commercial building. The energy efficiency levels and subcategories are discussed in the following subsections [78].

2.3.1.1 Conceptual level

The conceptual level is characterised by identifying activities to save costs, which requires a low level of skills and therefore involves less expertise. The activities involved in this phase are not advanced and do not include the addition of costly digital meters and data analysis. It is characterised mainly by managing energy regarding component analysis and the data for utility consumption.

The analysis of ITES is based on identifying the components of an HVAC's ITES cooling system, the consumption data, and simple activities to save costs. These factors are categorised into technology, equipment, operation, and performance efficiencies.

(a) *Technology efficiency at the conceptual level*

The electricity consumption of some commercial buildings is shown in Figure 2.4.

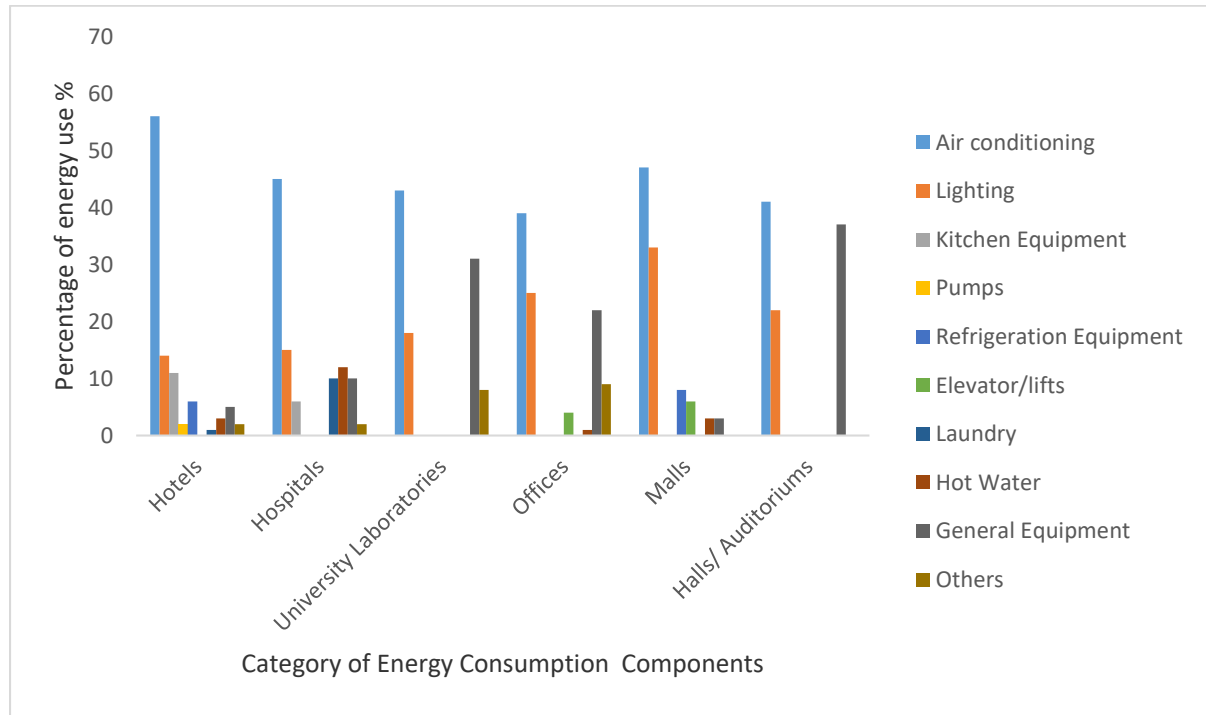


Figure 2.4: Typical energy usage distribution of some commercial buildings [164]

HVAC in hotels consumes the most significant amount of energy compared to other appliances. The electricity consumption of the cooling systems of the buildings was considered [99,100]. In a typical energy use spectrum of a hospital, the HVAC unit consumes the highest percentage of the energy cost [100]. HVAC is also the largest consumer of electricity in office buildings [100]. An energy audit of malls further confirmed the dominance of HVAC systems' energy consumption [101,102]. Details of an energy audit from the University of York indicated that the HVAC system attracted the highest costs associated with total energy use [103]. As a result, it is worth managing commercial buildings' energy with a focus on the air conditioning system of the HVAC.

Furthermore, HVAC cooling and heating loads may be considered, depending on the climate and region of usage [103].

(b) Equipment efficiency at the conceptual level

Based on the outcome of the energy audit, it is worth devising means to reduce energy costs in a commercial building by engaging in activities to improve the HVAC's energy consumption. The activities may include fixing, replacing, and maintaining the HVAC system. Moreover, adding components like storage and renewable energy is further recommended; however, it is essential to identify the major components of the HVAC system.

Various types of designs, such as centralised or decentralised types, depend on the size and location of the building. Choosing appropriate HVAC systems for specific buildings is essential. Other categories, such as all-air systems, air-water systems, all-water systems, water-source heat pumps, and heating and cooling panels, should be considered based on the medium used in the control system to provide the thermal energy [104,105]. Furthermore, system configurations use TES, which is either for heating or cooling ITES retention. In practice, various configurations are available [106].

HVAC systems are mainly composed of a mixed-air plenum and outdoor air control, air filter, supply fan, exhaust or relief fans and an air outlet, outdoor air intake, ducts, terminal devices, return air system, heating and cooling coils, self-contained heating or cooling unit, cooling tower, control, water chiller, humidification and dehumidification equipment, chiller system, and Ice Banks®. Each component is available for specific air conditioning purposes from the compressor for utilising the energy source, to increase the pressure and temperature of the refrigerant to the evaporator, such as to absorb or reject heat onto the refrigerant, providing a cold or warm fluid in the system [106,107]. The air handling unit (AHU) is used to re-condition and circulate air as part of an HVAC system [108]. The ice tank/bank or storage in an ITES system stores the cooling energy charged by the chillers and may be used for cost savings in most cases [109–111]. Furthermore, HVAC systems with thermal storage are utilised for district cooling; for example, the Baltimore Aircoil system is applied to district cooling to reduce peak utility demand in downtown Chicago [112].

It is important to first carry out the unit's maintenance processes, by cleaning, replacing high energy-consuming components, and replacing the whole unit or adding energy-saving devices to achieve an efficient system. It is advisable to avoid run-to-fail maintenance to save energy costs and efficiency, rather than to adopt preventive maintenance at the conceptual level. Table 2.1 shows activities to improve the energy efficiency of an HVAC system and the estimated percentage cost savings achieved from these practices.

Table 2.1: Options to improve HVAC systems at the conceptual level

Source	Activity	Description	Remarks
[113,114]	Cleaning	Cleaning the tube and water treatment to remove microbes. Microbes increase losses in heat transfer caused by scale deposits around microbes;thus leading to increased energy consumption.	10% to 35% savings may be achieved depending on the case.
[115,116]	Purging	Purge to clean the refrigerant charge from the air and to remove oil and other contaminants.	13% to 15% performance loss in chiller efficiency will be avoided for every 7% to 8% contamination.
[117,118]	Remove clogs and sediment	Retain flow rate by removing clogs in the hot-deck nozzle in the cooling tower, sediment in condenser tubes, and air in the system.	Reduce ~3% of energy consumption due to ~20% condenser reduction in flow rate.
[119–121]	Monitoring refrigerant level	Engage in optimal monitoring of the refrigerant level in the chillers according to the manufacturer's specifications. Reducing excess refrigerant charge leads to average energy efficiency reduction and capacity degradation.	Save ~20% energy costs due to decreased efficiency reduction and degradation.
[122,123]	Part replacement	Energy-efficient or functional parts such as sensors, seals, air filters, motors, and valves may be replaced.	40% savings on energy if a timely replacement is done to avoid malfunctioning of components such as the economiser, thermostat, and flow control devices.
[124,125] [131] [133]	System replacement/upgrade	Upgrade the entire HVAC system with a more efficient system. Variable speed drive (VSD). Variable refrigerant flow (VRF) from variable air volume (VAV).	Up to 90% savings on energy bills. Up to 400% increase in system efficiency.
[126–128]	Add-on components	Use of thermal storage such as ice thermal storage and use of renewable energy such as solar PV and photovoltaic thermal (PV/T) modules. Economisers may also be included.	

(c) Operational efficiency at the conceptual level

Immense cost savings on building energy bills may be achieved from simple activities such as switching off the system when it is not in use and adjusting the operating temperature. Timers may also be preset on the remote control via devices such as smartphones and computers. In addition, reducing infiltration by closing doors or mediums prevents ambient air influx into the cooled space. Table 2.1 showed simple concepts that can be adopted to save energy costs concerning the operation of various cooling systems. The savings realised from implementing the ideas presented in Table 2.1 may be temporary if applied; higher-level improvements are therefore required for long-term savings.

(d) Performance efficiency at the conceptual level

It is necessary to secure the technology by assessing and providing backup to avoid unwanted failure. In some cases, an adverse effect may cause more issues in the future, but if appropriate performance checks are in place, unnecessary losses may be avoided. However, it is also compulsory to quantify the savings and benefits realised from adopting these concepts.

2.3.1.2 Active level

HVAC-ITES systems involve validating collected data from the conceptual first level and additional methods or strategies to confirm possibilities for improving energy efficiency and savings for current HVAC-related systems. Active-level management may require initiatives to test technologies, such as VSD and VRF. Currently, validations are carried out by using equipment, software, and online monitors. Optimal management of an ITES system in its current state requires more accurate measures beyond the active level to improve its energy efficiency.

(a) Technology efficiency at the active level

Most concepts listed at the conceptual level are currently trending. Table 2.2 lists seven popular technologies adopted for energy cost savings and improvement in the HVAC industry [136,137]. The technology mentioned in Table 2.2, either combined or separate, has the potential to save costs and improve the efficiency of HVAC systems. Significant challenges are mainly initial costs and achieving optimal operation to meet demand targets.

Table 2.2: HVAC technologies to improve cost and efficiency

Technology	Description	Remarks/challenges
Smart controls	It involves automatic controls through sensors that may read the level of occupancy and capacity.	The accuracy of sensors regarding airflow may involve obstruction, thermal interference, and respiratory height level. The heat source may further affect the sensor reading: sunlight effects and closeness to a heat-emitting device in a conditioned space. Determining the correct orientation and receiving the mean readings for room space may be challenging.
Geothermal systems	Utilising underground energy sources.	Initial energy costs are significantly high.
Integration	Linking controls with lighting system and access to rooms.	Initial cost and optimal control may be the main challenges.
Variable speed controls	The speed of the compressor or input power is designed to operate based on peak or off-peak load and part of the full load.	The main challenges include the optimal operation and sizing of the systems.
VRF systems	It involves controlling the energy-demanding flow of refrigerant in the system to suit the variation in occupancy.	Higher initial cost; however, low ongoing energy and maintenance costs. The optimal operation could be complex.
Fuel cell: solid oxide fuel cell [138,139]	The vapour absorption refrigeration system is adopted from natural gas and heating for air conditioning in the building.	An electrical cooling efficiency of ~60% is obtainable.
Ice thermal storage	Involves the storing of energy during the cheaper tariff duration and discharging at peak periods and periods with high demand.	Approximately 60% savings can be realised; however, the main challenge is that conventional systems should be more optimal in operation; hence, it could be costly or lead to failure.

(b) Equipment efficiency at the active level

At this level, the equipment associated with the installation of the technologies is considered to improve the efficiency of HVAC systems in the building. Of the most critical pieces of equipment are sensors and controllers. Different sensors and controllers may be seen on the Honeywell Building control website, as summarised below [140]:

- CO₂ sensors are used to measure occupancy, based on the gas produced by each person. This type of sensor may triple the year-round savings on cooling.
- Dew point sensors monitor cooling water pipes and surfaces at dew point temperatures.
- Temperature sensors are used for applications ranging from averaging, outdoor and immersion sensors, to duct-mount, strap-on, and wall-mount sensors. Some sensors have solid-state component designs and are impervious to dust or dirt. At the same time, a few have wireless systems for quick and easy installation, reduced labour and material costs, as well as control ability with building automation.

- Pressure sensors measure building pressure, airflow, VAV filter status, and ducts. Types may include dry media, wet media, and gauges to measure a wide range of pressure from low to high, as well as small applications, such as small rooms, to large applications, such as high-capacity chiller systems.
- Current sensors are used to measure the operating levels in systems. It is helpful for monitoring and damage prevention.
- Enthalpy sensors sense humidity and temperature on two wires to measure the outdoor and mixed air.
- Economiser sensors assist in controlling the amount of fresh outdoor air supplied to a space for cooling and maintaining acceptable levels of CO₂.
- Humidity sensors are transducers that measure the relative humidity in applications. Applications include room comfort, rooftop units, air handlers, air conditioning, and anywhere relative humidity is tightly controlled.
- Occupancy sensors eliminate energy waste by measuring the CO₂ and number of occupants through a door switch.

HVAC controllers are now widely used to meet buildings' specific requirements. The properties of various components of the HVAC systems may be monitored via sensors, through a medium such as the Internet, to control and manage a building's HVAC system, and to maintain target requirements.

(c) Operational efficiency at active levels

Computer programming, with software incorporating settings to save energy and maintain comfort, is vital. Secondly, relevant staff may be trained and employed to understand how to efficiently operate the programs concerning conditional variation in factors that affect the building's cooling requirements.

In the current market, software such as ASCENT COMPASS™ and Niagara 4 are workstations that monitor energy management, such as efficient equipment start times, load optimisation, and energy use track optimisation to track savings [141].

(d) Performance efficiency at active levels

It is essential to consider that the technology adopted for energy savings may fail. Firstly, the outcomes from adopting the technologies should be provided on a database and investigated to avoid future reoccurrence. Appropriate security plans should be available to prevent excessive damages and losses. For instance, South Africa is currently experiencing load shedding in all sectors, which demands reliable and effective backup plans. A backup plan may involve switching the system's energy source, without causing further losses and damages.

2.3.1.3 Technical level

Further energy improvement, beyond the conceptual and active levels, is considered at this level. For effectiveness, the technology was narrowed down to ITES system technology and combined with renewable energy for cooling purposes. Implementing initiatives and verifying the claimed energy savings from the previous level may include further retrofitting, automation control, and other strategies to improve the ITES system's energy efficiency. A technical-level approach to enhancing the energy efficiency is essential for analysing the ITES system in a commercial building.

(a) Technology efficiency at the technical level

Vakiloroaya et al. highlighted the importance of weighing the pros and cons of each technology for improving the cooling load efficiency of HVAC systems through qualitative analysis of various cooling systems to select a suitable option for an energy storage system [142]. However, an energy dashboard should be established to compare the baseline and existing technology. This study considered the baseline as the conventional HVAC system and the proposed system as an optimised HVAC system that incorporates an ITES and renewable energy system. The baseline comparison will purposefully assist in tracking the worth of the technological initiatives of ITES and hybrid systems. Utilising ITES and renewable energy may require extra capital costs that can be recovered in a reasonable repayment period [143]. An additional shortcoming of ITES and renewable energy is the higher setup expenses as compared to conventional systems, particularly for the entire setup at installation, which is compensated for by the energy saved [144].

Furthermore, the difference between conventional and existing HVAC systems should to be clarified, as the current system may become a conventional system in the future. Conventional HVAC systems are existing systems and may include those with ITES and renewable energy systems; however, at present, an HVAC with ITES and renewable energy may be rare. The control system uses conventional control strategies that are programmed in the control unit's HVAC-required operation. The control units operate the system under predefined conditions, maintain occupant thermal comfort, save energy costs, and attain reasonable system efficiency. It regulates the operation of components, such as temperature control valves, flow diverters, power switches, and timers. However, a mixing valve controls the flow of fluids in the system at targeted conditions. Temperature, flow rate, humidity, and other properties are measured by the sensors in the cooling space or pipes of regions in the system. The transport medium may be cooling water, glycol, or refrigerant at various points in the HVAC system [145].

As noted in the previous section, conventional control strategies operate mainly in three modes: alternatively, proportionally, or concurrently. The mode depends on the load and comfort requirements of the HVAC's internal and external systems [146]. The charging and discharging processes of the system are attributed to the types, applications, and configurations for different cases of the HVAC controls [147,148]. For instance, an internal-melt-type ITES, used under forced circulation, applies to the mining industry [149].

Three common conventional control strategies are based on direct chiller mode, with storage discharge operation. Firstly, the chiller priority control, in which the ITES supplements any additional cooling load requirement after the refrigeration plant is at its capacity, supplies solely a portion of the design day cooling load; thus limiting the maximum demand of the chiller. Secondly, the storage priority control uses the ITES as often as possible during peak periods to meet maximum daily discharge. Afterwards, the refrigeration plant will take up the cooling load. The third is the constant proportion control, in which the refrigerating plant and ITES meet a portion of the cooling load under all conditions [150].

The conventional system and its control strategies may be improved by adopting a better option of various configurations, replacing working fluid and HTF, and using efficient components in the chillers, Ice Bank[®], pipes, and other parts of the entire HVAC system. Choices of the transport medium, particularly those that use PCM, may improve a

conventional system [151]. The cooling method, whether active or passive, is further pathed to improve an HVAC system [152]. The charging method is also an important option to improve the conventional system. Experimentally, the lowest energy consumption was achieved in the fast-charging tests [153].

(b) Equipment efficiency at a technical level

The ITES system has been proven to be feasible; however, certain conditions are required to achieve the intended energy cost savings. The requirements include a match between control strategies concerning DSM and electricity tariff structures, which simultaneously influence the ice storage rate and electricity price ratio, concerning the system economy for various commercial buildings [154]. Upgrading the AHU with an economiser may further minimise energy costs [155]. Hybrid energy systems may also assist the system by supplementing the energy supply to avoid total reliance solely on the grid, particularly during peak periods, and increasing options for cleaner energy sources and efficiency improvisation. For instance, the ice could be produced from PV through a direct current ice maker or by other means, such as a bidirectional inverter and an inverter air-conditioning system that works well with PV sources. Moreover, for a few daily cooling profiles, there is a match between the PV or PV/T profile and the cooling needed during the day, which makes the PV/T a suitable candidate for a hybrid energy system [156–161].

(c) Operational efficiency at the technical level

The operational efficiency may be improved using desktop models that aim to meet the energy requirements of a building. Software tools usually manage energy consumption relative to time and occupants' demands [162]. However, a limitation of ITES is that flat tariffs may lead to excess costs if misapplied. In some cases, the use of ITES experienced failure due to negligence in determining the feasibility of the ITES system [163].

As noted previously, various optimal control techniques can be applied to improve ITES operation. One such technique is the determination of optimisation approaches, which provide tools for economic optimisation as implemented, as shown by previous studies [164]. These techniques are further classified as described in Section 2.2.2.2 and comprise mainly mathematical programming and metaheuristics. The categories are further broken down and the choice depends on the outcomes with reasonable accuracy [165,166].

A control method mainly used and that has proven accurate is the MPC, which was further categorised by Verhelst et al. [167].

(d) Performance efficiency at the technical level

Cost, production, sources, and environmental effects were analysed to identify/validate/evaluate energy efficiency improvement opportunities. After the model selection and verification, the commissioning of HVAC systems in office buildings showed reasonable savings as compared to that of the baseline system [168].

2.3.1.4 Engineering level and prospective improvement

Energy management has four aspects, which range from technology to performance. At this level, future improvement, at an advanced level, is considered. The engineering level should be focused on in research work and analysis that will result in an innovative and accurate contribution to current technology. At this point, the energy savings and efficiency focus on a few of the concepts and the ITES and renewable energy of an air conditioning system. Engineering-level management generally involves a higher initiative, which results in longer repayment years and a higher percentage of total energy consumption savings.

(a) Technological efficiency at the engineering level

Adopting ITES for an HVAC system may save energy, but other factors, such as system efficiency, COP, and total energy consumption, still require attention to increase the reliability of ITES technology. A research-based approach to the design and modelling of the components of the ITES system, such as chillers, heat exchangers, and PCM, to improve the system is relevant. The inclusion of various renewable energy options and an upgrade of the ITES and HVAC system to a level above the technical level may be identified.

Including renewable energy technology and effective optimisation may improve the system and resolve previous challenges.

(b) Equipment efficiency at the engineering level

Security and maintenance plans should be analysed, rather than recorded on a dashboard. For example, technology with an automated troubleshooter and a maintenance tool may be programmed on the equipment.

Regarding technological efficiency, advanced building automation systems may be investigated to change the air conditioning temperature set point optimally and dynamically according to real-time weather conditions and occupancy level, energy rate, and energy consumption saving objectives; among others.

(c) Operational efficiency at the engineering level

Improvements are possible by applying advanced energy system optimisation skills. As a measure, the operation timetable of an HVAC system may be optimised by incorporating the building's maintenance schedule, occupancy level, ambient temperature, and moisture. A load-shifting plan integrated with real-time forecasting and ToU for the cooling load profiles on the ITES may be made. In reference is a study that illustrated the possibilities of implementing control techniques (on-off control, proportional-integral-derivative), robust control, adaptive control, and intelligent control) by providing simulation examples in the analysis of control performance and energy consumption [169]. Secondly, HVAC systems can easily be modelled and simulated with sophisticated software in an MPC environment [170]. The model may be implemented in a modified swarm optimiser, which can result in potential energy savings of up to 54%, when determined by hourly supply water temperature and circulator availability involving thermally activated building systems, in contrast to the baseline. The baseline was set to minimise energy costs by hourly cooling of the set point, which suggests 5% cost savings during the study period. Success was recorded for static and dynamic optimisation for some case studies [171]. Although drawbacks were encountered, energy savings of approximately 16.5% were still achieved. In addition, optimal control of the AHU, to minimise total energy consumption and cost, is an option to improve operational efficiency [172].

(d) Performance efficiency at the engineering level

Here, the information provided by the existing energy console may be further expanded. As mentioned earlier, all the major performance efficiency indicators, such as energy costs, energy waste, carbon emission, staff knowledge, skill level, lifecycle costs, and return on interest, may be added to the console. Real-time optimisation achieved over 50% energy cost savings, without compromising thermal comfort, by weighing factors such as CO₂ effects, temperature, pressure, humidity, and occupancy as variables [172].

The active level of energy efficiency improvement may require additional equipment and software. This level emphasises validating the energy usage data and energy efficiency improvement methods previously established at the conceptual level. Further effort is required to improve overall efficiency at this level. These advanced-level challenges are not sufficiently accurate and suffer from simulation speed lag. They may be resolved by applying high-performance computing technologies, advanced modeling, and simulation techniques.

2.4 DISCUSSION AND KEY FINDINGS

ITES systems are installed in buildings and their operation relies on pre-specified conventional control strategies that are aimed at reducing the cost of electricity consumption and maintaining high chiller efficiency with moderated demand, while responding to the occupants' thermal comfort at the same time. Conventional control strategies currently use temperature-controlled valves, flow diverters, power switches, and timers to operate the chillers and ITES system either alternatively, proportionally, or concurrently, depending on the load requirement, especially at the temperature set point of the thermal comfort and cooling load storage strategies of the HVAC system. The heat flow rates are determined by the temperature sensors in the control valve on the water in the system, while the flow rates are controlled and remixed to a set temperature through a mixing valve.

Given that electricity tariff, the demand, and the ambient temperature are dynamic variables, the conventional control strategy is only optimal at certain times. Maximum potential cost savings of an ITES operation are also only occasionally achievable. Currently, an optimal control strategy that may minimise energy costs at a reasonable chiller efficiency with ITES was accurately formulated to predict or accommodate possible disturbances arising from the variation in building cooling load and ambient conditions in real time. One of the reasons for inaccuracies arises from the failure to implement simulations in the optimal control and management of ITES in an HVAC system. Moreover, the absence of comparisons and validations of results by through utilising control and optimisation and prediction tools, such as fuzzy logic, neural networks, closed loop, and other effective means, by taking further advantage of the off-peak tariffs and consumers' demands, in accordance with the ToU and maximum demand, is more reason for the inappropriate application of ITES systems.

An approach to achieve the optimal operation of ITES with an HVAC system is highlighted as follows:

- The information from the investigation may be used to develop a model and simulate various configurations and components of an ITES system. The modelling software and designs depend on recommendations, availability, and accuracy that are suitable for the intended purpose. Existing models could be considered, modified, and adopted if required.
- Verification and validation may be carried out based on the experimental approach, using existing systems that will match the numerical model. This may involve the use of data and measurements of existing plants, both for commercial and experimental purposes.
- Simulation of models may be applied to verified models and re-verification may be carried out thereafter.
- Implementation of the simulation may be considered for applicable commercial buildings, such as school buildings, hospital complexes, shopping malls, and religious buildings. The choice of building may depend on accessibility and the approval of the owners.
- Propose and suggest the possible management of the ITES system for the buildings currently in operation, which could benefit from the results of an optimised ITES for the HVAC system.
- Aspects of components (such as the ice storage bank, evaporators, and chillers), operation strategies (such as full load and partial load), and working fluid or HTF (glycol compounds, glycol-water percentage mixtures, water), design types or application (static, indirect, external melt, ice-on-coil cool Ice Bank® system), as well as configuration may be accounted for regarding the proposed buildings.
- Techno-economic and operational improvement from the outcomes of the optimally managed system may be evaluated.

After reflecting on the investigation and review of studies on HVAC with ITES systems, Table 2.3 presents a general summary and comparison of the findings.



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Technology, Free State
Table 2.5. Summary of related studies

Source	Case study	System type	Control strategy type	Outcome	Algorithm	Remarks
[72]	MPC for four commercial sites	HVAC with no storage	Grey-box model	0-9% savings	MPC	Comfort is not affected by savings.
[73]	Several strategies compared	HVAC with no storage	Data-driven, physics-based, and grey-box methods	Not specified	Single-input-single-output or multiple-input multiple-output systems	Grey box has better accuracy than others.
[74]	Advanced scheduling technique	HVAC with no storage	Semi-analytical, exponential set point equation-based semi-analytical, load weighted-averaging	Peak demand reduction up to 19-41%	Predicted mean vote	Solution to limitations was identified.
[75]	Three computational intelligence algorithms were introduced to solve the proposed optimisation model	HVAC with no storage	Control of VAV and room temperature ramp rate	15.7-18.5% energy savings	Computational intelligence algorithms	The results demonstrated that simultaneous minimisation of energy and room temperature ramp rate is more beneficial than minimisation of energy only.
[76]	Experimental model-based predictive optimal control of active and passive building thermal storage in real time using ToU-differentiated electricity prices without a demand charge	HVAC with storage	Short-term forecasting, optimisation, and post-processing and control command implementation modelled in the transient systems simulation program TRNSYS and computing environment in MATLAB	17-27% cost savings COP from 2.1 to 2.4	Optimal controller, the energy resource station	Need to avoid local minimisation in the optimisation algorithm and developing fail-safe routines in case the communication between the optimiser and the building automation system breaks down. An option is to create an optimal controller for the same control application that does not rely on a model.
[77]	Three heuristic strategies	HVAC with storage	Optimisation algorithm of sequential quadratic programming	11.3% per day and 9.3% per month	Gaussian processes regression	The optimal strategy presented will be implemented and tested in the actual TES system of the shopping mall.



Source	Case study	System type	Control strategy type	Outcome	Algorithm	Remarks
[69]	Strategies for building-wide optimisation in real-time environments	HVAC	Implicit Euler discretisation scheme primal-dual interior point filter line search algorithm	50% energy saving	Real time	Real-time price anticipation difficulties due to the slow dynamics of the building.
[44]	ITES assessed in five cities and five archetypes of commercial buildings using two different operation strategies and two types of chillers for new installations and retrofits	HVAC with storage	Simplified approach to the heat balance method	Not specified	Energetic analysis Economic analysis	New installations and retrofits require available space for additional equipment, including storage tanks, which may affect the feasibility of the project. ITES systems in hospitals and hotels might require larger chillers than conventional systems due to reduced capacity during the ice-making time.
[68]	Solve the dynamic optimisation problem with energy storage by decomposing the problem into multiple static MINLP problems. Campus combined heat and power was considered	HVAC system with storage	Static optimisation adopting MINLP and further solved with the relaxed non-linear program Dynamic optimisation A trial solution of the full, dynamic MINLP is solved in 27 CPU clock hours (on a 2.8 GHz processor) using the branch and bound solver BONMIN.	16.5% energy savings realised	MINLP and real time	Drawbacks from the dynamics of the non-storage processes as they are ignored. Enforcing constraints from one step to another is challenging as they are treated independently. Further research is needed to find methods for the global solution to the problem. Non-convexity for the dynamic problem is a crucial issue.

ITES has the advantage of shifting the cooling load from peak to off-peak, with the aid of stored energy in the ice by the chillers. According to observation, applying ITES has merits; however, most buildings are yet to utilise the technology. Moreover, a new finding indicated a lower COP compared to a conventional chiller system. The cost effectiveness of ITES is thus justified solely when the electricity consumption is charged under the ToU tariff and efficiently optimised. It is evident that most studies previously focused on optimal control, particularly in real time, and involved an HVAC system without ITES.

From the review of the perspective of the POET energy management framework at each level, the estimated typical efficiency and percentage energy cost savings are plotted for a building HVAC system in Figure 2.5.

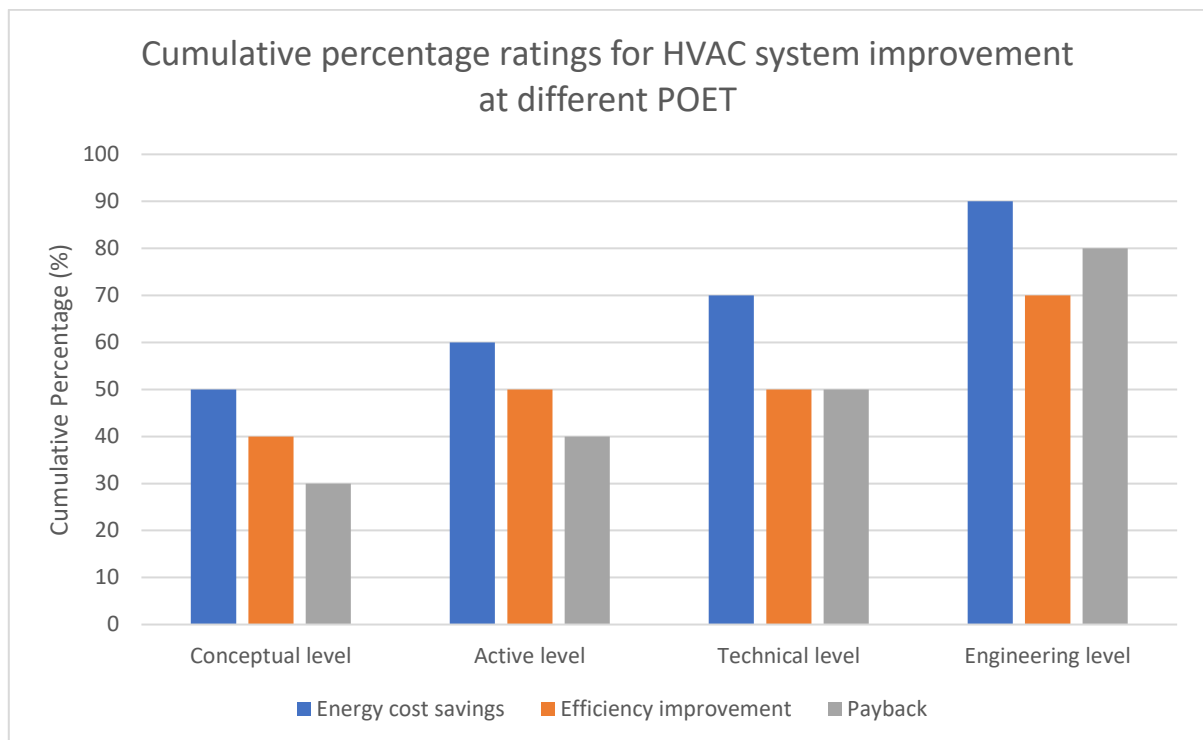


Figure 2.5: Comparison of HVAC system improvements at the different POET management levels [164]

In conclusion, improving an HVAC system at the engineering level is worth the effort, and a higher percentage of improvement may be achieved in the long run.

Regarding research on a commercial building in South Africa, the study analysed and compared the monthly power output data over a year for buildings using conventional and

optimally controlled chiller power inputs and maintaining the same cooling load. Several findings were derived from this comparison [173].

Figure 2.6 shows that the optimally controlled chiller presently provides the required output. Power consumption over time is reasonable for a system that has not yet implemented optimal control in the simulation. This indicates that with optimal control, the system achieves higher power output with minimal power input [173].

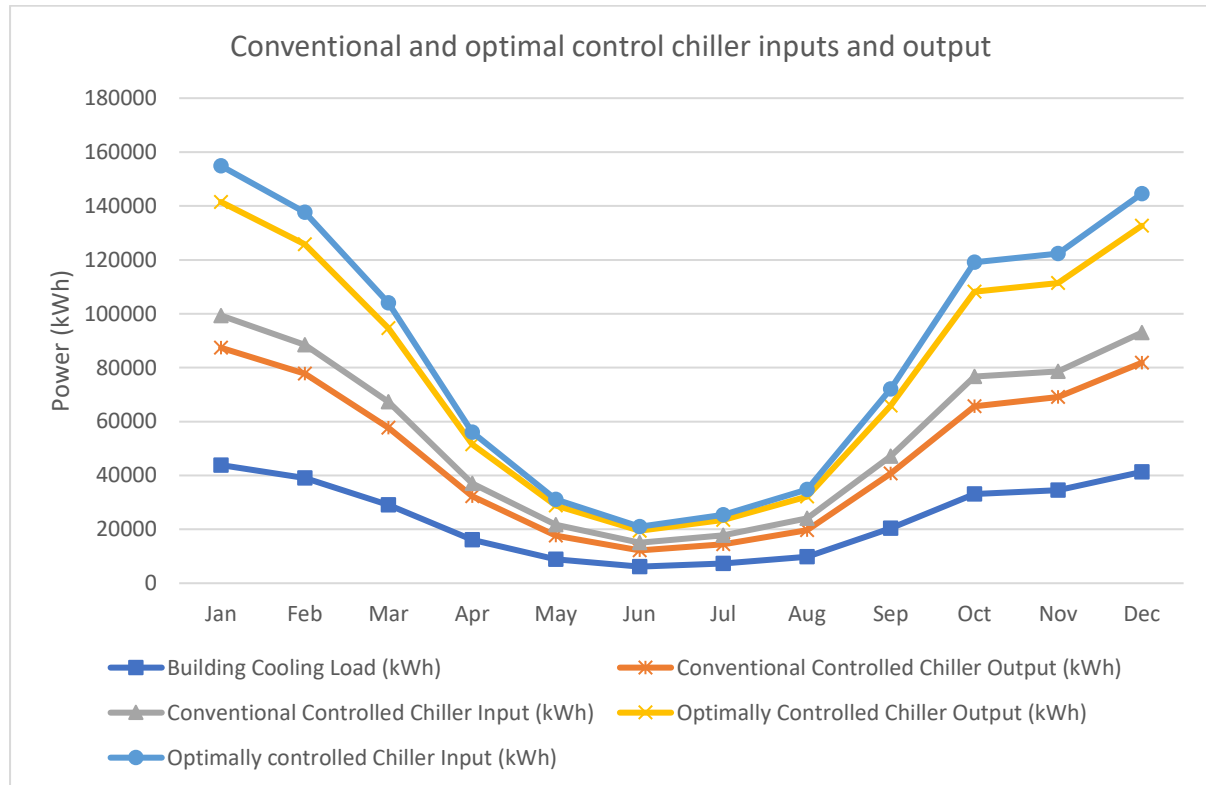


Figure 2.6: Cooling load, power input, and output profiles of the chillers [164]

As shown in Figure 2.7, the COP improved significantly after optimisation. The yearly average COP for the conventional system was 2.82, while the optimised system achieved a COP of 3.07. The COP for HVAC systems typically ranges from 3 to 4, which indicates that the optimised system is approaching industry standards for energy efficiency. The value indicates that an optimally controlled system may improve the COP of the chillers.

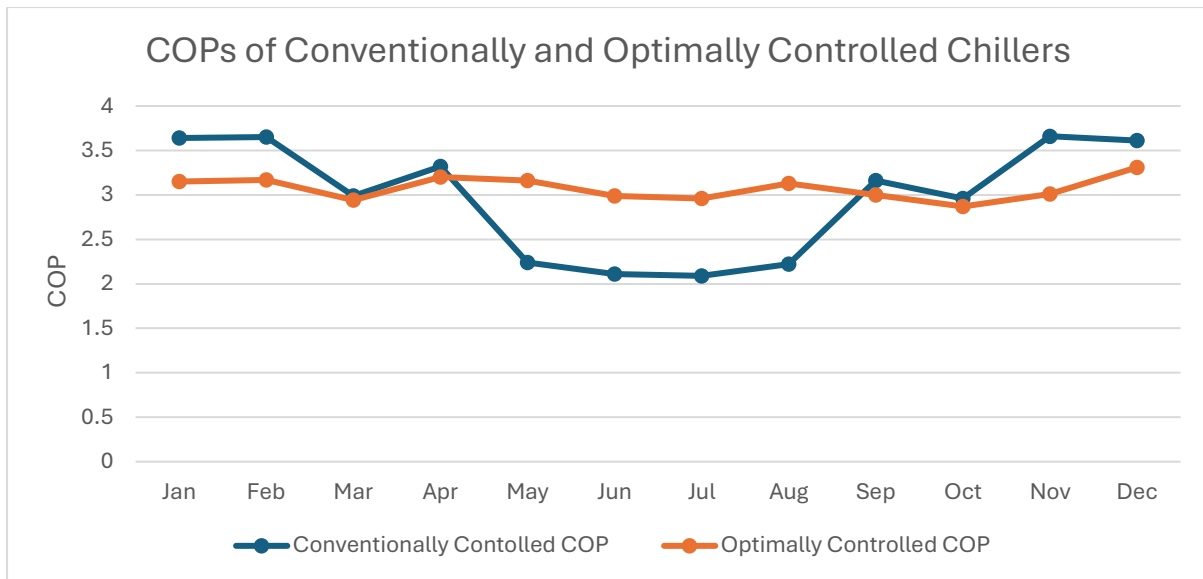


Figure 2.7: The COPs of the chillers [164]

Figure 2.8 illustrates how much energy cost savings can be realised from the optimally controlled system. The energy costs decreased from R41 159.70 to R31 086.00, with a savings of R10 073.70 after optimally controlling the system.

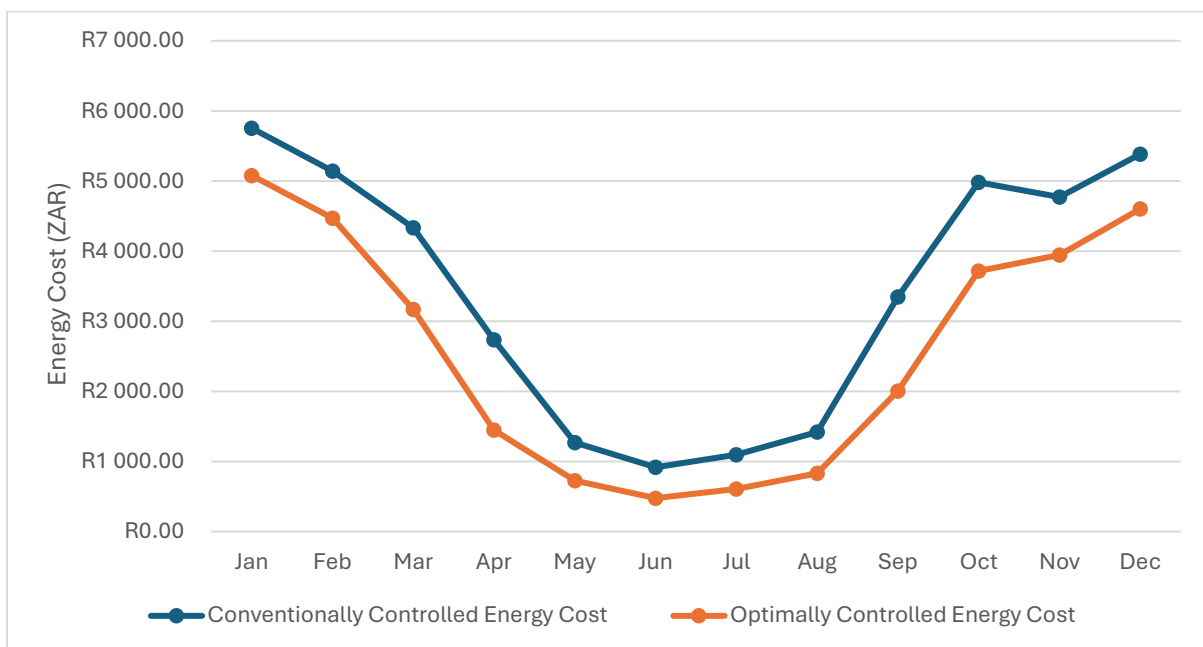


Figure 2.8: The energy costs of the chillers [164]

2.5 CONCLUSION

The use of ITES currently has vast potential and tendencies for saving energy consumption. More research efforts and exploration, particularly in Africa, are, however, still necessary. Regarding the potential of ITES systems, progress can be made in achieving energy cost savings and performance optimisation of the ice thermal storage and overall cooling system when applied to different types of buildings. It is further evident that ITES systems are applicable and beneficial to commercial buildings, such as schools, malls, religious-purpose halls, offices, hotels, and hospitals.

However, despite the current advantages and applications of ITES, challenges such as early depletion of stored ice and high energy consumption, which lead to capital wastage, remain evident in the utilisation of this technology. Currently, the problems and challenges faced by using ITES, especially with non-optimal operations and inaccuracies, may be solved by applying an optimisation approach. Proposed stepwise objectives and possible future research work to solve current ITES problems are as follows:

- The development and simulation of models for conventionally controlled HVAC systems with ITES.
- The development and simulation of models for an optimally controlled HVAC system with ITES.
- Comparison, validation, and verification of the simulated models.
- Identification and improvement of the accuracy of the optimal controlled ITES, if necessary.
- Presentation of the results from the final models of the ITES for commercial buildings.
- Conducting case studies and analyses to verify the accuracy of the model.
- Comparison of model results to reveal the potential cost savings of the optimal operation control strategy applicable to commercial buildings.
- As shown by the results, establishing evidential tools and contributions for optimally controlled ITES for energy cost savings and improved operational efficiency applicable to commercial buildings.

The energy usage in commercial buildings, among other sectors, is high and requires some attention. The commercial sector's annual average electricity cost increased tremendously in the decade 2008 to 2018, from 31.61c/kW/h to 111.25c/kW/h. HVAC systems in commercial buildings contribute to the increase in the electricity demand and account for up to 60% of the buildings' overall energy cost. It is worth highlighting activities that could improve energy efficiency and save costs to reduce the current energy crisis.

The POET framework provides structured and thorough guidelines for energy management and to evaluate the energy-saving and efficiency-improvement potential. After investigating multiple options by adopting each level and step of the POET framework, the optimal control of an HVAC-ITES system combined with renewable energy was proposed for future solutions.

A case study of a commercial building further revealed the potential savings that can be realised from adopting optimal control strategies for ITES systems in HVAC.

With the potential revealed in the study, an existing building with ITES was considered for further optimisation, which involved the following:

- Using on-site historical cooling to confirm optimally controlled ITES system results.
- Mathematical models for optimal control of the hybrid energy system (PV and grid) connected to HVAC and ITES. A model of each isolated system (HVAC, ITES, and PV) may precede the combined system to achieve this. Isolating the setup may allow a baseline comparison with the proposed method.
- The suitability of control strategies that include both open-loop and close-loop techniques, such as optimal control and MPC, may be considered under various conditions. Further recommendations may therefore be provided.
- Techno-economic analysis of the proposed optimally controlled system, compared to the baseline system (existing system without ITES and PV system).
- The proposed system's lifecycle cost analysis to analyse its feasibility.

CHAPTER 3: APPLICATION OF ARTIFICIAL NEURAL NETWORKS (ANNs) IN PREDICTING THE PERFORMANCE OF AN ITES SYSTEM

3.1 INTRODUCTION

This chapter focuses on the development of an ANN model by considering a shallow neural net fitting app (nftool) to predict the necessary ITES systems for non-linear input variables. A comprehensive dataset was generated and utilised to build and validate the ANN model, comprising input variables such as the dry-bulb temperature and temperature flow rates, as well as the state of the control valves at the inlets and outlets of the system's components. The study demonstrates the application of machine learning to an ITES cooling system and the resulting model serves as a benchmark for assessing the effectiveness of ANN methodologies in prediction and provides insight into the impacts of parameter variation for ITES cooling systems. Moreover, apart from time and cost savings on feasibility studies, these technologies may potentially aid in developing more efficient strategies for optimising energy consumption, particularly considering ToU tariff pricing periods based on timestamp data. The findings from the study undeniably showcase the accuracy of neural networks in the prediction parameters associated with an HVAC with ITES system.

The layout of this chapter is as follows: Section 3.2 describes the ANN model development. Section 3.3 presents the results and discussion of the case studies, using the parameters from an ITES plant. Section 3.4 concludes the chapter.

3.2 ANN MODEL DEVELOPMENT

3.2.1 System data description

The selected case study involved the Morningside Mediclinic hospital complex in Johannesburg, South Africa. This three-storey building with a basement features varying floor areas: 6 234 m², 5 588 m², 5 289 m², and 1 330 m² for the basement, first, second, and third floors, respectively. The chillers within the HVAC system's cooling unit employ the Ice Bank® Thermal Storage Tank from CALMAC® (model 1190CV2F, serial number

21530). This innovative Ice Bank[®] enables the use of smaller chillers, constituting approximately 40% to 50% of the size of other HVAC systems. The chiller manages the building's cooling load by operating on the Ice Bank[®] tanks during peak daytime hours. Conversely, during off-peak periods, the chillers charge a water-glycol solution mixture in the Ice Bank[®] Tank, lowering it to -4 °C.

The Mediclinic facility opts for a 30% propylene glycol solution over the standard 25% ethylene glycol to elevate the melting point, thereby mitigating risks to humans in a hospital setting. The use of a non-toxic working fluid is imperative in this environment. A welded, closely spaced, counter-flow-heat tube heat exchanger of polyethylene is integrated to facilitate heat transfer from the water-glycol solution to the water around the AHU. Preventive measures are taken to ensure that the ice surrounding the pipes does not freeze in order to avoid potential damage to the tank.

The ice-building chiller exhibits a peak cooling capacity of 421 kWt for a full day, with a recorded capture of 1 698 kWt on a specific day, as shown by the dataset. The necessary input power to the compressor fluctuates, amounting to an average estimate of 95.6 kW_e for the entire day, 91 kW_e for full-night operation, and 50 kW_e for half a day. The chiller's refrigeration unit comprises two compressors that operate on a double-stage cycle. The working fluid involves a 60 kg charge of R-134a in the refrigeration circuit, while the evaporator's HTF, ethylene glycol, was replaced with polyethylene due to medical considerations. The SCADA system visually represents the HVAC plant's schematic by displaying input and output variables, component inlets and outlets, as well as various variables, such as temperature, power inputs, flow rates, pressure drops, tank levels and thermal energy. The SCADA system also incorporates warning alarms, offers remote control capabilities, and stores historical data of system variables.

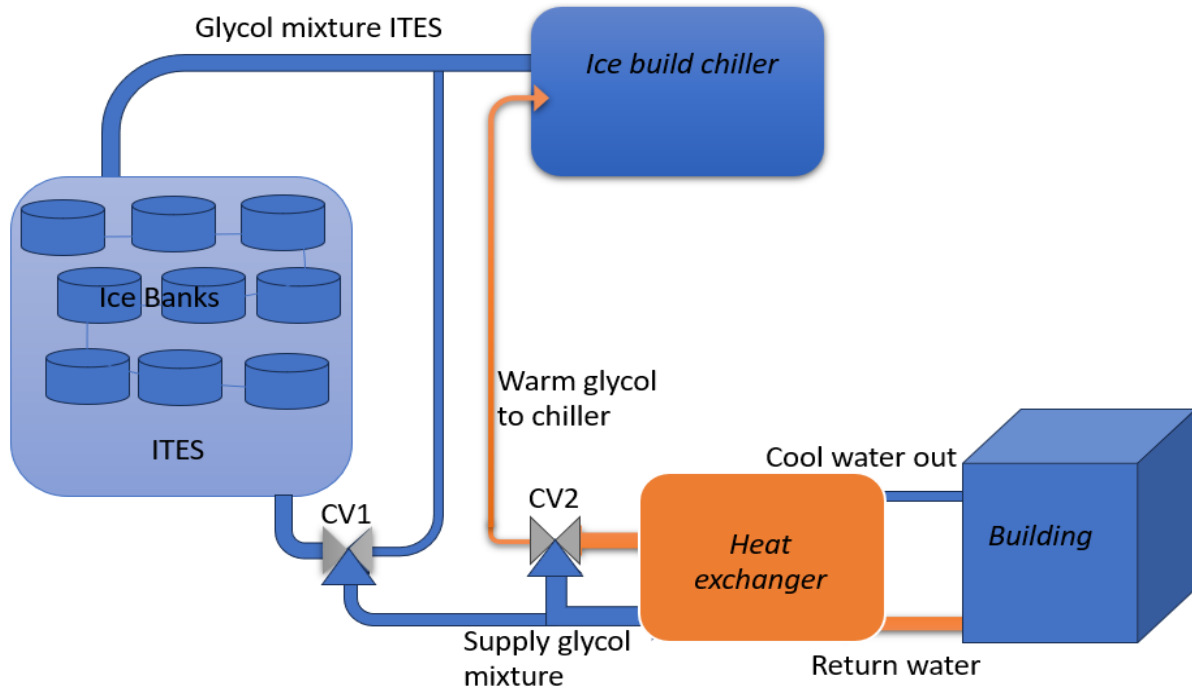


Figure 3.1: Schematic of the ITES plant [161]

Figure 3.1 illustrates the intricate workings of the ITES cooling system. This system derives its energy input from grid electricity to power the ice-building chiller. The ice-building process occurs in multiple Ice Banks® within the ITES unit, as facilitated by a glycol solution serving as the HTF. The control of HTF flow during the charging process is overseen by Control Valve 2 (CV2). Control Valve 1 (CV1) opens when in discharge mode, enabling the HTF from the ITES to cool the building through the heat exchanger. Chilled water, acting as the HTF, circulates the cooling between the secondary section of the heat exchanger and the building's AHU.

Warmer water, having completed its cooling cycle within the building, returns and is transferred to the primary side of the heat exchanger to interact with the glycol solution. During the charging phase, the glycol solution is mainly directed back to the ice-building chiller to recommence the ice-building process. The entire system is orchestrated to optimise the building's energy efficiency and thermal regulation.

3.2.2 Variable selection for the ANN model

Factors such as temperature, flow rates, properties of the HTF, size of the plant, and the dimensions of the system's components influence the cooling requirements of a building. It is crucial to conduct an analysis and prediction to understand how these factors are

interconnected and affect the demand output, such as the state of the ITES tank, COP, and power input to the chillers, as well as cooling loads. One practical approach is using an ANN model, which mimics the functioning of the brain's neurons. This model helps to solve fitting problems by establishing non-linear relationships between responses and targets. The ANN model operates by transferring signals, and its accuracy and computational speed greatly depend on training, testing, and validation. Moreover, using the ANN model simplifies the building process and reduces the computation time required for system modelling. The following steps were considered for the prediction model:

3.2.2.1 Dataset

Data were generated from the formulations given in Equations 3.1 to 3.10. The input variables are ranged based on the possible actual values, while the targets are derived from the energy balance and evaluated accordingly.

Equation 3.1 shows the energy balance (energy into the system is equal to energy out of the system):

$$E_{in} = E_{out}, \quad (3.1)$$

Equation 3.2 shows the energy balance (described later in Section 4.2):

$$E_1 + E_3 = E_2 + E_4, \quad (3.2)$$

Equation 3.3 expresses the thermal energy balance, according to the cycle:

$$Q_{chill}(t) = Q_s(t) + Q_L(t) + Q_g(t), \quad (3.3)$$

Equation 3.4 expresses the thermal energy stored in terms of the chiller, load, and gain from the surroundings:

$$Q_s(t) = Q_{chill}(t) - Q_L(t) - Q_g(t), \quad (3.4)$$

Equation 3.5 expresses the thermal energy stored in terms of the storage capacity and temperature of ice in the ITES:

$$Q_s(t) = SCAP \times T_{ice}(t), \quad (3.5)$$

Equation 3.6 expresses the chiller thermal energy in terms of the power input and COP:

$$\dot{Q}_{chill}(t) = P_{chill}(t) \times COP, \quad (3.6)$$

Equation 3.7 expresses the total thermal gain, considering the surface area of the ITES tank:

$$Q_g = q_g \times S, \quad (3.7)$$

Equation 3.8 expresses the total specific thermal gain based on heat transfer by conduction and convection:

$$q_g = \frac{T^{DB}(t) - T^{ice}(t)}{\frac{\Delta x}{kc} + \frac{1}{h}}, \quad (3.8)$$

Equation 3.9 expresses the thermal load in the ITES:

$$\dot{Q}_L(t) = \dot{m}_{gly} c_{gly} (T_{gly} - T_{ice}), \quad (3.9)$$

Equation 3.10 expresses the temperature state of the ITES tank:

$$\dot{T}_{ice}(t) = \frac{P_{chill} \times COP(t)}{SCAP} - \left(\frac{S \left(\frac{T^{DB}(t) - T^{ice}(t)}{\frac{\Delta x}{kc} + \frac{1}{h}} \right)}{SCAP} - \frac{\dot{m}_{gly} c_{gly} (T_{gly} - T_{ice})}{SCAP} \right). \quad (3.10)$$

According to Figures 3.1 and 4.1 (see Chapter 4), the energy balance between the chiller, ITES storage, and building is expressed in Equation 3.1. Equation 3.2 calculates energy E_{in} input energy to the ITES system, E_{out} energy out from the ITES system, and E_1 cooling energy supplied to the ITES tank during off-peak ToU or directly to the building E_3 . Cooling energy stored E_2 in the ITES is discharged to the facility during peak ToU. Building cooling energy is denoted by E_4 in Equation 3.3, which expresses the equation in terms of the thermal energy from the chiller Q_{chill} , thermal energy consumed by the building (Load) Q_L , and the heat Q_g gained from the surroundings to the ITES. (t) represents the time conversion at a specific time. Equation 3.4 presents the cooling energy of the storage $Q_s(t)$ as the state determinant. At the same time, Equation 3.5 shows that the capacity of energy stored depends on the variation of ice temperature at a specific time. In Equation 3.6, the thermal output Q_{chill} is related to the rated power of the chiller compressor P_{chill} and the COP of the refrigeration system. Heat gained by the ice from the surroundings is expressed in Equation 3.7, where the specific heat gain per unit area q_g and the surface area S are considered. Specific heat gain per unit area is expressed in terms of dry-bulb (surrounding) temperature T^{DB} , the temperature of the ice T^{ice} , the thickness of the ITES tank Δx , thermal conductivity kc , and heat transfer coefficient h in Equation 3.8. Equation 3.9 expresses the cooling load in terms of the temperature of glycol T_{gly} , the temperature of the ice, the mass flow rate of glycol $\dot{m}_{gly}$, and the specific heat capacity of glycol c_{pgly} , in the system. Equation 3.10 expresses the state of the ITES in terms of the change in temperature at a specific time.

3.2.2.2 Determining targets

Equation 3.10 was used to evaluate the ice storage temperature, including the control valve's flow. Evaluating COP in the performance analysis of ITES systems may be valuable. It provides insight into how effectively the system utilises stored thermal energy to meet cooling demands, thereby influencing overall energy efficiency and cost effectiveness. This evaluation can highlight areas where ITES systems may underperform or where adjustments in operational strategies can enhance performance.

Furthermore, evaluating the COP in the context of an ITES system's performance analysis can offer valuable insight into optimising energy efficiency and operational effectiveness. The COP was calculated from the ratio of the refrigeration effect on the glycol solution to the power input of the chiller. The cooling load was the amount of thermal energy gained in the system, while the power input for the chiller was randomly generated and values were in the range specified by the manufacturer based on the system's capacity.

3.2.2.3 Importing data into MATLAB

This involved importing the collected data into variable spaces (classifying the inputs and target-based required prediction) into the nftool application's ANN. However, variables should be clean (avoiding blanks and unacceptable values) and the data should be aligned to avoid errors that negatively affect the prediction results. Furthermore, in evaluating the performance of the predictive models, it is pertinent to specify acceptable metrics such as the coefficient of determination regression and root mean squared errors (MSEs), which vary depending on specific application domains. In this study, acceptable values were defined as a minimum regression of 0.8 and root MSEs of not more than 20% after training. These criteria ensured that the models achieved robust predictive accuracy while accounting for the inherent variability in real-world data.

3.2.2.4 Training and testing the ANN model

During this stage, training, validation, and testing of the ANN model were carried out using proportions for different variable configurations. The training was mostly set at 70%, while the validation and testing were set at 15%. The hidden layers were assigned a value of 10. Regression analysis and performance measures were used to assess the accuracy of the target predictions. Acceptable regression and MSE values were considered for scenarios during the analysis.

3.2.3 Input and output of the ANN model

Inputs are crucial to improve prediction accuracy and they should be diverse to contain as much information as possible. Based on the literature review, meteorological parameters, HVAC system operation parameters, and occupant behaviour parameters are most commonly used [174]. Inputs should meet the requirements of solid correlation with

outputs and must be easily measured [175]. The units and the range were further included; however, high-impact parameters were considered for the prediction. In some cases, the targets were used as the input for different values. Some constant parameters were further considered, including the surface area, flow rate, maximum storage capacity, thickness of the storage tank, thermal conductivity, and heat transfer coefficient. The inputs and targets of the ANN model in this study are shown in Table 3.1.

Table 3.1: Features of inputs and outputs

Type	Parameter	Unit	Range
Inputs	Control valve	%	0–100
	Dry-bulb temperature	°C	0.0–34.66
	Initial temperature of the ice in the storage tank	°C	-3–1
	Chiller condenser temperature	°C	24–29
	Chiller evaporator temperature	°C	2–6
	Temperature of glycol solution after heat transfer in the ITES	°C	5–11
Targets	ITES tank state temperature	°C	
	Building cooling load	kWt	
	COP		
	Chiller power	kW	90–100

3.2.4 Structure and description of ANN model input-output fitting, regression, and curve-fitting (nftool)

This section describes the input-output fitting, regression, and curve-fitting application, adopting the Levenberg-Marquardt (LM) algorithm for optimal prediction, which is used for training neural networks. In addition, the LM algorithm was selected due to the ability to model dynamic systems with feedback and to minimise the error or loss function during the training process [176].

However, with the LM algorithm, the specific details of the implementation may vary. Equations 3.11 to 3.13 provide a general overview of the algorithm and its application to neural network training, including nftool in MATLAB.

3.2.4.1 Objective function

The goal is to minimise an objective function, typically the MSE or another appropriate loss function.

$$E(w) = \frac{1}{2} \sum_{i=1}^N [y_i - f(x_i, w)]^2. \quad (3.11)$$

Where:

w is the vector of network parameters;

N is the amount of training;

y_i is the actual output for sample i ; and

$f(x_i, w)$ is the predicted output.

3.2.4.2 Weight update

The LM algorithm iteratively updates the weights using the following equation:

$$w_{(k+1)} = w_k + (J_k^T J_k + \lambda_k I)^{(-1)} J_k^T r_k \quad (3.12)$$

Where:

w_k is the weight vector at iteration k ;

J_k is the Jacobian matrix of partial derivatives of the network outputs for the weights;

r_k is the residual vector (difference between predicted and actual outputs);

λ_k is a damping parameter; and

I is the identity matrix.

3.2.4.3 Damping adjustment

The damping parameter λ_k is adjusted during each iteration to control the step size. It is increased or decreased based on the progress in reducing the error.

$$\lambda_{k+1} = \max(\lambda_k / v, \lambda_{\min}) \quad (3.13)$$

Where:

v is a damping adjustment factor; and

$\lambda_{\min}$ is a minimum damping parameter.

The network diagram presented in Figure 3.2 was created in Simulink form in MATLAB (2023 version). The network diagram considered in this study is shown in Figure 3.2 for a case with nine inputs, one target, and 10 hidden layers.

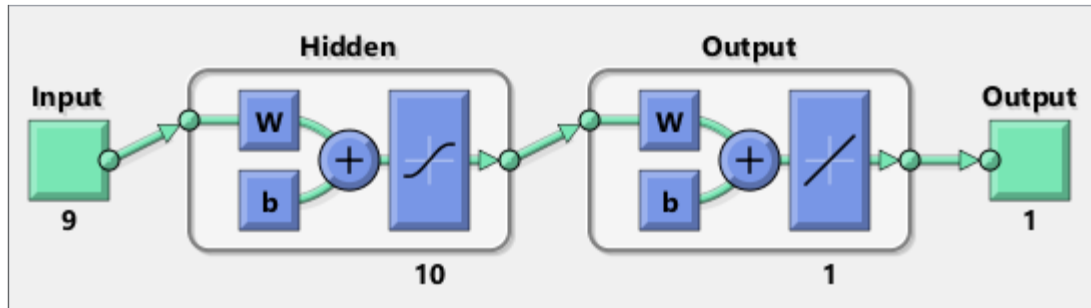


Figure 3.2: Network diagram for input-output fitting, regression, and curve-fitting (nftool)

3.2.5 Configuration to predict the performance indicators

Visualising and analysing the variation in performance indicators, set as target variables, were considered. The targets and the output after training, validation, and testing comparison assisted in checking the accuracy and robustness of the model. The results of the model may be used to optimise the charge and discharge processes, maintaining ice storage levels to meet demand, and simultaneously minimising costs by implementing rule-based algorithms based on ToU. The following targets were considered to comprehend the behaviour and to analyse the performance of the ITES:

- **State of charge (SoC) temperature:** The SoC in storage devices helps to know the state of health and performance of the system. In some cases, the ice level in the tank may be considered as the SoC. However, in this case, the storage temperature was used to estimate the SoC. The absolute temperature unit in Kelvin was used to avoid a sizeable negative set of values, which may influence the prediction results.
- **COP of the chiller:** The performance of the refrigeration system is measured by the COP and it is highly recommended that the COP be analysed for different configurations. A configuration with a higher COP output may be selected for efficient operation of the chiller.

- **Cooling load:** The system's purpose is to cool a building; predicting the cooling load may benefit the sizing and allow the correct configuration choice for optimal and cost-saving operation. For instance, integrating solar PV in line with the cooling load for pumping operations would result in cost saving in the ITES system in the long run.
- **Chiller power input:** The power input to the chiller may measure the energy consumption. With knowledge of possible energy consumption, operating the ITES plant effectively to minimise cost and achieve the required performance, based on demand and power supply for cooling in ITES, would be easier.

Generally, this information enhances understanding of the intricate dynamics between cooling supply and demand, which will enable informed decision making and effective energy management.

3.3 RESULTS AND DISCUSSION OF THE PREDICTIONS

3.3.1 Prediction of the storage tank temperature

Considering the prediction of the power storage tank temperature values using the nftool in the ANN model, 70% of the samples (corresponding to 70 samples) were used for training purposes, 15% of the samples (corresponding to 15 samples) were used for validation, and the remaining 15% (corresponding to 15 samples) were used for testing. The validation and testing data were used to evaluate the capabilities of the ANN model. Appendix A shows the codes related to the model. Figure 3.3 compares the predicted temperature against the actual values. The regression value R of 0.9198 for all samples related to the temperature indicates that the prediction is accurate. Equation 3.14 expresses the linear relationship from the linearisation of the data, with a gradient of 0.97 and intercept of 8.2.

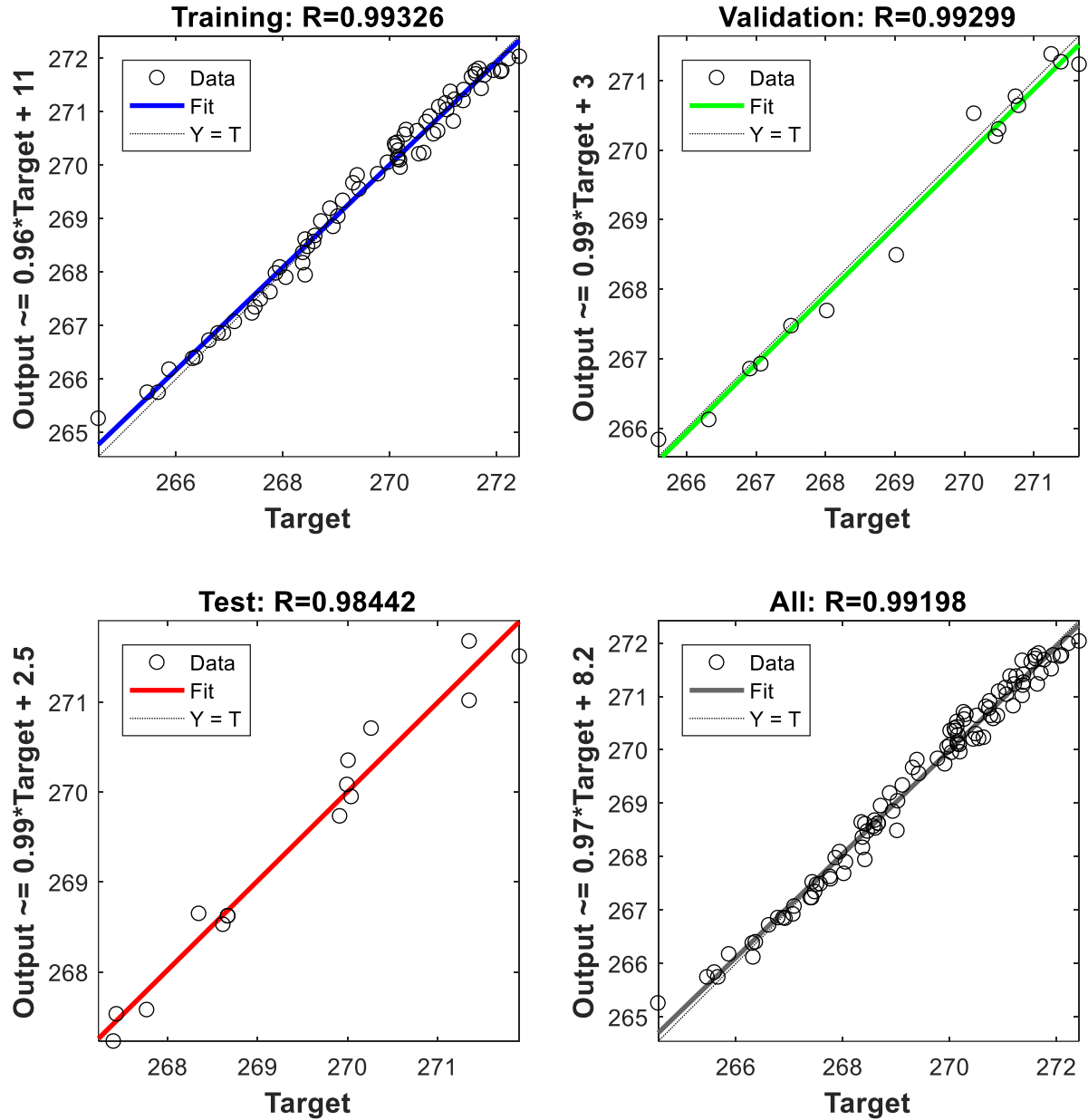


Figure 3.3: Regression plot of training, validation, testing, and all predictions for the temperature of the storage tank

$$\text{Output} \approx (0.97 \times \text{Target}) + 8.2 \quad (3.14)$$

Figure 3.4 presents the ANN predictions versus the target data of the temperature that were considered, using eight input variables. The predicted and the target data mostly match, with most deviations below 10% and a higher discrepancy of approximately 27% for the data, which correspond to temperature value less than 1 K and a maximum of 3 K

respectively. The predicted values are shown in Appendix B. The analyses show the potential of ANN to predict with higher accuracy.

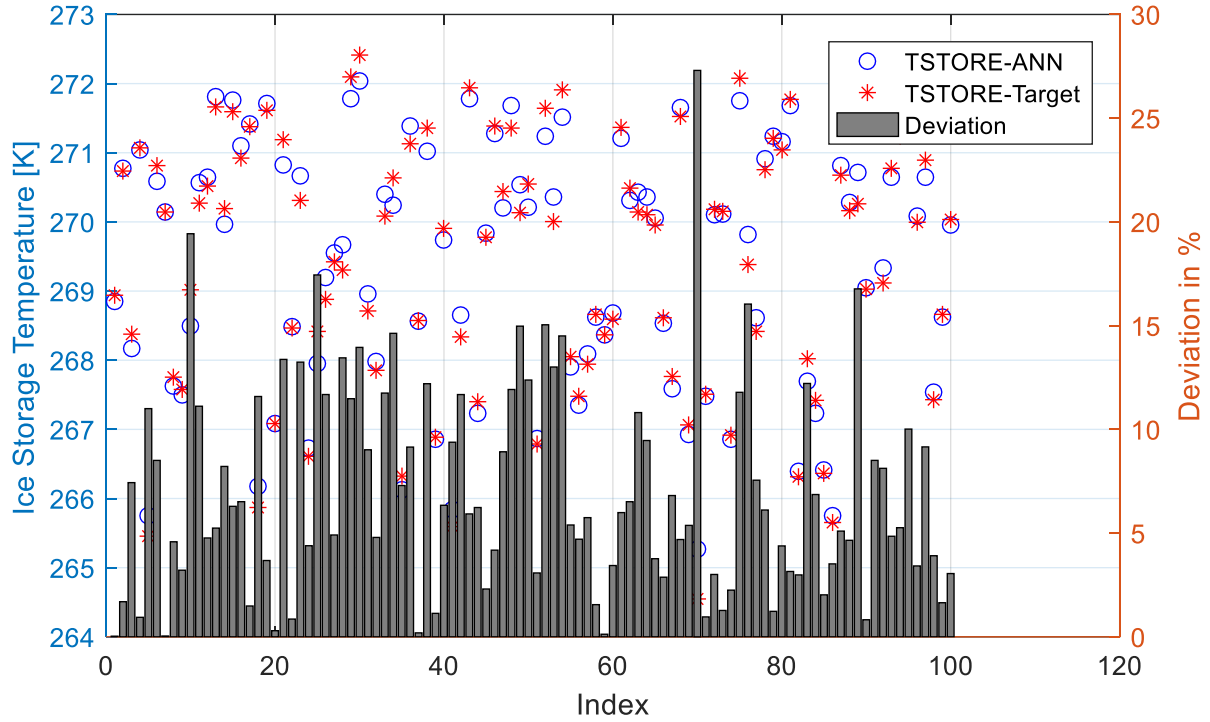


Figure 3.4: ANN prediction versus target temperature parameters with percentage deviation

3.3.2 Prediction of the chiller COP

Exact numbers of samples were considered in this configuration and different input variables and targets were used as the COP data. The LM algorithm was further evaluated, with 10 hidden layers. The training, validation, and testing were kept at 70%, 15%, and 15% respectively. The values predicted by ANN are shown in Appendix C. In Figure 3.5, the regression value for all predictions is 0.99944, which indicates high accuracy in the prediction.

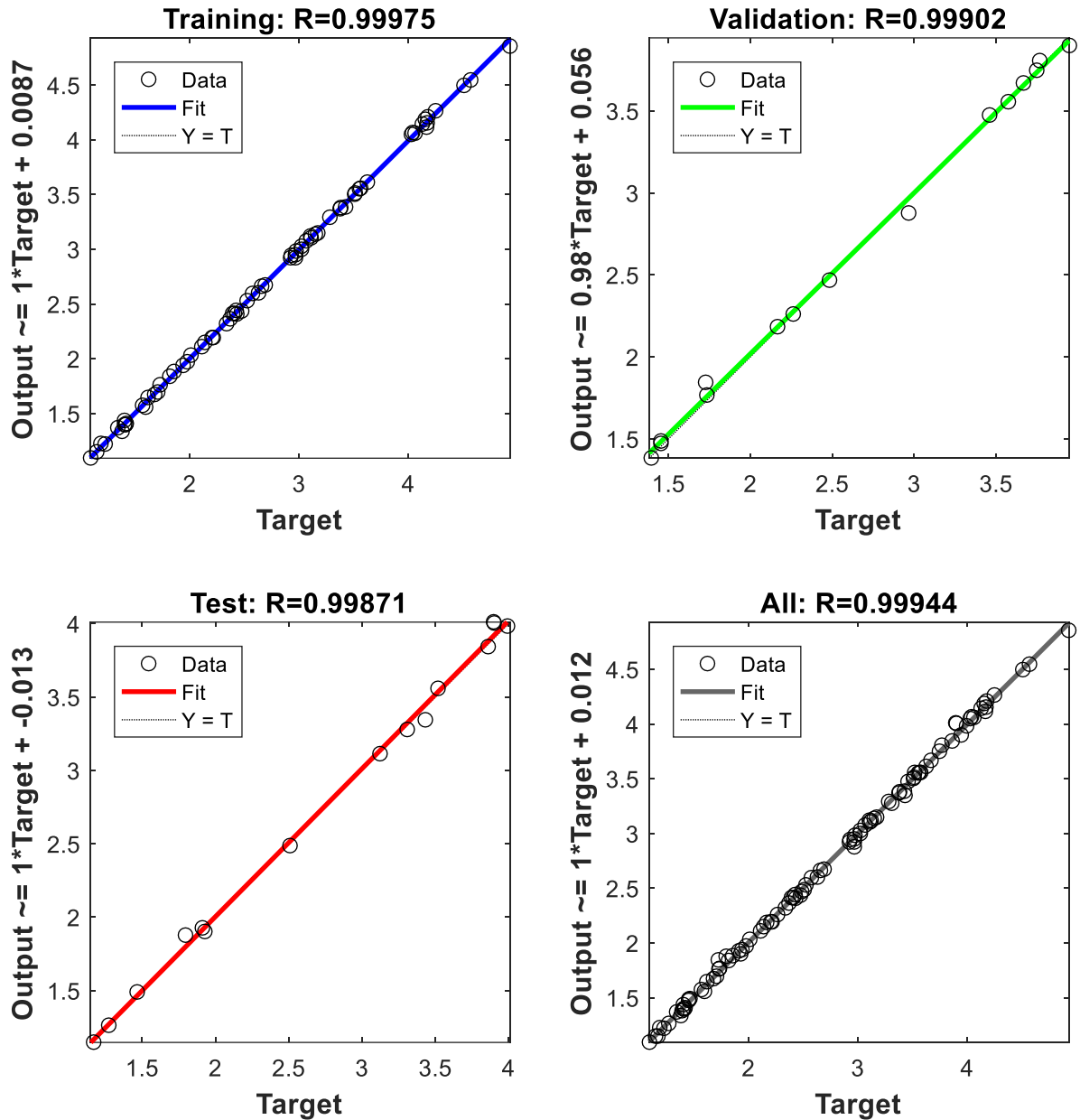


Figure 3.5: Regression plot of training, validation, testing, and all predictions for the chiller's COP

According to Figure 3.6, most predicted and target data matched the accuracy of the ANN prediction. The deviation derived from the forecast and the target data was mostly less than 4%, with the highest discrepancy being 7%, which corresponded to an approximate value difference of 0.1 and 0.3 respectively.

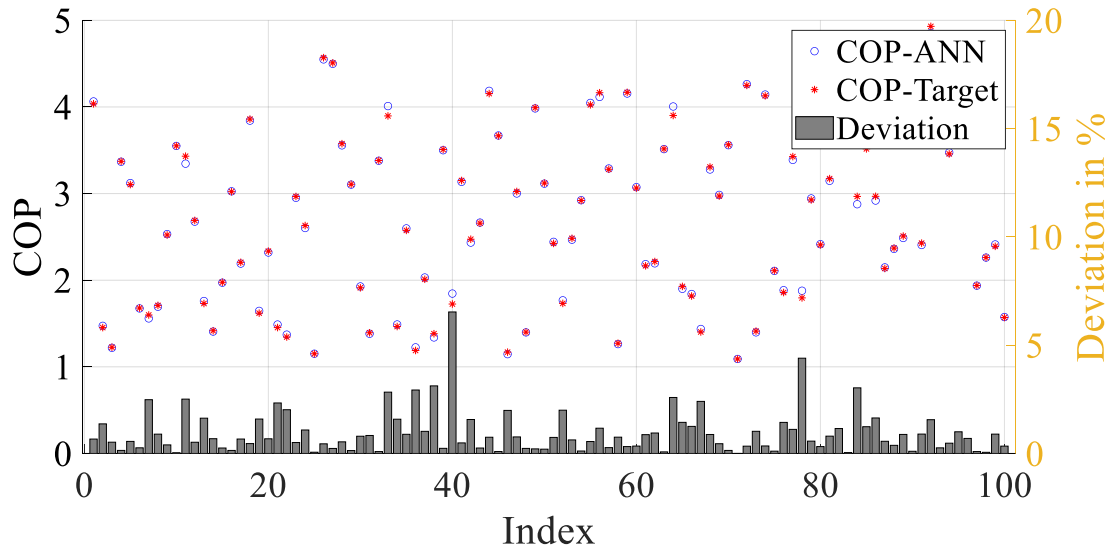


Figure 3.6: ANN prediction versus target COP parameters with percentage deviation

3.3.3 Prediction of the cooling load

As mentioned earlier, estimating the cooling load for the primary purpose to be achieved is essential. The ANN prediction procedure was repeated with the training, validation, and testing kept at 70%, 15%, and 15% respectively. The hidden layers were maintained at 10. The predicted values of the cooling load are shown Appendix D. The regression plot is shown in Figure 3.7, with a regression value of 0.99867 and the gradient of the linearisation at 0.99, to validate the accuracy of the prediction. The intercept of 1.5 kWe indicates little difference in the overall prediction, if scaled from a range of the cooling load values.

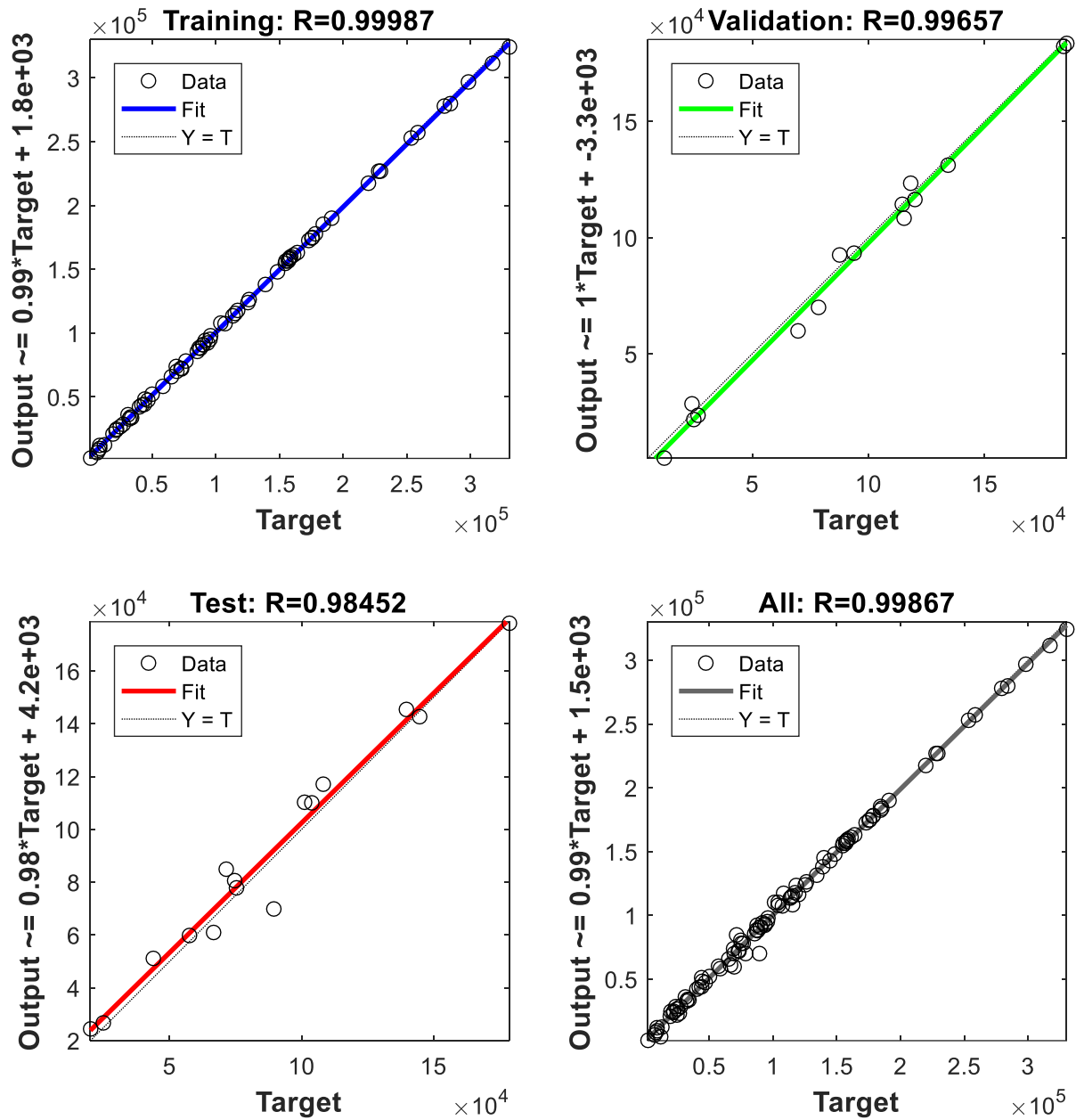


Figure 3.7: Regression plot of training, validation, testing, and all predictions for the cooling load

As shown by Figure 3.8, most derivation values fell below 10%, with a single value at a maximum discrepancy of approximately 60%. Most of the predicted and target values matched in the scatter plots.

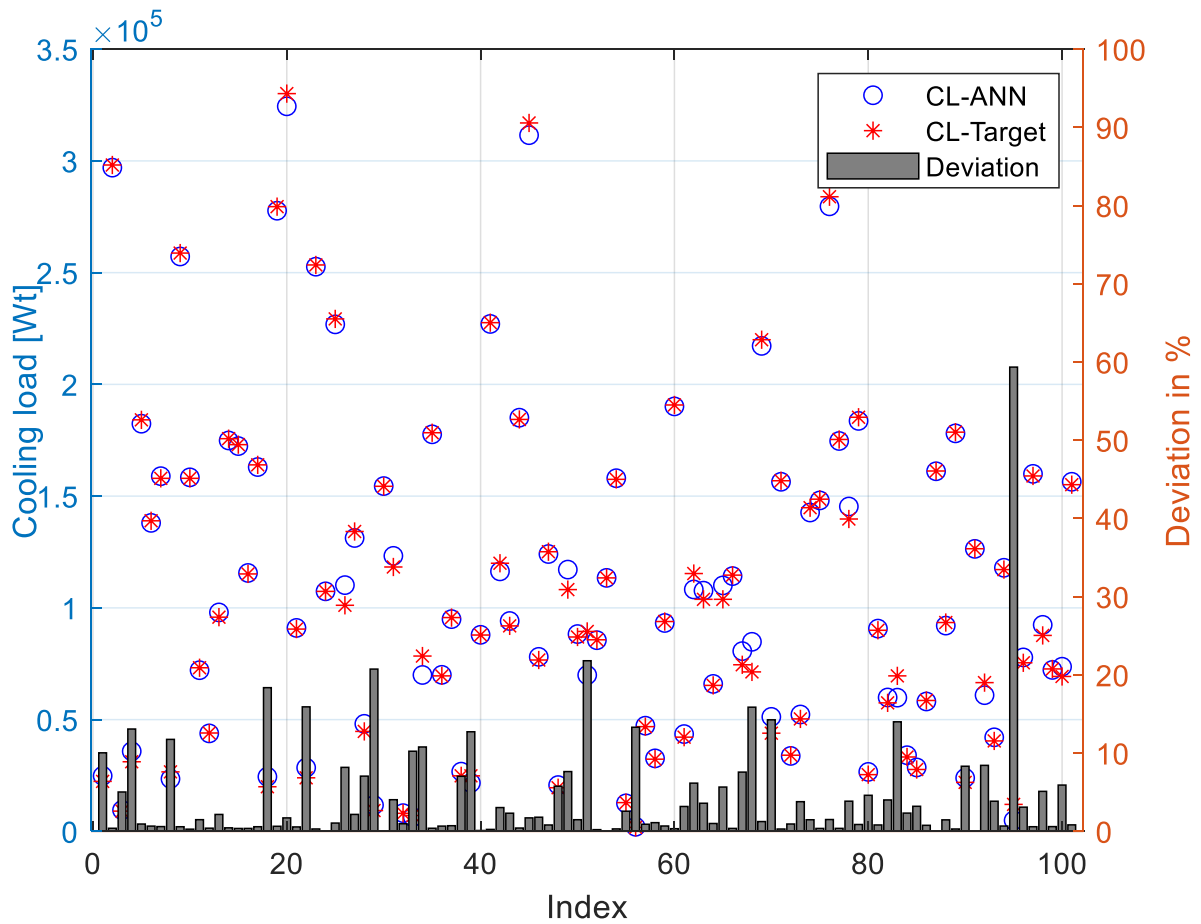


Figure 3.8: ANN prediction versus target cooling load parameters with percentage deviation

3.3.4 Prediction of chiller power input

The chiller consumes the highest percentage of electrical power. Predicting the chiller power consumption and other system components, such as the pumps, fan, and distribution board, may be advantageous in sizing the HVAC-ITES and solar integration in the future. From the outcome illustrated in Figure 3.9, the regression value of 0.9893 related to the chiller power prediction, using ANN, showed that the output and the target were on track, which indicates an effective prediction. The predicted values of the chiller power input is shown in Appendix E.

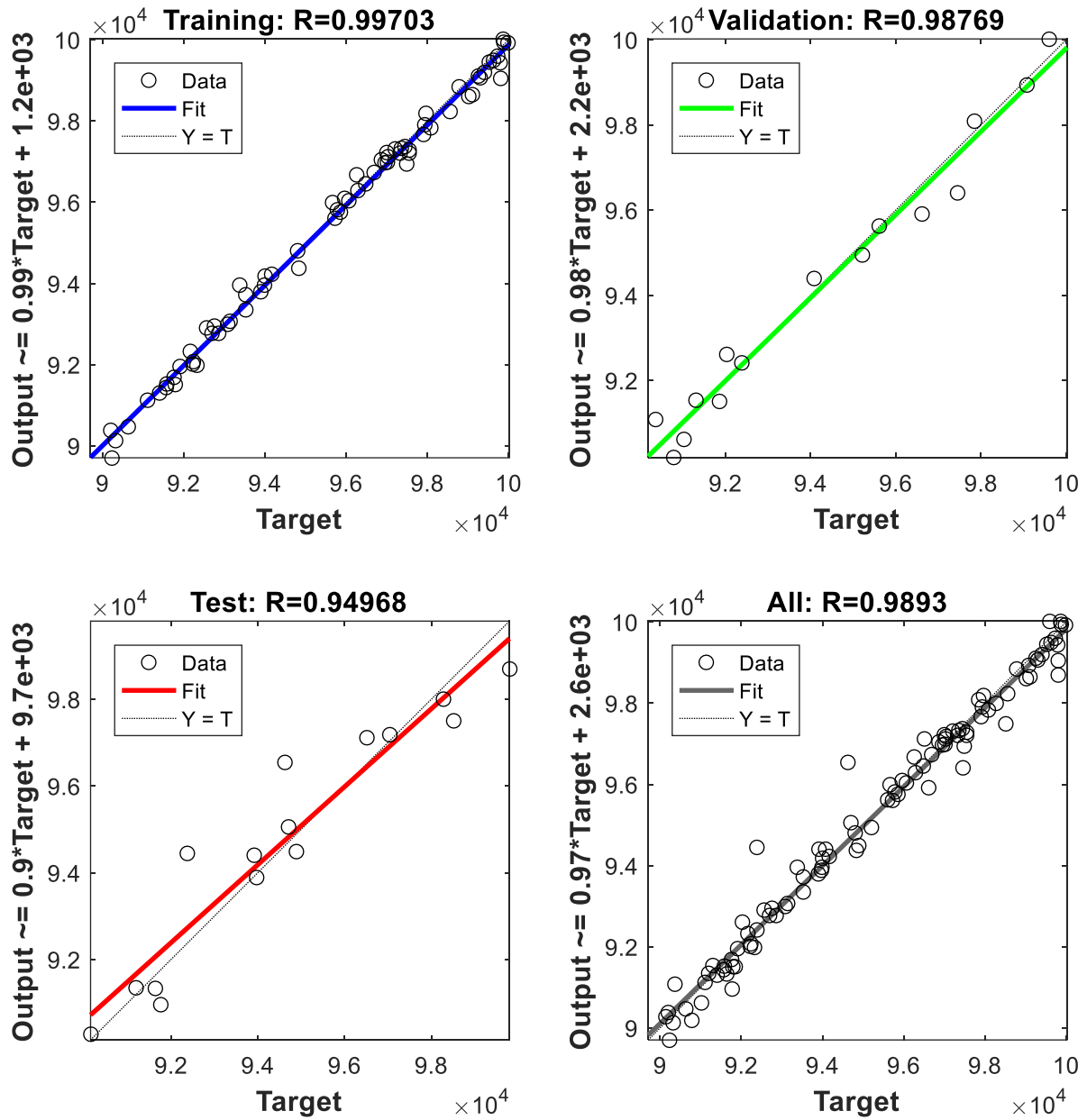


Figure 3.9: Regression plot of training, validation, testing, and all predictions for power input

Figure 3.10 shows that most of the deviation percentages of the predicted values were below 1%, while the value with the lowest accuracy was approximately 2%. In summary, the ANN prediction for chiller power is highly accurate.

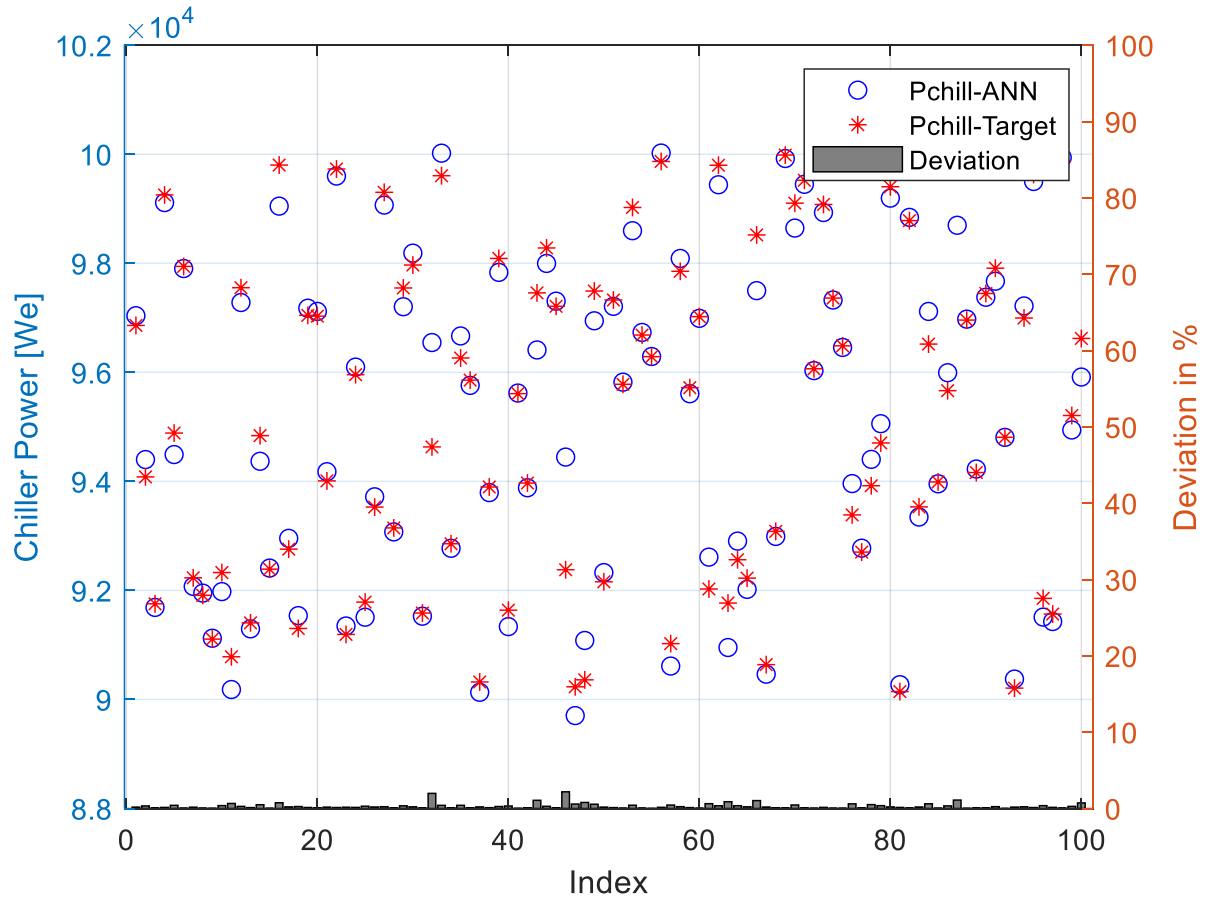


Figure 3.10: ANN prediction versus target power input parameters with percentage deviation

3.4 CONCLUSION

In this chapter, the neural network fitting tool in the ANN application was successfully applied to the ITES system, with various configurations of input variables randomly selected to predict the four performance parameters. One hundred datasets were generated from the energy balance base formulation of the ITES cooling system. The training regression values for storage tank temperature, COP, cooling load, and chiller power were 0.99233, 0.99975, 0.99987, and 0.99703 respectively. The validation regression values for storage tank temperature, COP, cooling load, and chiller power were 0.99299, 0.99902, 0.99657, and 0.98769 respectively. The testing regression values for storage tank temperature, COP, cooling load, and chiller power were 0.98442, 0.99871, 0.98452, and 0.94968 respectively. The regression values for storage tank temperature, COP, cooling load, and chiller power were 0.99198, 0.99944, 0.99867, and 0.98930 respectively. These values showcase the high accuracy in prediction using ANN. In addition, the outcomes of

the predicted and target value percentage deviations were low for all cases, except for some data that showed discrepancies.

Finally, the numerical and visual results demonstrated that the forecasting framework exhibited high accuracy, stability, and robustness. The proposed deterministic ANN approach therefore has high potential for practical applications in energy systems, such as HVAC and ITES systems. The ANN prediction can assist engineers in making better configuration choices to save time and costs in physical experimental setups. ANN prediction may further be useful in adequately applying ITES systems to minimise operational costs and to improve efficiency.

CHAPTER 4: OPTIMAL ENERGY MANAGEMENT OF GRID-CONNECTED PV FOR HVAC COOLING WITH AN ITES SYSTEM

4.1 INTRODUCTION

This chapter discusses the comprehensive control model with the SCIP solver algorithm that was carried out. The model aimed to minimise energy consumption, optimise charging efficiency, and prevent early depletion.

Section 4.2 elaborates on the model development of the system, in terms of the mathematical relationships and energy balance. Section 4.3 presents the model's case study and parametric analysis aspects. Section 4.4 discusses the simulation results and findings after optimisation. The economic analysis of the outcomes and output from the results are also discussed in this section. Lastly, the conclusions are highlighted in Section 4.5.

4.2 MODEL DEVELOPMENT

4.2.1 Description of the system

The major components are the chillers for the refrigeration process to build ice or to direct cooling to the ITES system. The ITES comprises sets of Ice Banks[®] that store thermal energy in the form of ice. Figure 4.1 shows the system configuration, which comprises a grid and PV power source for the chiller compressor and HTF pumps.

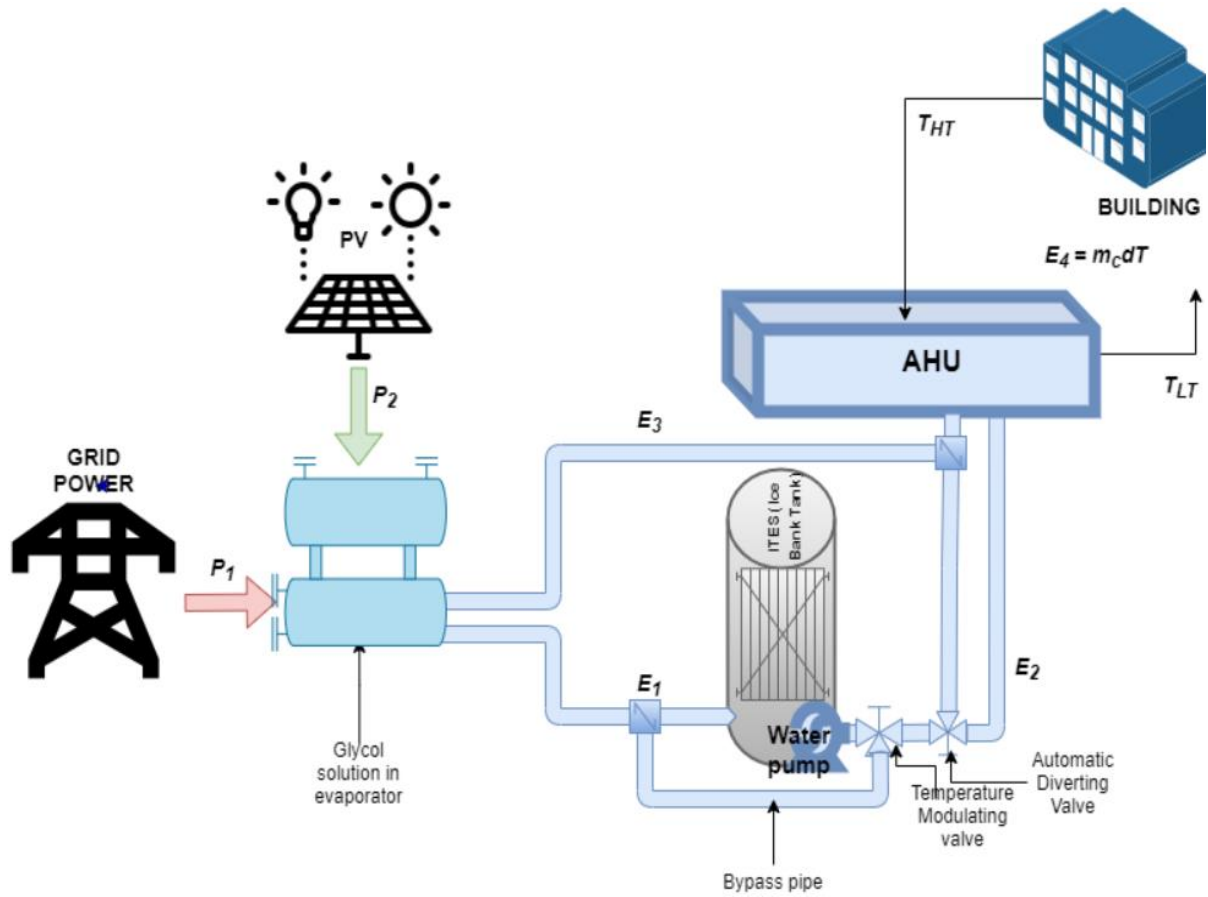


Figure 4.1: Schematic layout of the ITES system for cooling a building [25]

Cooling is transmitted in the AHU, comprising the heat exchangers and fan coil units (FCUs), to administer the thermal flow to the building, as well as the building where the cooling load is consumed. The model considers the present and proposed systems, including the electrical power flow and the heat energy transfer in the system. The significant components in the system include the chiller, pumps, heat exchangers, and the ITES. A binary switch between the grid and PV power source was further considered. The study focused on the ITES cycle regarding the charge and discharge operation related to energy consumption, energy cost, and thermal requirements or comfort.

4.2.2 Chiller, ITES, and PV model

Firstly, the electrical power balance for the system is described by Equation 4.1. Although PV power is not present in the current system, it was included in the equation for future upgrades to consider using renewable energy sources. Some systems use multiple chillers

for heat recovery and ice-built operation; the expression was further included in Equation 4.1.

$$P_{grid}(t) + P_{PV}(t) = P_{ch1}(t) + P_{ch2}(t) + P_{spump,ch1} + P_{spump,ch2} + P_{rpump,ch2} + P_{rpump,ch2} + P_{spump,HX} + P_{pump,r} + P_{ctrl} + P_{fan} \quad (4.1)$$

Where:

P_{grid} is the power supply from the grid energy source;

P_{PV} is the power source from PV;

P_{ch1} represents the input power to the heat;

P_{ch2} is the input power to the ice-making chiller 2;

$P_{spump,ch1}$ and $P_{rpump,ch1}$ are the cool glycol supply and return pump power input for chiller 1;

The power supply to supply and return pump for chiller 2 are denoted by $P_{spump,ch2}$ and $P_{rpump,ch2}$ respectively;

$P_{spump,HX}$ is the input power to the heat exchanger pump;

P_{ctrl} represents the controller unit and circuit power supply; and

P_{fan} is the power supplied to the AHU fan, which may be considered for future modelling.

According to the manufacturer Trane, ITES systems may be classified into six operating modes:

- Cool building with chiller only;
- Cool building with ice only;
- Cool building with chiller and ice;
- Make ice;
- Make ice and cool building; and
- Off [177].

These modes enable ITES systems to adjust to energy requirements, electricity pricing structures, and environmental conditions. This ensures efficient energy usage and cost savings.

However, the manufacturer CALMAC describes a scenario for a partial-storage ITES system with three cycles: charge, discharge, and bypass [177]. According to a design specification, the HTF glycol solution constantly flows at 18.4 l/s. HTF enters the ice-making chiller at an instantaneous temperature of approximately 11 °C, which reduces to approximately 5 °C after cooling. Referring to Figure 4.1, the chiller cools the glycol solution during the charging cycle at off-peak and is thereafter transported with cooling energy E_1 to the Ice Bank[®] tank. The fluid is then circulated through a counter-flow heat exchanger to cool the surrounding heat exchanger, in which approximately 95% of the water becomes frozen, while the outer part remains liquid. In the context of the proposed model, the chiller and other components, such as pumps and electrical components, source electricity from either the grid (P_1 or P_{grid}) or the PV (P_{PV}), depending on the choice that allows optimal and less costly operation. For a partial-storage system, the solution from the storage re-enters the chiller carrying energy E_3 , which in turn cools the glycol solution back to the supply temperature of the Ice Bank[®].

During peak demand and ToU, the stored, cooled glycol solution releases cooling energy from the Ice Bank[®] to the water to become chilled. With the aid of the temperature modulating valve, the required temperature is achieved by mixing the bypass and the Ice Bank[®] fluid supplied to the AHU. Chilled water, with cooling energy E_2 , is pumped to the AHU, where the cool air is circulated via an FCU. For a partial-storage system, the solution from the AHU re-enters the chiller carrying energy E_3 , which in turn cools the glycol solution back to the supply temperature of the Ice Bank[®]. The automatic diverting valve allows fluid diversion between the modulating valve, chiller, and AHU pipes.

The third mode of operation is the bypass, which allows unlimited capacity control utilising the temperature modulating valve. In addition, the bypass cycle prevents the unnecessary use of Ice Banks[®] during mild temperature days; thus saving the costs accumulated when charging the storage.

Finally, the cooling energy E_4 is transferred via the AHU, at the lower temperature T_{LT} and warmer fluid T_{HT} returns at a higher temperature. The mass (m_c) and specific heat capacity of air help determine the cooling load of the room space. Furthermore, the system may further operate on full storage, where the charging process is shifted to off-peak hours and the chiller runs solely during this time. The cooling load depends solely on stored energy [178].

Moreover, the optimal control will require ITES charging during the off-peak pricing period, when the ToU tariffs are relatively more affordable. Therefore, minimal power from the grid (mainly during the peak tariff period), maximum use of ITES cooling energy, and excess power from PV are considered. Furthermore, other desirable factors, depending on the application of the system, were investigated.

In most systems, two chillers are utilised – one dedicated to ice-making and the other to heat recovery. The central objective of this study aligns with minimising energy costs and maintaining thermal comfort by implementing effective load shifting. The power input to the chiller's compressors assists the cooling system in supplying HTF to the Ice Bank® and heat exchanger. The switching of compressors and pumps' input power is varied and controlled to optimise the stored energy output. For the energy balance, the relationship between the power input and thermal output, known as the COP, should be established mathematically. Depending on the power supply, the COP for cooling varies with the heat removed from the chiller [178]. The chiller load demand was therefore modelled as a fixed entity over discrete intervals. For accuracy, the model considered data captured at five-minute intervals.

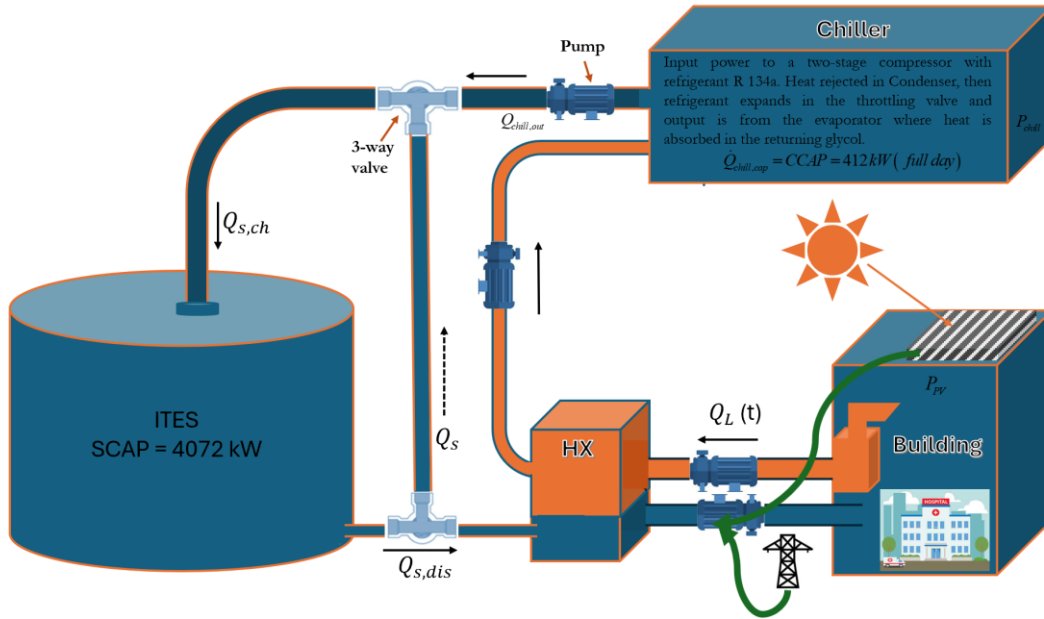


Figure 4.2: Simplified schematic of the chiller, ITES, and building plant [25]

Chillers receive electrical power through the compressor, condenser, and pumps. Refrigeration circuits commonly use R-134a or R-412A as refrigerants. The chiller's cooling energy may be evaluated using the given pressure drop of 52.9 kPa.

In the scenario, heat is rejected to the atmosphere through a fan-driven condenser, which results in a temperature of 28.4 °C, with an atmospheric temperature of 25.3 °C. Thereafter, the refrigerant flows to the throttling device at constant enthalpy, before entering the evaporator, which absorbs heat from the HTF, which is 30% propylene glycol. The chiller achieved 87.5% capacity, with a temperature drop of 9.1 °C to 5.5 °C in the glycol.

The state and rate of charge and discharge, with constraints, are determined using the energy balance. A simplified schematic of the chiller, ITES, and building plant was shown in Figure 4.2.

Considering a system with a PV power supply, the output power may be modelled using Equation 4.2 [180]:

$$P_{PV} = P_{PV,STC} N_{PVS} N_{PVP} \frac{TI}{1000} [1 - \alpha(T_C - 25)]. \quad (4.2)$$

Equation 4.3 may be used to find the solar irradiance on a tilted surface, calculated from further components of solar irradiance [180]:

$$TI = DNI \cos \theta + DHI \left(\frac{1 + \cos \beta}{2} \right) + \rho_r GHI \left(\frac{1 - \cos \beta}{2} \right). \quad (4.3)$$

Equation 4.4 shows how the cell temperature may be determined [180]:

$$T_c = T_a + \frac{TI}{800} (NOCT - 20). \quad (4.4)$$

Equation 4.5 expresses energy from the PV as a second source of power:

$$P_2 = P_{PV}. \quad (4.5)$$

Equation 4.6 indicates that the constrained power source varies from zero to maximum as a safety requirement:

$$0 \leq P_{PV} \leq P_{PV}^{max}, 0 \leq P_{PV} \leq P_{PV}^{max}. \quad (4.6)$$

Where (for Equations 4.2 to 4.6):

P_{PV} symbolises the power input represented at the maximum power point and standard test condition (STC);

$N_{PVS} T_C$ and N_{PVP} are the number of PV panels in series and parallel respectively;

The total irradiance is TI and α represents the temperature coefficient with reference to power output, which is the temperature of the PV cell in °C. T_a is the temperature of the surrounding air in °C;

DNI , DHI , and GHI are the direct normal irradiance, diffuse horizontal irradiance, and global horizontal irradiance respectively;

$NOCT$ is the nominal operating cell temperature in °C;

ρ_r are the reflectance factors of the location; and

θ and β are the tilted angle and the incidence angle of solar radiation on a sloping surface respectively [179].

According to Figure 4.1 and the model development in Section 3.2 of Chapter 3, the energy balance between the chiller, ITES, and building is expressed in Equation 4.7. Equation 4.8 described E_{in} input energy to the ITES system, E_{out} energy out from the ITES system, E_1 cooling energy E_1 supplied to the ITES tank during off-peak ToU or directly to the building E_3 . Cooling energy stored E_2 in the ITES is discharged to the facility during peak ToU. Building cooling energy is denoted by E_4 . Equation 4.9 expresses the equation in terms of the thermal energy from the chiller Q_{chill} , thermal energy consumed by the building (Load) Q_L , and the heat Q_g gained from the surroundings to the ITES. (t) represents the time conversion at a specific time. Equation 4.10 presents the cooling energy of the storage and $Q_s(t)$ as the state determinant. At the same time, Equation 4.11 shows that the energy storage capacity $SCAP$ depends on the variation of ice temperature $\dot{T}_{ice}$ at a specific time. In Equation 4.12, the thermal output Q_{chill} is related to the rated power of the chiller compressor P_{chill} and the COP of the refrigeration system. Heat gained by ice from the surroundings is expressed in Equation 4.13, where the specific heat gain per unit area q_g and the surface area S are considered. Specific heat gain per unit area is expressed in terms of dry-bulb (surrounding) temperature T^{DB} , the temperature of the ice T^{ice} , the thickness of the ITES tank Δx , thermal conductivity kc , and heat transfer coefficient h in Equation 4.14. Equation 4.15 expresses the cooling load in terms of the temperature of glycol T_{gly} , the temperature of the ice, the mass flow rate of glycol $\dot{m}_{gly}$, and the specific heat capacity of glycol C_{pgly} in the system. Equation 4.16 expresses the state of the ITES in terms of the change in temperature at a specific time.

$$E_{in} = E_{out}, \quad (4.7)$$

$$E_1 + E_3 = E_2 + E_4 \quad (4.8)$$

$$Q_{chill}(t) = Q_s(t) + Q_L(t) + Q_g(t) \quad (4.9)$$

$$Q_s(t) = Q_{chill}(t) - Q_L(t) - Q_g(t), \quad (4.10)$$

$$Q_s(t) = SCAP \times T_{ice}(t), \quad (4.11)$$

$$Q_{chill}(t) = P_{chill}(t) \times COP, \quad (4.12)$$

$$Q_g = q_g \times S \quad (4.13)$$

$$q_g = \frac{T^{DB}(t) - T^{ice}(t)}{\frac{\Delta x}{kc} + \frac{1}{h}} \quad (4.14)$$

$$Q_L(t) = \dot{m}_{gly} c_{gly} (T_{gly} - T_{ice}), \quad (4.15)$$

$$\dot{T}_{ice}(t) = \frac{P_{chill} \times COP(t)}{SCAP} - \left(\frac{S \left(\frac{T^{DB}(t) - T^{ice}(t)}{\frac{\Delta x}{kc} + \frac{1}{h}} \right)}{SCAP} - \frac{\dot{m}_{gly} c_{gly} (T_{gly} - T_{ice})}{SCAP} \right). \quad (4.16)$$

The state, control, and constraints equations from the energy balance equations are presented in Equations 4.17 to 4.20:

$$A(t) = \left(\frac{\left(\frac{S}{\frac{\Delta x}{kc} + \frac{1}{h}} \right)}{SCAP} - \frac{\dot{m}_{gly} c_{gly} (T_{gly} - T_{ice})}{SCAP} \right), \quad (4.17)$$

$$B(t) = \frac{P_{chill} \times COP(t)}{SCAP}, \quad (4.18)$$

$$C(t) = \left(\frac{S \left(\frac{S \times T^{DB}(t)}{\frac{\Delta x}{kc} + \frac{1}{h}} \right)}{SCAP} - \frac{\dot{m}_{gly} c_{gly} T_{gly}(t)}{SCAP} \right), \quad (4.19)$$

$$\dot{T}_{ice} = -A(t) + BSw(t) + C(t). \quad (4.20)$$

Where:

A represents the terms of initial variables of the system;

B defines the terms of the control variable of the system;

C describes the terms of disturbance of the system; and

Sw describes the terms of the binary switch.

4.2.3 Discretising the ITES Ice Bank[®] temperature

To enable the realisation of the temperature change rate (indication of the SoC) of the water/ice inside the storage tank at any given time interval, Equation 4.20 is discretised from a continuous form for the ice storage temperature function, at any given time interval. Thereafter, applying the forward Euler method, the space equation is expressed in Equation 4.21 to indicate the time instance [181]. The method applies to the charging and discharge process since heat addition and rejection are considered in the state equation.

$$T_{s,k+1} = T_{s,k} (1 - t_s A_k) + t_s BSw_k + t_s C_k. \quad (4.21)$$

$T_{s,k+1}$ is the first value of temperature after the initial value $T_{s,k}$ at the sampling time t_s and, if expressed as $T_{s,1}$ at $then k = 0$, then the initial value becomes $T_{s,0}$. The control variables and disturbance terms thus become Sw_0 and C_0 respectively, as shown in Equation 4.22.

$$T_{s,1} = T_{s,0} (1 - t_s A_0) + Sw_0 + t_s C_0. \quad (4.22)$$

Similarly, the next interval shows when $k = 1$ $T_{s,2}$ is expressed in Equation 4.23:

$$T_{s,2} = T_{s,1} (1 - t_s A_1) + t_s BSw_1 + t_s C_1. \quad (4.23)$$

Considering the replacement of $T_{s,1}$ in Equation 4.22, Equation 4.21 was substituted into Equation 4.23, to give Equation 4.24. After factorising, the expanded form of $T_{s,2}$ is shown in Equation 4.25 as:

$$T_{s,2} = [T_{s,0} (1 - t_s A_1) + t_s BSw_0 + t_s C_0] + (1 - t_s A_1) + t_s BSw_1 + t_s C_1, \quad (4.24)$$

$$T_{s,2} = T_{s,0} [(1 - t_s A_0)(1 - t_s A_1)] + t_s [B(1 - t_s A_0)Sw_0 + Sw_1] + t_s [(1 - t_s A_1)C_0 + C_1]. \quad (4.25)$$

Furthermore, applying the same steps from Equation 4.22 to Equation 4.24, the expression for $T_{s,3}$ is given in Equation 4.26:

$$T_{s,3} = [(1 - t_s A_0)(1 - t_s A_1)] + t_s B[(1 - t_s A_1)(1 - t_s A_2)Sw_1 + Sw_2] + t_s [(1 + t_s A_1)(1 + t_s A_1)C_1 + C_2]. \quad (4.26)$$

Equations for subsequent expressions could be determined by repeating the previous steps. A general term for the discretisation relationship is therefore shown in Equation 4.27:

$$T_{s,(k+1)} = T_{s,0} \prod_{j=0}^k (1 - t_s A_j) + t_s B \sum_{j=1}^k Sw_j \prod_{j=0}^k (1 - t_s A_j) + t_s \sum_{j=0}^k C_j \prod_{j=i+1}^k (1 - t_s A_i). \quad (4.27)$$

In addition, Equation 4.27 allows visualisation of the changes at sampling time t_s , the temperature $T_{s,k}$ at an interval of k , with the initial temperature $T_{s,0}$ of the ITES tank, including the binary on or off (1 or 0) control Sw_j , as well as disturbance factors.

4.2.4 Objective function, boundaries, and constraint

4.2.4.1 Objective function

The main objective is to minimise the costs of the energy supplied to the chiller and to maximise the PV power source. The minimisation of the energy cost subjected to the ToU tariff. Fundamentally, the control algorithm should find the optimal switching solution that would result in energy usage during the low-cost regions, while avoiding peak periods. Simultaneously, available PV power sources, mostly higher during sunny and hot weather, are maximised in the system. The primary objective function is therefore given by Equation 4.28:

$$J = t_s \left(\sum_{k=1}^N P_{rf(k)} \psi_k Sw_{(k)} - P_{PV(k)} \right). \quad (4.28)$$

Where:

J represents the total cost function, measured in ZAR;

t_s is the sampling time (hours);

$P_{rf(N)}$ is the rated power of each of the electric resistive elements (kW);

Sw_k is the switching status function for each component of the associated chiller; and

ψ_k is the ToU hourly pricing period, described in Equation 4.29 for weekdays and Equation 4.30 for Saturdays.

A five-minute sampling time was considered in the model with the sampling interval $k = 1, \dots, N$, where $N = 24$.

$$\psi_{wd}(t) = \begin{cases} \psi_p; t \in T_k, T_k = [7, 10][18, 20); \\ \psi_o; t \in T_k, T_k = [0, 6][22, 24); \\ \psi_s; T_k, T_k = [6, 7][10, 18][20, 22). \end{cases} \quad (4.29)$$

$$\psi_{we}(t) = \begin{cases} \psi_p; t \in T_k, T_k = [6, 9][17, 19); \\ \psi_o; t \in T_k, T_k = [0, 6][22, 24); \\ \psi_s; T_k, T_k = [9, 17][19, 22). \end{cases} \quad (4.30)$$

Where:

ψ_p is the cost of energy during the peak pricing period;

ψ_o is the cost of energy during the off-peak pricing period; and

ψ_s is the cost of energy during the standard pricing period.

The power rating is included in the objective function so that the objective function value, after optimisation, equals the total energy cost incurred.

The secondary objective is to ensure fixed final state conditions by minimising the difference between them, as expressed in Equation 4.31:

$$J_s = \sum_{t_0}^{t_f} (T_s(t) - F(t))^2. \quad (4.31)$$

Where:

J represents the fixed final temperature state function, measured in °C;

t_0 is the initial sampling interval at $T_s(t) = T_s(t_0)$ (initial temperature); and

t_f is the final sampling interval at $F(t) = T_s(t_f)$ (final temperature).

The aggregate objective function then becomes the expression in Equation 4.32:

$$J = t_s \sum_{k=1}^N (P_{rf(k)} \psi_k S w_{(k)} - P_{PV(k)}) + \sum_{t_0}^{t_f} (T_s(t) - F(t))^2. \quad (4.32)$$

Where: J represents the aggregate objective function (dimensionless).

4.2.4.2 Constraints and boundaries for charge and discharge

The objective function is subjected to constraints in Equations 4.33 to 4.36. The minimum and the maximum temperatures are constrained to meet the building's thermal requirements. Moreover, the switch function should appropriately control the charging and discharging. If not set correctly, energy cost minimisation may lead to temperatures beyond thermal comfort.

The objective function, subjected to the minimum constraints, is shown in Equation 4.33.

$$T_0 \prod_{j=0}^k (1 - t_s A_j) + t_s \sum_{j=0}^k Sw_j \prod_{i=j+1}^k (1 - t_s A_i) + t_s \sum_{j=0}^k C_j \prod_{j=i+1}^k (1 - t_s A_i) \leq T_{s_{min}}. \quad (4.33)$$

The objective function, subjected to the maximum constraints, is shown in Equation 4.34:

$$T_0 \prod_{j=0}^k (1 - t_s A_j) + t_s B \sum_{j=0}^k Sw_j \prod_{i=j+1}^k (1 - t_s A_i) + t_s \sum_{j=0}^k C_j \prod_{j=i+1}^k (1 - t_s A_i) \leq T_{s_{max}}. \quad (4.34)$$

Equation 4.35 shows the function of the binary switch:

$$Sw_k \in \{0,1\}. \quad (4.35)$$

The general expression attained in Equation 4.36 represents the actual temperature of the ice in the storage tank. $T_{s_{min}}$ denotes the minimum permissible temperature that the water in the storage tank may reach. $T_{s_{max}}$ is the maximum threshold that the temperature may not exceed for any given interval:

$$T_{s_{min}} \leq T_k \leq T_{s_{max}} \quad (4.36)$$

Moreover, the latent form of ice may be expressed as shown in Equation 4.37:

$$X_{k+1} = X_k + u_k \quad (4.37)$$

Where:

X_k is the initial SoC of the ITES at a given time;

X_{k+1} is the final SoC of ITES at a given time; and

u_k is the non-linear constraint for charge and discharge rate.

Lastly, the conditions for charge and discharge are shown in Table 4.1.

Table 4.1: Constraints conditions for charging and discharging cycles

Parameter	Charging	Discharge	Comment
Q_k^{chill}	$Q_k^{chill} = u_k$ (4.38) Q_k^{chill} the thermal energy absorbed from glycol in the evaporator	$Q_k^{chill} = Q_k^{LB} + u_k$ (4.39) Q_k^{LB} the cooling load of the building	Cooling load depends on the mode, which could be passive (bypass the ITES and thermal output), charging, or discharging.
u_k	$u_k > 0$ (4.40)	$u_k \leq 0$ (4.41)	Rate charging and discharge inequalities.
T_k^{evap}	$T_k^{evap, ice}$ (4.42)	$T_k^{evap, gly}$ (4.43)	During charging, ice builds and glycol transfers heat.
$Q_k^{chill-R}$	274 kW	421 kW	Hospital-rated chiller capacity.
	$0 \leq u_k^{max_{scap}}$ (4.44)	$-Q_{scap} \leq u_k^{min} \leq 0$ (4.45)	Q_{scap} is the ITES system's storage capacity in kWh. The maximum thermal energy rate should not exceed the storage capacity and should be greater than zero and vice versa for the discharge process.
T^R	25 °C	35 °C	Rated air inlet temperature from the surroundings.
$\dot{Q}_{dis}$	$\dot{Q}_{dis} = 0$ (4.46)	$\dot{Q}_{dis} = u_k \frac{\dot{Q}_{scap}}{\Delta t}$ (4.47)	The thermal discharge rate of the system.
$\dot{Q}_{ch}$	$\dot{Q}_{ch} = u_k \frac{\dot{Q}_{scap}}{\Delta t}$ (4.49)	$\dot{Q}_{ch} = 0$ (4.48)	The thermal charge rate of the system.
$\dot{Q}_k^{BL}$	$\dot{Q}_k^{chill} = \dot{Q}_k^{BL}$ $\dot{Q}_k^{BL} = 0$ (Cut-off discharge) (4.50)	$\dot{Q}_k^{chill} = \dot{Q}_k^{BL} - \dot{Q}_{dis}$ $\dot{Q}_k^{BL} > 0$ (discharge / idle) (4.51)	The thermal rate of the chiller to building cooling load for the processes. The cooling load switches off and becomes zero for charging facilities, whereas the cooling load engages greater than zero on discharging.
Sw_M	$Sw_M = 0$ (4.52)	$Sw_M = 1$ (4.53)	Switching mode is binary 0 when cooling is off and 1 when the user cools the building.

4.2.4.3 Assumptions in the model analysis

The assumptions of the mathematical model of the ITES system include the following:

- Only the cooling load cycle of the HVAC-ITES system was modelled.
- Multiple chillers were modelled as a single chiller.
- Multiple Ice Banks[®] were modelled as single Ice Banks[®].
- The electrical energy of some devices, such as the secondary supply pumps and FCUs, was not included in the simulation.

4.2.5 Implementation of model optimisation in MATLAB

The input parameters, constants, and functions were coded in MATLAB. At the same time, the optimisation was initially carried out in SCIP in the OPTI-toolbox in MATLAB, which was selected as it aligned well with the problem domain. The following factors were further considered:

Firstly, with the MIP capabilities, SCIP is designed to handle optimisation problems with decision variables, which perfectly fit the research model. It has a track record of solving a wide range of problems.

Secondly, SCIP, with improved computational efficiency, utilises advanced algorithms and optimisation techniques to provide high-performance solutions. It employs branching rules, effective heuristics, and cutting plane algorithms to explore the solution space, resulting in improved computational efficiency and shorter solution times [181].

Within this MATLAB model, the input variables outlined in Figure 4.3 were sourced from the screened data in the Microsoft Excel file, while the constants were defined within the code itself. The model formulation and optimisation equations were written in MATLAB's M file. Following this, the model was executed with appropriate debugging to generate outputs. These outputs were subsequently compared with similar models, as part of the validation process. The MATLAB script used for the optimisation is attached in Appendix F. This script encompasses the definition of the objective function, constraints, solver settings, and the optimisation execution. In addition, the model employed multi-objective optimisation, focusing on the following objective functions: cost minimisation, thermal discomfort minimisation, and PV usage maximisation.

To address the multi-objective nature of the optimisation problem, the model utilised a weighted sum approach. This method allowed the combination of the different objectives into a single composite objective function by assigning appropriate weights to each individual objective. The weights were chosen based on their relative importance as follows: weight for cost minimisation (W1): 0.4; weight for thermal discomfort minimisation (W2): 0.3; and weight for PV usage maximisation (W3): 0.3.

The weighted sum approach transformed the multi-objective optimisation problem into a single-objective optimisation problem, which was then solved using the SCIP solver in MATLAB. Figure 4.3 shows the diagrammatic flow chart of the optimisation model, which was implemented using MATLAB.

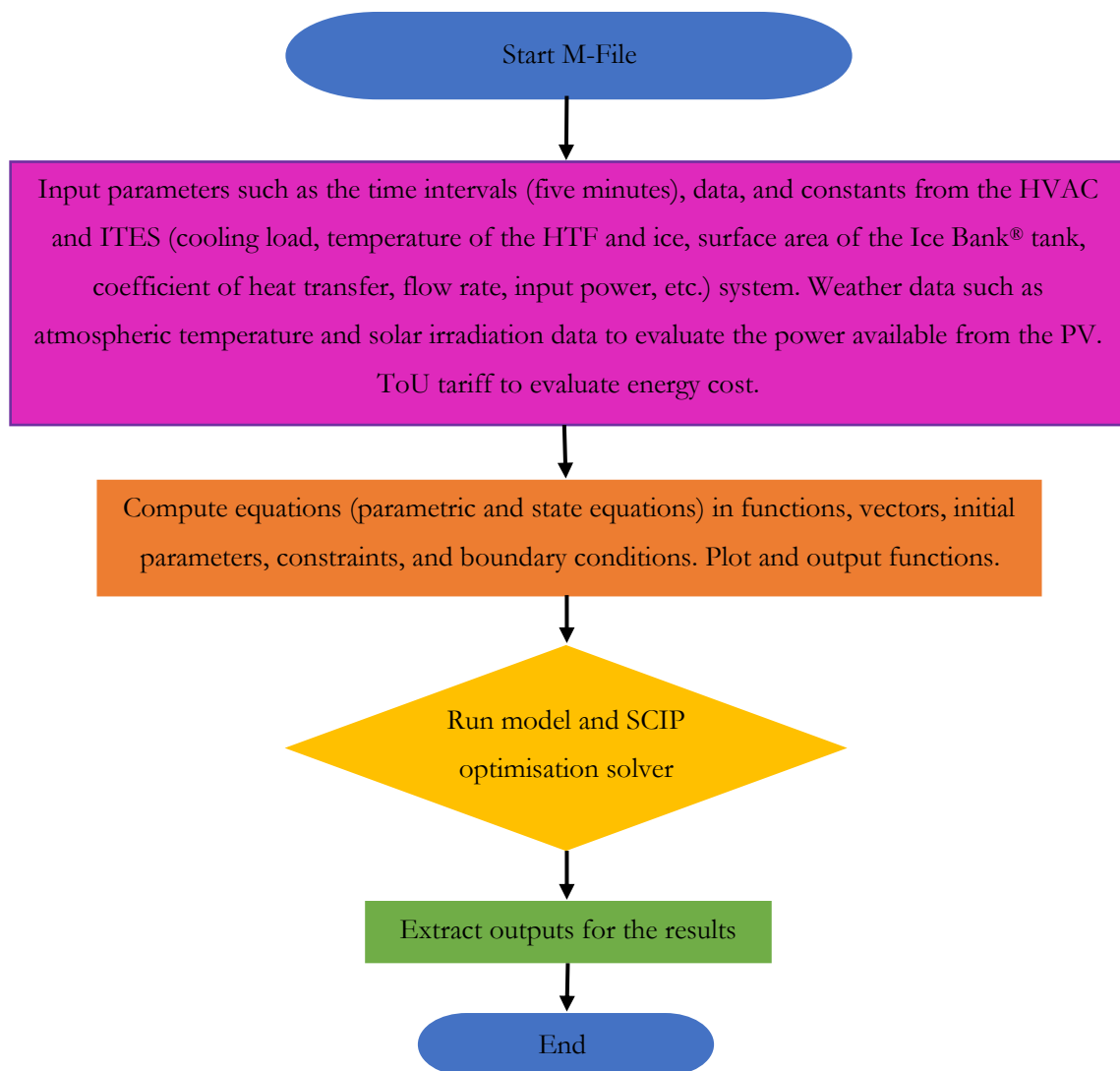


Figure 4.3: Diagrammatic flow chart of the optimisation model

4.2.6 Economic analysis

Economic analysis was used to analyse the viability of the work and the investment's present value in the future. It is worth mentioning that, in the long run, the installation of a solar PV system may save energy and associated costs. It is therefore imperative to undertake a comprehensive assessment of the economic viability of this practice. An estimate of the repayment period concerning the net present value will allow a prediction of when the investment will be recovered. Factors such as inflation, depreciation, operation cost, and maintenance were considered to evaluate the repayment period of the investment. Mathematical expressions for the economic analysis are given in Equations 4.54 to 4.56, which estimate the present value of money in the future, net present value, and the repayment period respectively [182].

Equation 4.54 shows the expression for present value of money in the future:

$$PV_E = \frac{\text{Cash flow}(n)}{(1+r)^n}. \quad (4.54)$$

Equation 4.55 shows the expression for net present value:

$$NPV_{n=1}^m = \sum_{n=1}^m PV_E(n) - CC. \quad (4.55)$$

Equation 4.56 shows the expression for the repayment period:

$$\text{Payback Period} = m_y + \frac{-NPV_{n=1}^m}{PV_E(m_y + 1)}. \quad (4.56)$$

Where:

PV_E is the present value of money in the future;

n is the cash flow of the n -th year;

r is the discount rate;

m is the number of years;

NPV is the net present value;
 CC is the capital cost of the project; and
 m_y is the last year with a negative NPV .

Additionally, the lifecycle cost analysis was estimated using Equation 4.57 [182]:

$$LCC = C_{I(i)} + C_{R(i)} + C_{OM(i)} + C_{EC(i)} - C_{S(i)} \quad (4.57)$$

Where:

C_I, C_R, C_{OM}, C_{EC} , and $C_{S(i)}$ are the initial cost, salvage cost, replacement cost, operation, maintenance costs, and energy cost respectively that are linked to each system component.

In general, Section 4.2 provided a simulation and the energy costs for the baseline and proposed systems. As shown in Table 4.2, the estimated investment cost is \$9 900 for the PV inclusion, while that with batteries raised the price by \$3 000.

Table 4.2: Cost of investment in solar PV and batteries

Initial capital investment	Cost (\$)	Cost (\$)
275 W 24 volt direct current (VDC) solar PV panel cost		
26 units	169x26	4 400
Batteries cost		3 000
Controller cost	1 100	1 100
Inverters and accessories cost	3 300	3 300
Installation cost	1 000	1 000
Total investment	9 800	12 000

4.3 CASE STUDY DATA AND PARAMETRIC ANALYSIS

The case study focused on the cooling unit of Morningside Mediclinic's HVAC system (Johannesburg, South Africa). The system chiller utilises the Ice Bank® Thermal Storage Tank from CALMAC®, model 1190CV2F, serial number 21530. The Ice Bank® allows smaller chillers, which are 40% to 50% of the size of other HVAC systems. To manage the

building's cooling load, the chiller may operate with the Ice Bank[®] tanks during peak daytime hours [183].

However, during off-peak hours, the chillers charge the mixture of water-glycol solution in the Ice Bank[®] tank to up to -4°C . Mediclinic plants use a 30% propylene glycol solution, instead of the 25% ethylene glycol solution prescribed by most manufacturers to increase the melting point and to avoid potential risk to humans that may arise from the choice of ethylene glycol. It is unsafe to use toxic working fluid in a hospital environment. A welded, closely spaced, counter-flow heat tube heat exchanger made of polyethylene is incorporated to transfer heat from the water-glycol solution to the water around the AHU. The ice surrounding the pipes cannot freeze, to avoid tank damage [184,185].

The ice-building chiller has a peak cooling capacity of 421 kWt for a full day and 1 698 kWt was captured on one of the days, as taken from the dataset.

The required input power to the compressor is 95.6 kWe for the entire day, which drops to 91 kWe, if full-night operation is considered, and 50 kW for half a day.

The chiller's refrigeration unit comprises two compressors with a double-stage cycle. The working fluid is 60 kg charge of R-134a in the refrigeration circuit, while the evaporator HTF ethylene glycol was replaced due to the medical application thereof, as mentioned above. The performance parameters for the chiller related to the European seasonal energy efficiency ratio (ESEER), with a value of 5.93 and the integrated part load value of 6.33. The system operates in capacity steps of 0-25-37-50-75-87-100. Considering the COP that is acceptable in thermodynamic analysis and expressed in SI units instead of English units, the COP equals ESEER divided by the value of 3.41214 [179].

4.3.1 Data collection

Mediclinic Morningside is situated in the Morningside suburb of Sandton, Johannesburg, South Africa. The hospital is equipped with three types of HVAC systems: one with Ice Banks[®], one with a VRF system, and a variable air refrigeration system to keep abreast of cooling and heating load demands, including the thermal comfort of the occupants. All the systems are connected to a SCADA system to monitor the operation and performance of the systems. The focus was on the ITES system with Ice Banks[®]. The hospital includes wards, offices, a mortuary, a laundry, maintenance workshops, utility areas, and a ground floor, with a total area of 6 069 m².

The hospital is a four-storey building with a basement. The first, second, third, and fourth floors have a total area of 6 234 m², 5 588 m², 5289 m², and 1 330 m² respectively.

The SCADA system displays the HVAC plant's schematic, with the input and output parameter values and various component inlets and outlets. The parameters include temperature, power inputs, flow rates, pressure drops, tank levels, and thermal energy. The SCADA system also has warning alarms and a remote control for the system. Furthermore, the software may store the system variables' historical data. A five-minute interval capture was extracted from the application and missing values were approximated on the spreadsheet.

The MATLAB code read the input data from the Microsoft Excel spreadsheet and assigned the constant and variable. It then calculated the terms of the state equation. The decision, control, and disturbance were stated in the state equation. Constraints that involved both the terms "equality" and "inequality" were further included in the codes. The optimal function evaluated the storage's output temperatures and optimal cost. Some outputs are displayed in the plot highlighted in Section 4.4 of the chart.

The weather data were provided by the South African Weather Service, while other data were taken from the Southern African Universities Radiometric Network's website [187,188]. Other information is available in the plant's operational manual. The description and some specifications were highlighted in Section 4.1. Table 4.3 presents a summary of the constant parameters used in the model.

Table 4.3: Summary of the constant parameters used in the model

Parameter	Value	Unit	Description
ρ_{gly}	1 031	$\left(\frac{kg}{m^3}\right)$	The density of the glycol mixture in the system.
$\dot{V}_{gly}$	18.4	$\left(\frac{l}{s}\right)$	The volume flow rate of glycol.
V_{gly}	0.634	(m^3)	The volume of glycol in the storage tank.
$UA_{tank,inner}$	78 632	$\left(\frac{W}{K}\right)$	Internal overall heat transfer coefficient.
c_{gly}	4 145	$(J / kg ^\circ C)$	Specific heat capacity of glycol in the system.
h_{ice}	33 600	(J / kg)	Latent heat of fusion of ice.
P_{rf}	95 600	(W)	Rated power to the chiller compressor.
$m_{chw,ITES}$	6 685	(kg)	Mass of chilled water in the system.

Parameter	Value	Unit	Description
$C_{chw,ITES}$	2.1	(J / kg °C)	Specific capacity of chilled water in the system.
$\dot{T}_{chw,ITES}$	5-11	(°C)	The temperature of chilled water in the system.
m_{air}	3 540	(kg)	The mass of air in the building.
C_a	1.012	(J / kg °C)	Specific capacity of air in the building.
$\dot{T}_{air}$	7.3-11	(°C)	The temperature of chilled water in the system.

The ToU tariff chart for the municipality of the hospital's location is shown in Table 4.4. The rate was calculated from an online platform at \$1 = R18, approximating the exchange rate at the time the calculations were made [33]. Additional charges are incurred apart from the hourly rate. The service charge costs R2 028 (\$113) per month and the capacity charge is R26 233 (\$1457) per month. There is a maximum demand charge of R240 per kVA (\$13) for both summer and winter.

Table 4.4: Summary of the ToU tariffs used in the model

Symbol	Region	Winter cost (R/Wh)	Winter cost (\$/Wh)	Summer cost (R/Wh)	Summer cost (\$/Wh)
ψ_p	Peak	4.9629	0.2527	2.0856	0.1159
ψ_o	Off-peak	1.2983	0.0721	1.2070	0.0671
ψ_s	Standard	1.8949	0.1053	1.5703	0.0872

4.3.2 Data processing

A thorough inspection of the values was carried out to correct the effect of some missing and inaccurate data. Linear interpolation and extrapolation were adapted to accommodate the input data to the model. Interpolation was further used to fix the raw data extracted for five-minute intervals due to some data being captured erroneously by the SCADA system. Processing involves extracting relevant data points and organising them into a dataset that may easily be analysed.

Appropriate data processing is crucial to the success of the solar PV- and ITES-integrated HVAC system for cooling. Ensuring accurate and consistent data results in the

ability to make informed decisions and ultimately achieving significant energy savings and sustainability.

For a full day, the chiller data were generated at an interval of five minutes from the SCADA software designed by Landis and the South African Engineers and Founders Association (specialising in system integration of building management systems with closed-circuit television, access control, and fire detection). The software captures the parametric data in intervals of five minutes, but this could not be achieved at the time of capture. The ice storage tanks are installed in the hospital's parking area (south side). It is composed of a looped pipe to transport the glycol solution around the ice. The system was designed to provide a net usable cooling capacity of 570 kWh per tank, a maximum operating temperature of 38 °C, factory-tested pressure of 1 724 kPa, and maximum working pressure of 620 kPa.

Furthermore, the dimensions are 2 260 mm wide, 2 310 mm long, and 2 590 mm high, and 14 m³. Considering that the tank as a cylinder, the radius is 1 130 mm, the height is 2 590 mm, and the surface area is estimated to be 26.40 m². The estimated thickness of the tank's outer material is 100 mm. In volumetric capacity, the tank takes 3 955 l of water per ice in the system, with a glycol solution of 375 l. After a few years of operation, Mediclinic purchased three extra tanks to increase the overall cooling capacity to approximately 4 560 kW_t.

The pumps, in conjunction with the valves, control the mode of operation. Considering the pumps that are connected to the ice-making chiller, such as the chilled water pumps, the required power is 18.5 kW. The AHU is the air processing unit, which is powered by a motor on the supply and return air fan through ducts. The air is conditioned to the appropriate temperature, speed, and humidity and cleaned through filters and a mix of fresh air. During a particular day taken from the dataset, the return air at 21.1 °C was mixed with 27.6 °C to produce the desired air temperature of 17.5 °C. The set-point temperature ITES was maintained between -2 °C and -6°C, 22 °C to 24 °C for the operating rooms, and 22 °C to 26 °C for the comfort zones, such as patient rooms, waiting areas, and offices. The AHU motors power the fan in different spaces, such as offices, wards, theatres, mortuaries, and halls. The total energy consumed by the motors is rated at approximately 22 kW_e.

4.4 SIMULATION RESULTS AND DISCUSSION

This section presents the results of the simulation. The baseline system results include load profile, control techniques, temperature variation, and energy consumption. Thereafter, the proposed system outputs are compared to the baseline system. The baseline system control depends on the set-point temperature. In contrast, the proposed system operates on optimal control that maintains the desired temperature and saves energy consumption and energy costs from the grid. The proposed system further utilises the grid's power to pump the system's HTF.

4.4.1 Baseline system

The current system includes the HVAC and a set of Ice Banks[®] integrated to form the ITES system. Periodic load profile, weather data, ToU tariffs, and other data enable appropriate analysis of the system's energy management. The recorded pump input power consumption per five-minute interval profile for the baseline system is shown in Figure 4.4.

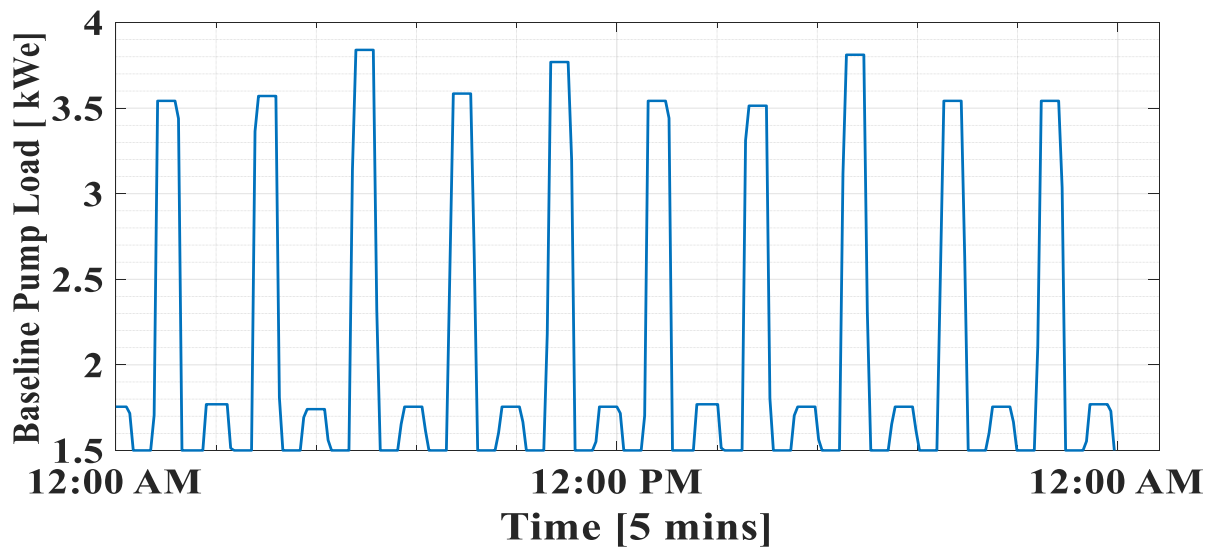


Figure 4.4: Five-minute interval instantaneous cooling load for a summer day

The input energy was evaluated from the cumulative readings of the energy meter, considering the difference in the time interval of the readings taken from the SCADA software. The variation in power consumption showed a continuous power supply to the system. The higher values indicated the chiller involved, while the lower values indicated

the pump input power. The power input remained consistent when there were changes in demand, due to the need to maintain the desired temperature (with ITES maintained between -2 °C and -6 °C, 22 °C to 24 °C for the operating rooms, and 22 °C to 26 °C for the comfort zones), as expected in a ToU tariff period [189]. This stability is affected by factors such as the cooling load (demand) and its direct effect on the importance of maintaining the desired temperature. However, cost savings may not be achieved by solely shifting the load relative to ToU tariffs. This indicates the need for optimisation and the inclusion of PV and batteries to accommodate the situation and improve the system's energy efficiency, as well as cost savings.

4.4.1.1 Load profile

The chiller pump ranges from 3.5 to 3.8 kWe throughout the day to meet the cooling demand. The 1.5 kWe base indicates the pump load. Both charging and discharging processes require the continuous pumping of HTF, either by the charging pumps that supply cooling energy to the Ice Bank® or the discharge pumps that supply cooling energy to the building's AHU, which ensures uninterrupted power consumption by the pumps. In Figure 4.5, the cumulative active energy consumed by the pumps was plotted for a summer day. Approximately 600 kWh of energy was consumed by the end of the day.

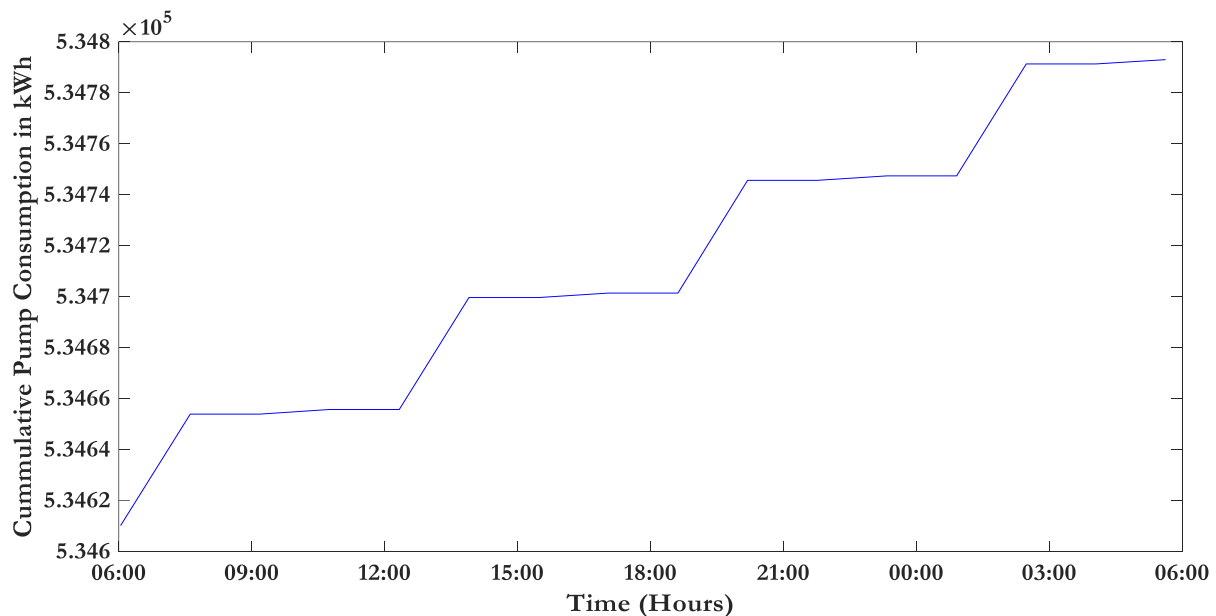


Figure 4.5: Cumulative active energy of the pump in kWh

The daily energy costs may be reduced, as discussed in Section 4.4.5. Furthermore, the cumulative active energy input by the ice-building chiller was plotted, with variations over two months, the end of summer and the beginning of autumn, as illustrated by Figure 4.6.

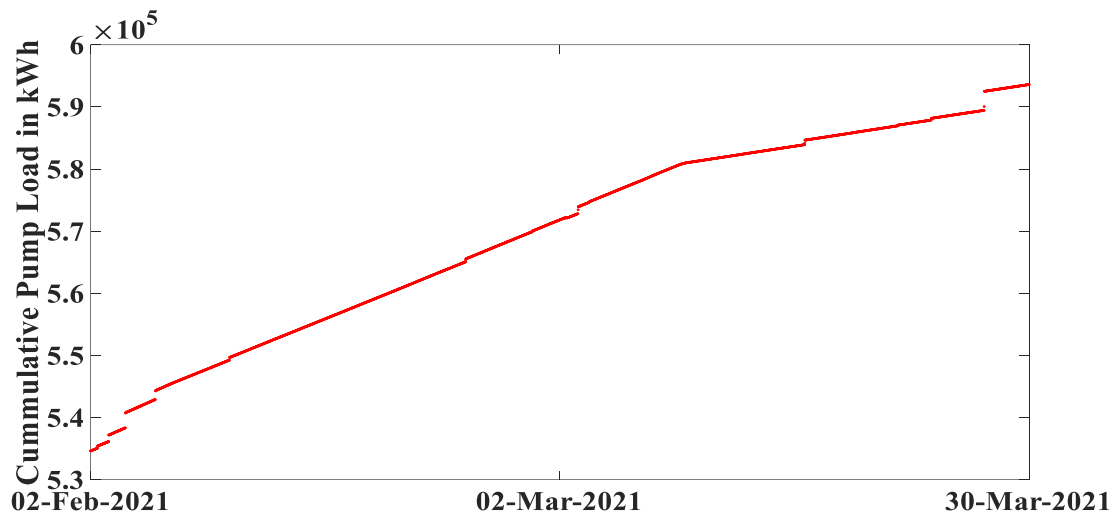


Figure 4.6: Cumulative active energy of the pump in kWh

The monthly value of energy consumption indicates high energy usage; hence the call for measures to reduce the usage. Figure 4.7 considers the increments at each time interval to visualise the baseline load characteristics.

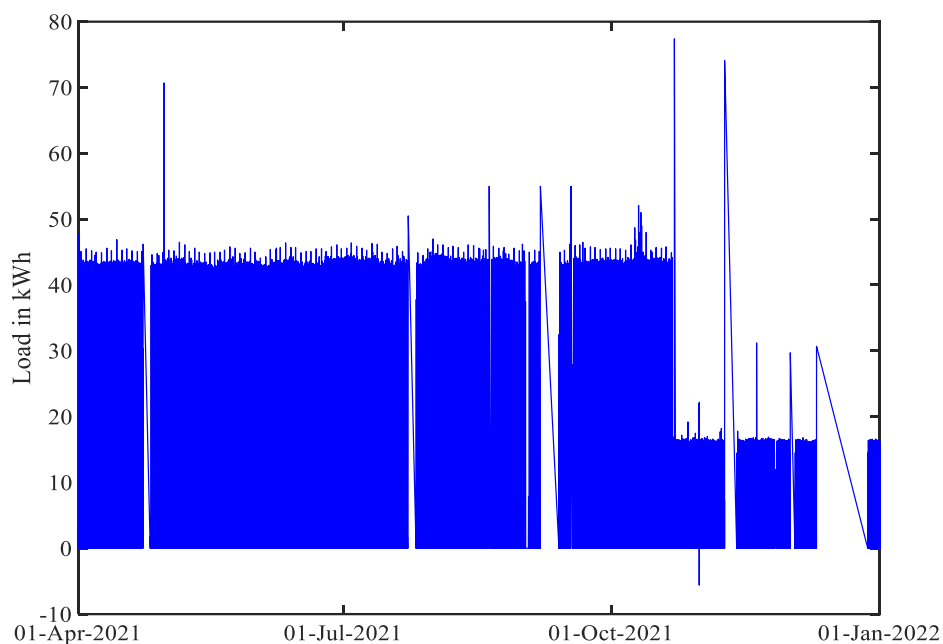


Figure 4.7: Two-month differential data of active energy of the ice-building chiller

Figure 4.8 shows the cooling load variation of the building on a summer day. The highest demand is in the off-peak region. This may be due to hotter nights, the impact of COVID-19 at the time the study was conducted, increased occupancy, and increased hospital activity during the night shift, particularly the mortuary. The consumption during the peak ToU region was lower than expected, possibly due to fewer cooling requirement activities, alternative cooling supply by the variable air flow and VRF air conditioning unit installed, the control system, and other possible factors. However, the baseline system should be optimised to detect potential energy cost savings, using ITES.

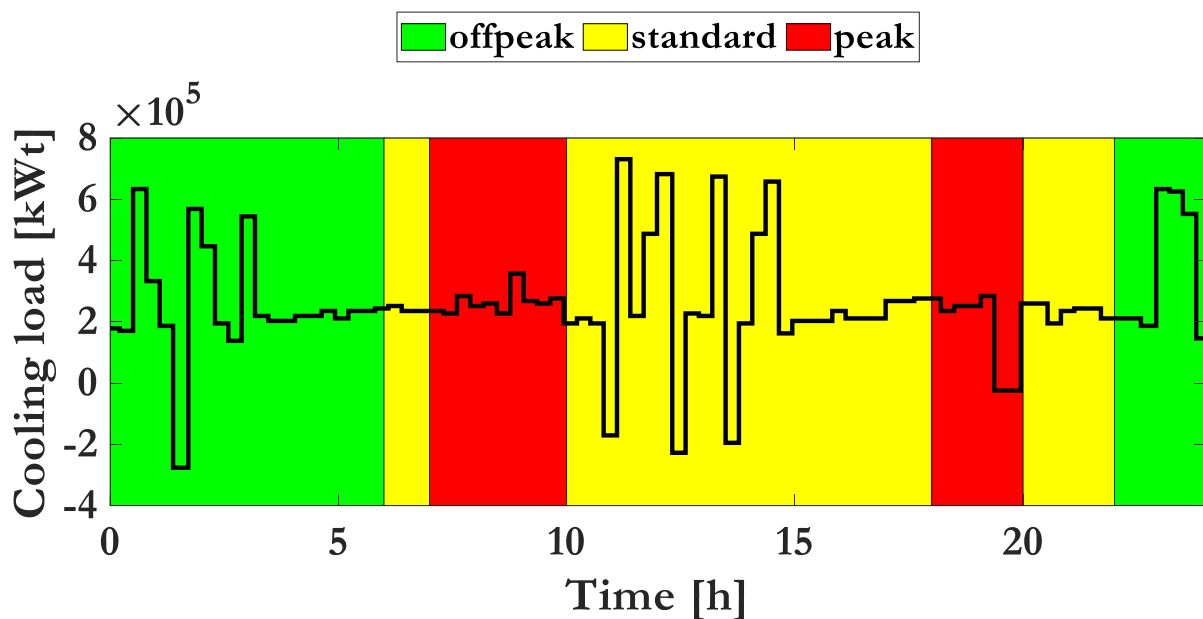


Figure 4.8: Cumulative active energy of the ice-building chiller in kWe

4.4.1.2 Atmospheric, Ice Bank®, and building temperature variations

Storage temperature variation enables the visualisation of the need to maintain the set-point temperature required for thermal comfort against the ambient temperature. Figure 4.9 shows the atmospheric temperature on a summer day over five-minute intervals.

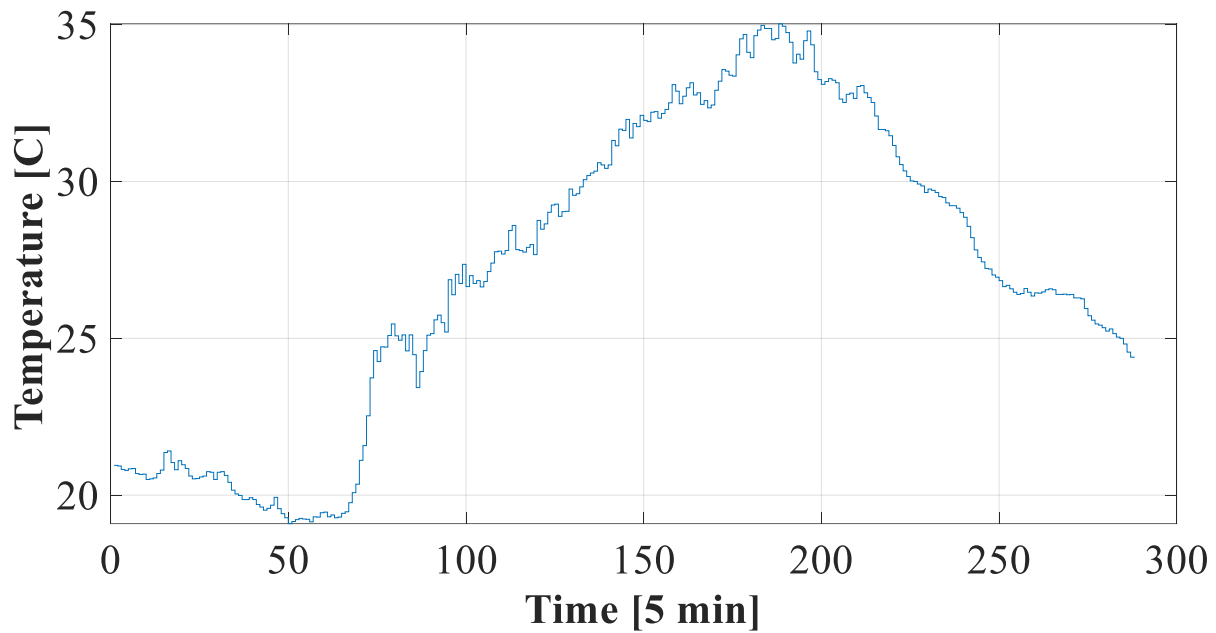


Figure 4.9: Variation of the atmospheric temperature of the environment

A maximum temperature of 35 °C was observed for the selected day. During the peak pricing period, the ambient temperature rises at 06:00 to the maximum value and begins to decrease at approximately 15:00. The ambient temperature remains at the lowest value during the off-peak pricing period. However, the cooling demand is not dependent solely on the ambient temperature. Furthermore, factors such as the occupancy heat generation, office and medical equipment, as well as other appliances in the building may affect the heat generated during the summer. The effect of the building cooling load may be observed from the cooling fluid temperature returning from the building.

The temperature variation of the Ice Bank® is illustrated in Figure 4.10 for the same day based on the comfort zone and in Figure 4.11 concerning ToU pricing.

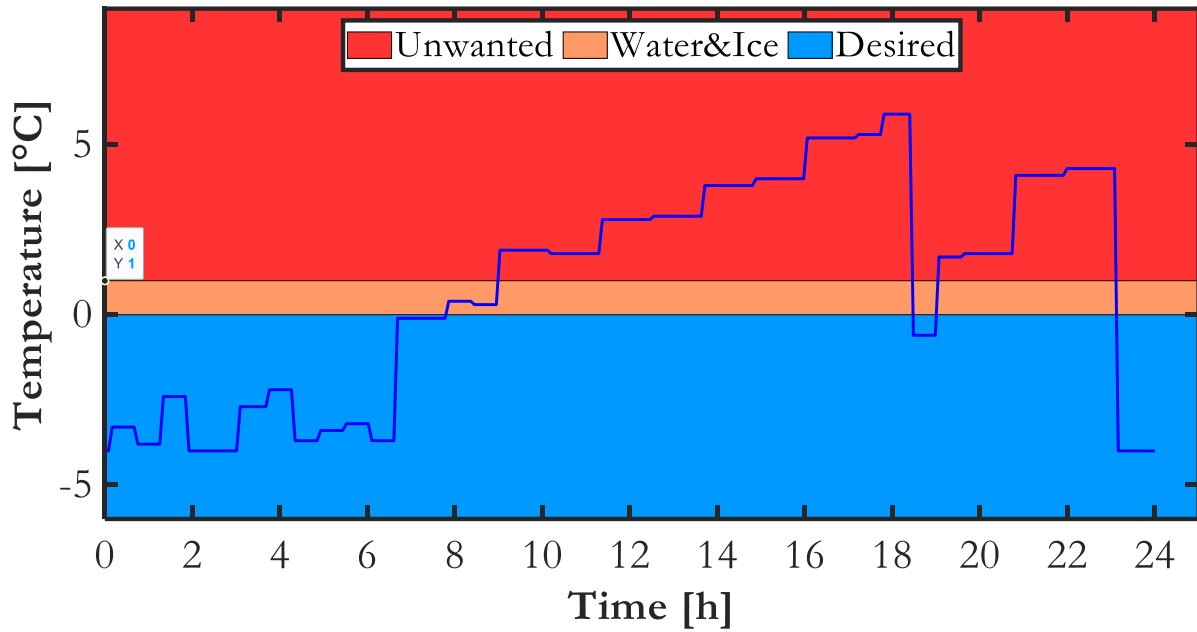


Figure 4.10: Variation of the ITES baseline temperature of the environment

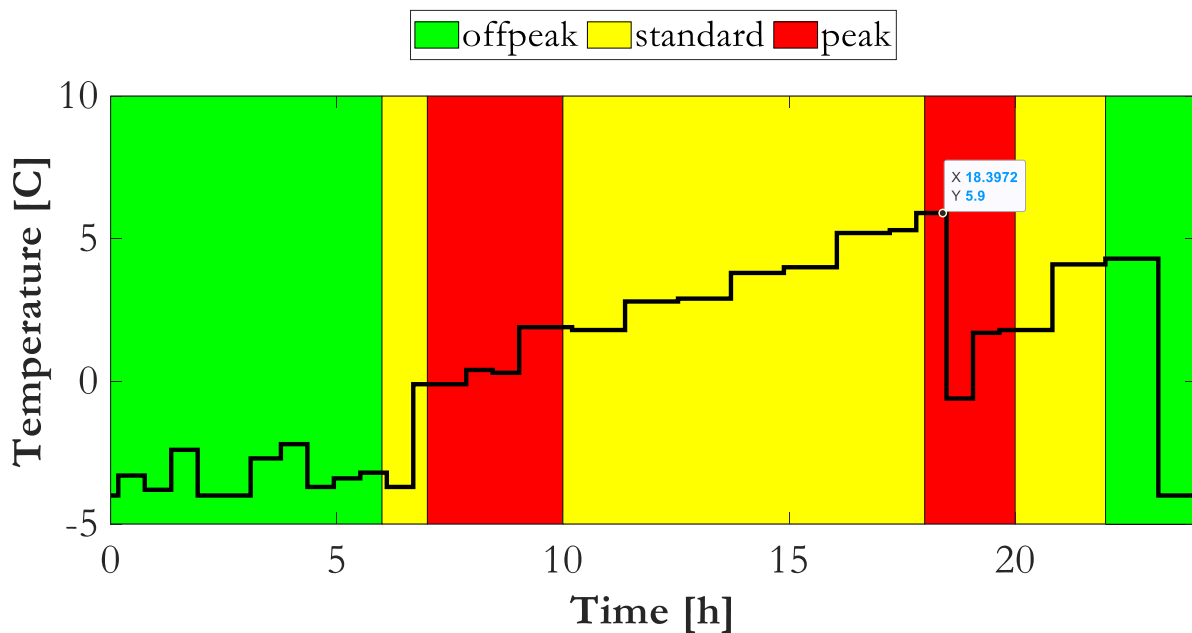


Figure 4.11: Variation of the ITES (water/ice) temperature

It may be seen that the ice depleted quickly. This may be due to inadequate charging during the off-peak pricing period and higher cooling demand resulting in direct cooling by the chiller and bypassing of the ITES system. The fluid temperature variation from the building to the secondary heat exchanger is plotted in Figure 4.12. During the off-peak pricing periods, 22:00 to 24:00 and 00:00 to 06:00, the temperatures (water/ice) were

unexpectedly higher, which indicates higher demand. At the standard pricing periods, 9:00 to 17:00 and 1:00 to 22:00, the temperatures (water/ice) increased; however, not to peak maximum value. During the peak pricing periods of 07:00 to 10:00 and 18:00 to 20:00, the temperature (water/ice) stayed at the medium value. Due to this unpredictable variation, an appropriate optimal control technique was recommended to improve the system.

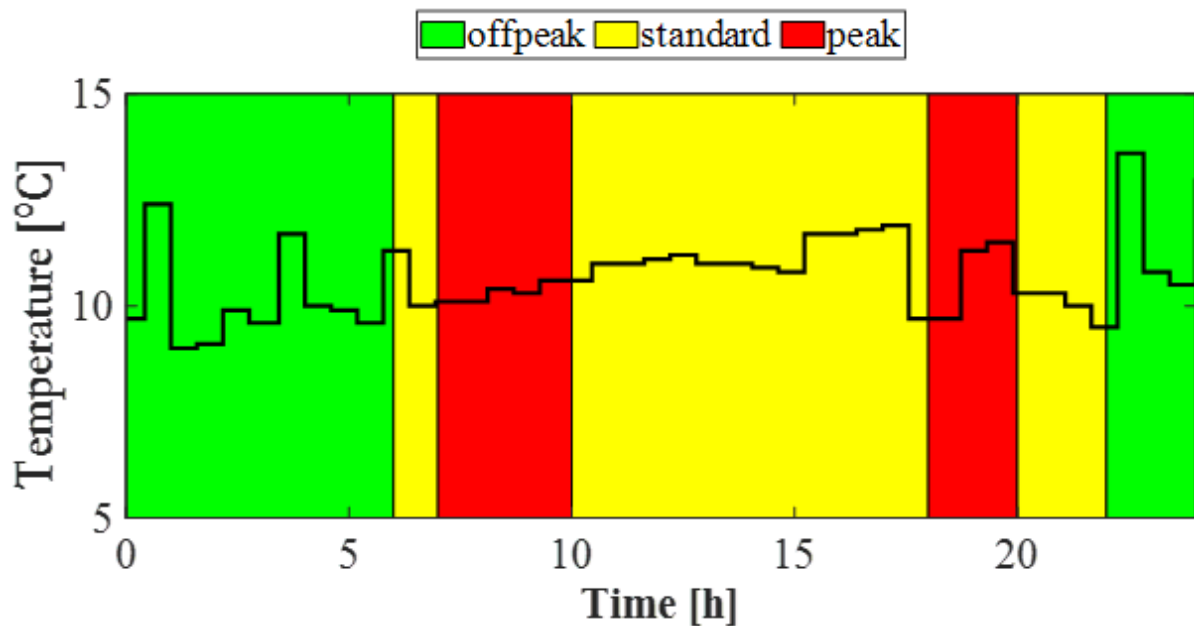


Figure 4.12: Variation of the building water return temperature

4.4.2 Solar irradiation available and solar power from PV

It is vital to predict the power that can be realised from the PV system; appropriate sizing of the plant must therefore be carried out. As mentioned earlier, greenhouse gas is reduced, which leads to cleaner energy usage [190,191]. According to the model, the PV power source would be used to power the pumps and the fan units during the discharge of the ITES to allow minimal or no power sourced from the grid during cooling. The solar irradiation and power output available for the area per square metre are shown in Figures 4.13 and 4.14.

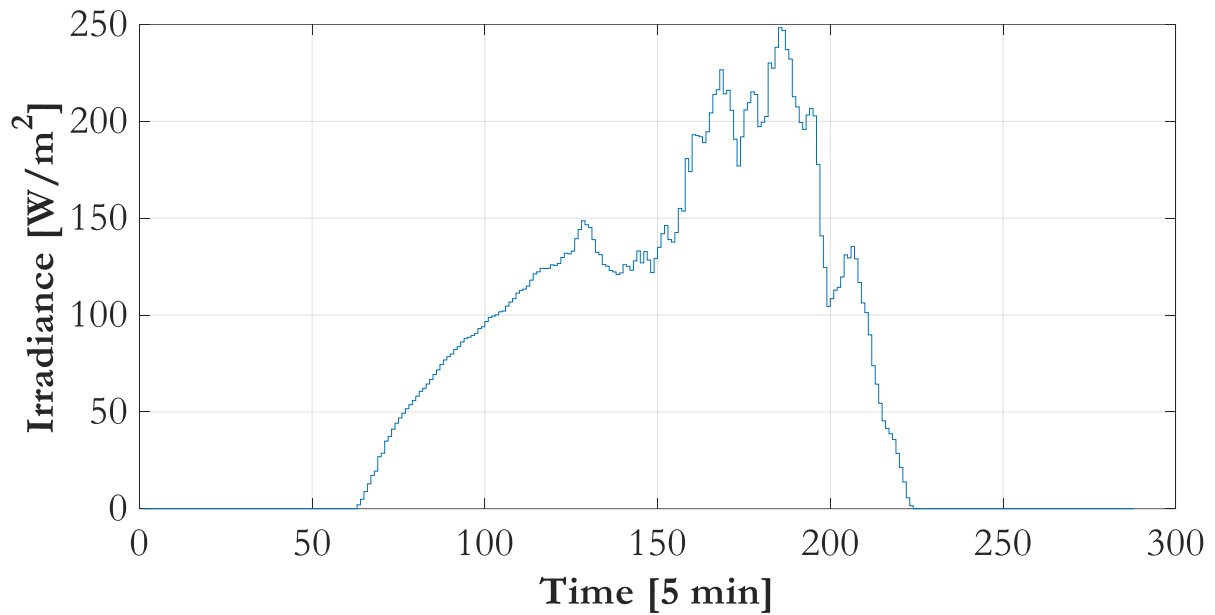


Figure 4.13: Hourly irradiation for the system over the year

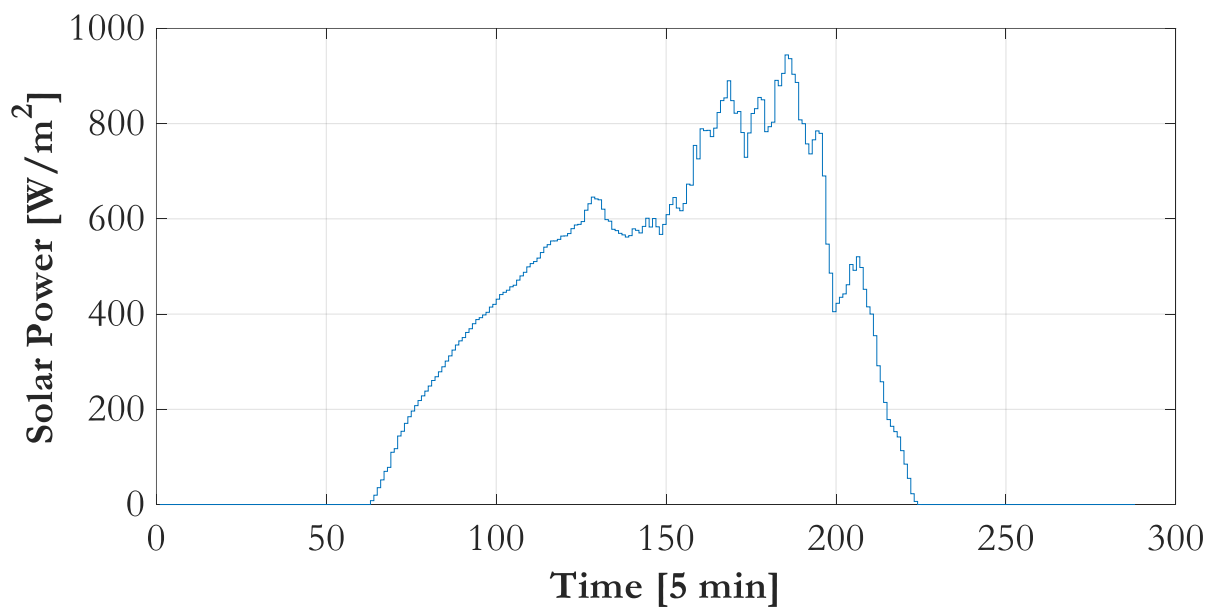


Figure 4.14: Hourly solar power for the system for a day

A substantial amount of solar power may be realised if adequately sized during summer. The system's dependence on the grid during the day may be minimised advantageously during certain periods. However, solar energy sources would produce reasonable power input to the cooling system during the warmer seasons. In this case, the battery may need to store energy to account for both the charging and discharging phases, as the charging and discharging patterns may not be perfectly synchronised.

The pumps for transporting the HTF, which is a water and glycol solution, are the ice-building chiller condenser water pump (CWP-2), ice chiller water pump (CHWP-3), and the heat exchanger secondary circuit chilled water pump (CHWP-2). Considering the total power required by the pumps for the discharge process, the necessary input in the motor rating is $(18.5+18.5 \text{ kWe})$ 37 kWe. Approximately 26 units of 275 W 24 VDC solar panels would be required. The estimated cost of the panel (R80 000) and inverter (R60 000) is R140 000. A typical FCU used for this system has a power supply output of 160 We and a maximum power rating of 360 We. The estimated power requirement for the fan is 3 kWe. The FCU would require at least the addition of two solar panels and inverters, with an estimated cost of R15 000. The cost implications are discussed further in Section 4.5. Lifecycle costs and inflation factors should be evaluated to predict whether the investment in solar PVs and batteries is worth considering.

4.4.3 Binary switch of the time-of-use (ToU) region

Figure 4.15 shows the variation in the ToU tariff cost for the switching consideration, based on minimising energy costs and retaining thermal comfort.

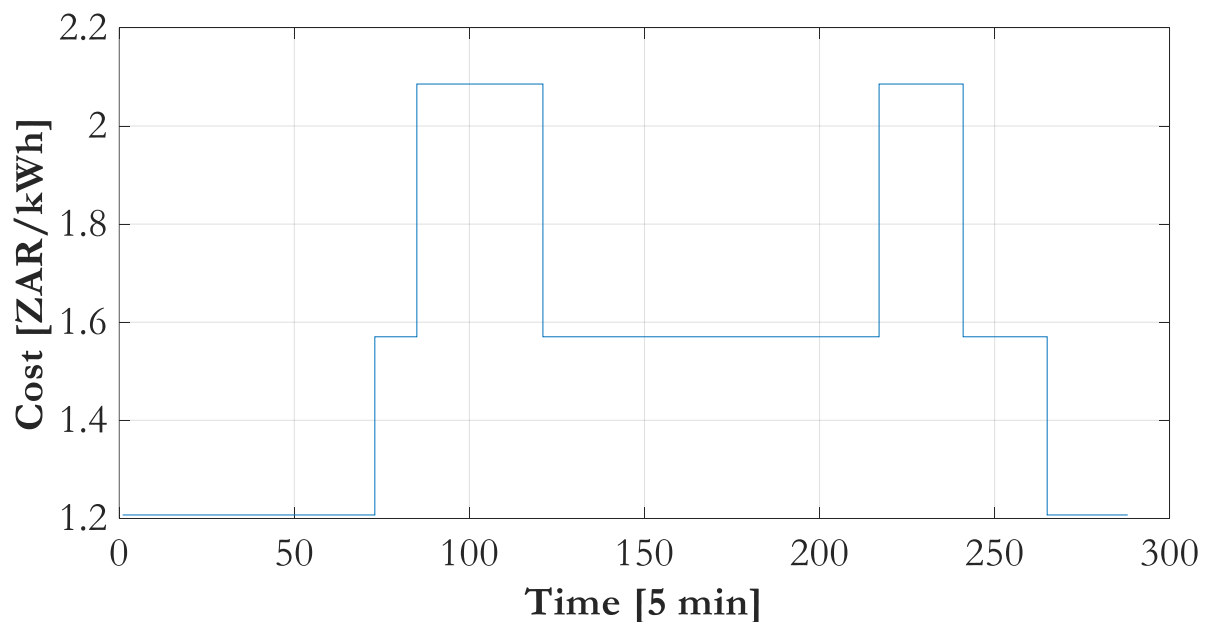


Figure 4.15: ToU tariff function cost variations for a day

The switching function outcomes for selected summer days are shown in Figures 4.16, 4.17, and 4.18 respectively. The switching outcome in Figure 4.17 corresponds to the day selected for the load and temperature profiles, which were shown in Figures 4.6 and 4.12.

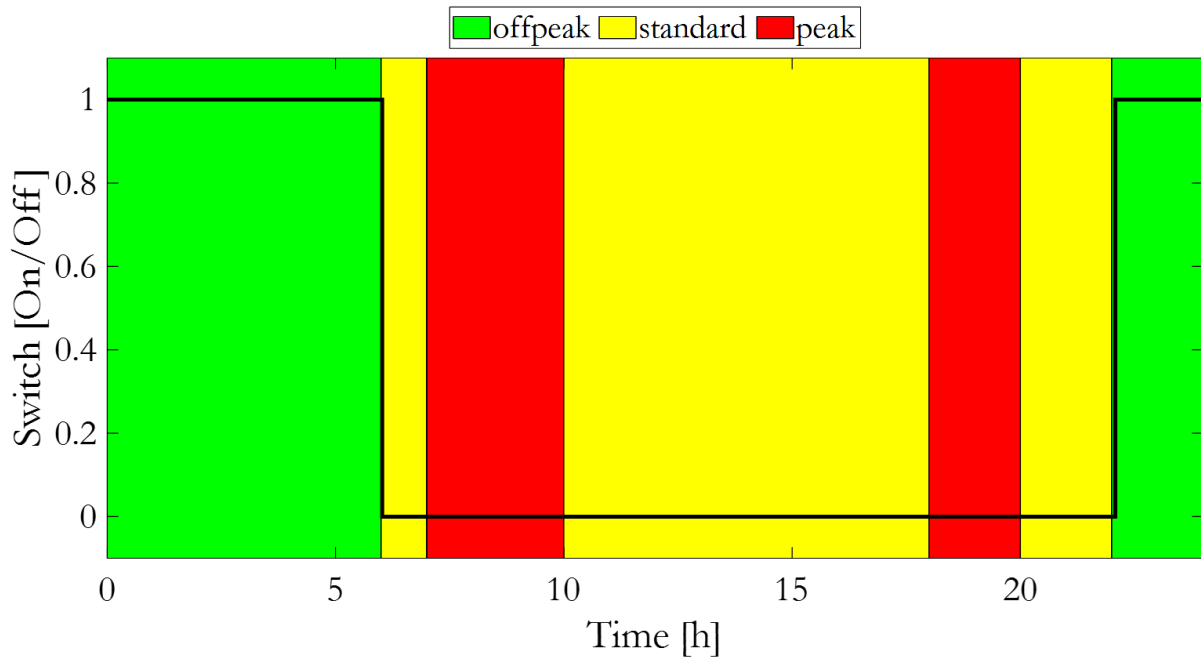


Figure 4.16: Optimal switch variation for the chiller for a particular day 1

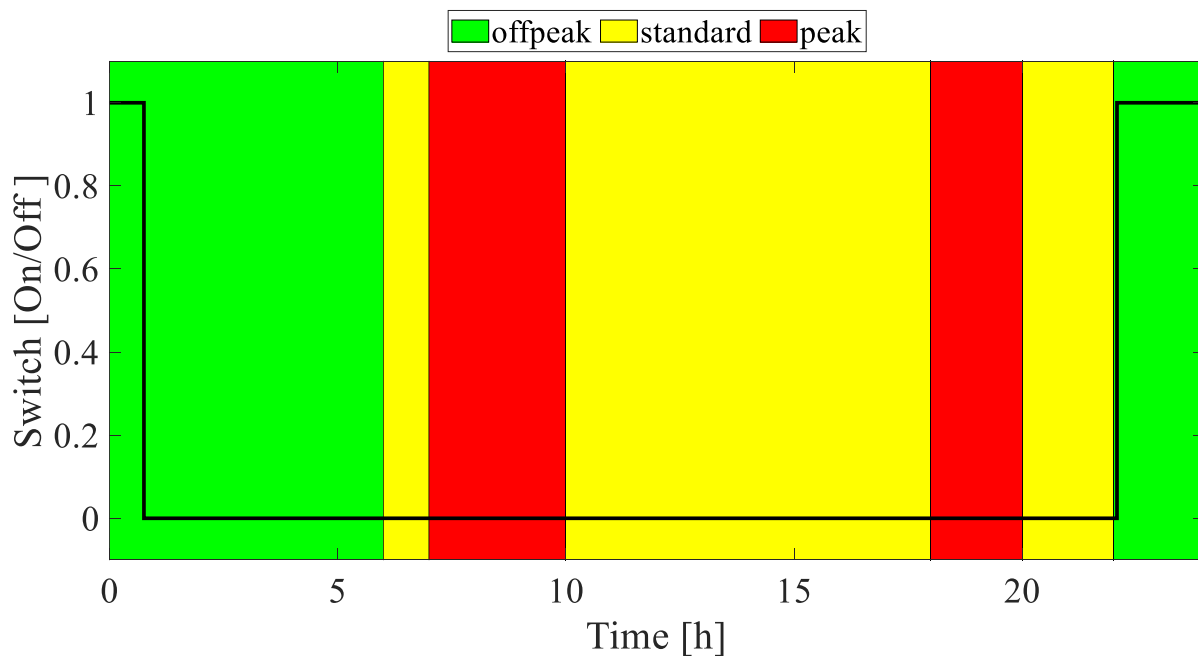


Figure 4.17: Optimal switch variation for the chiller for a particular day 2

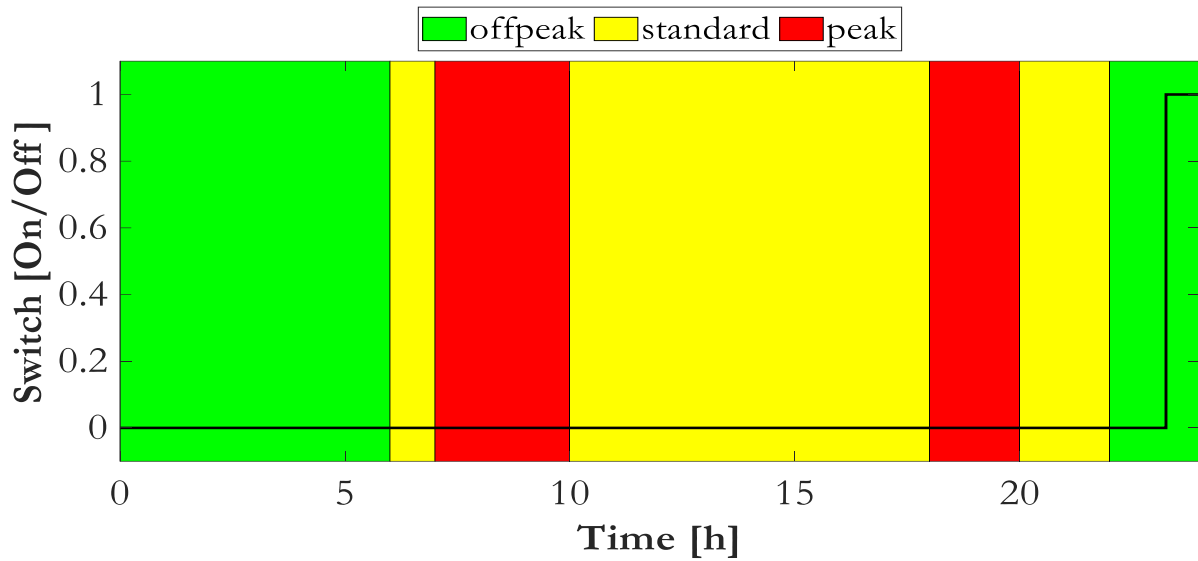


Figure 4.18: Optimal switch variation for the chiller for a particular day 3

The chiller was switched on during the off-peak period to build the required amount of ice for the next day's operation. However, during the peak pricing period and standard pricing period, the chiller remained switched off, as the demand was not high. The outcome is agreeable if the objective is to achieve cost savings while maintaining the set-point temperature required for thermal comfort.

4.4.4 Optimised system ITES temperature variation

The ITES-optimised temperature variation, compared to the baseline system, as depicted in Figure 4.19, indicates that thermal comfort was maintained during the operation.

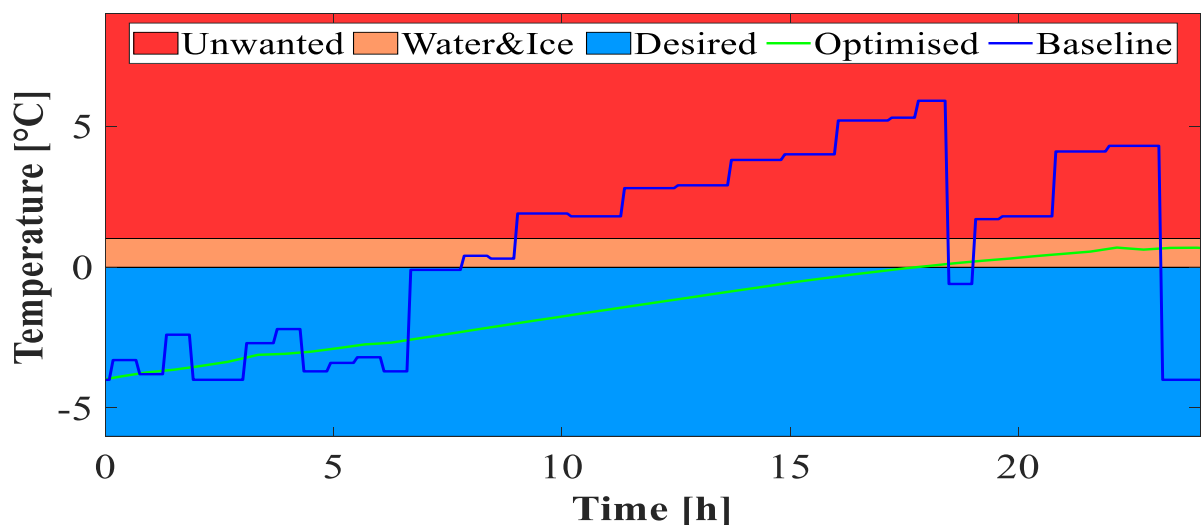


Figure 4.19: Baseline and optimised ITES temperature variations for a day

The temperature was maintained below the unwanted region. Compared to the baseline system, the temperature rose in the undesirable region. The optimisation technique proved worth it, as the thermal level would be retained. The SoC for the optimally controlled system was retained to meet the cooling demand, while the baseline SoC showed early ice depletion in the ITES. Figure 4.20 plots the SoC for the baseline (baseline ice tank level data from the SCADA software expressed in percentage) and the optimally controlled system SoC (expressed as the percentage change if the ice temperature in the ITES) against the ice-building chiller input electric energy (the load profile).

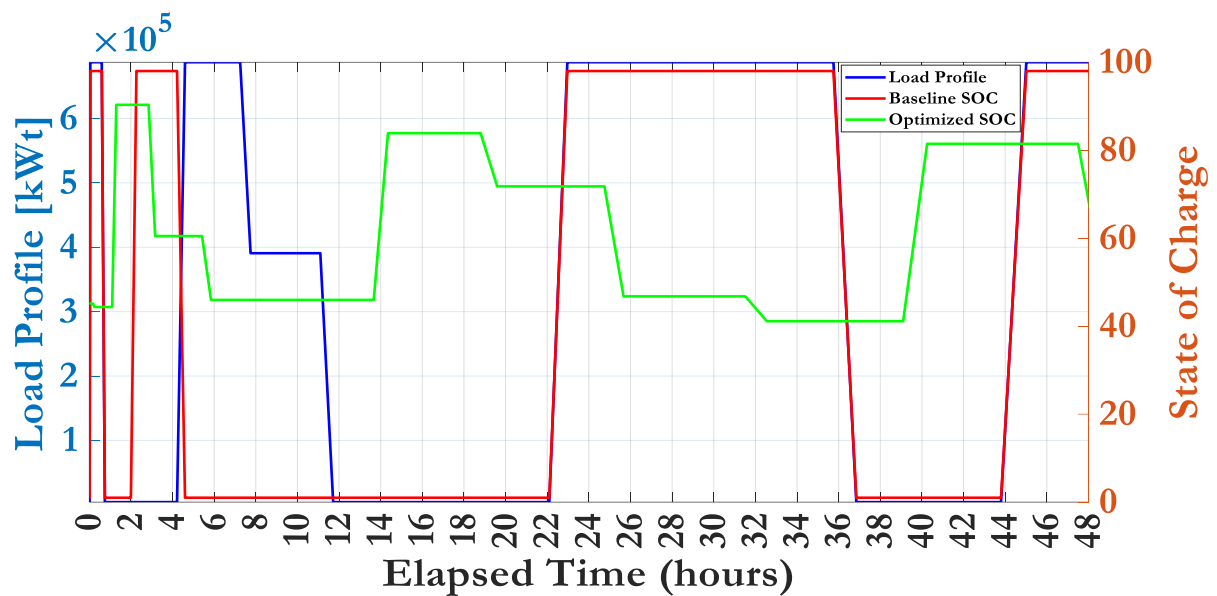


Figure 4.20: Cooling load variation with baseline and optimised ITES SoC for two days

4.4.5 Energy consumption and cost savings of the proposed system

Figure 4.21 depicts the input power profile after optimisation and solar PV inclusion. The region with zero power indicates the use of solar PV to pump the fluid in the system, which, as a result, would cause the energy costs during this period to be due to the solar energy costs and not the grid.

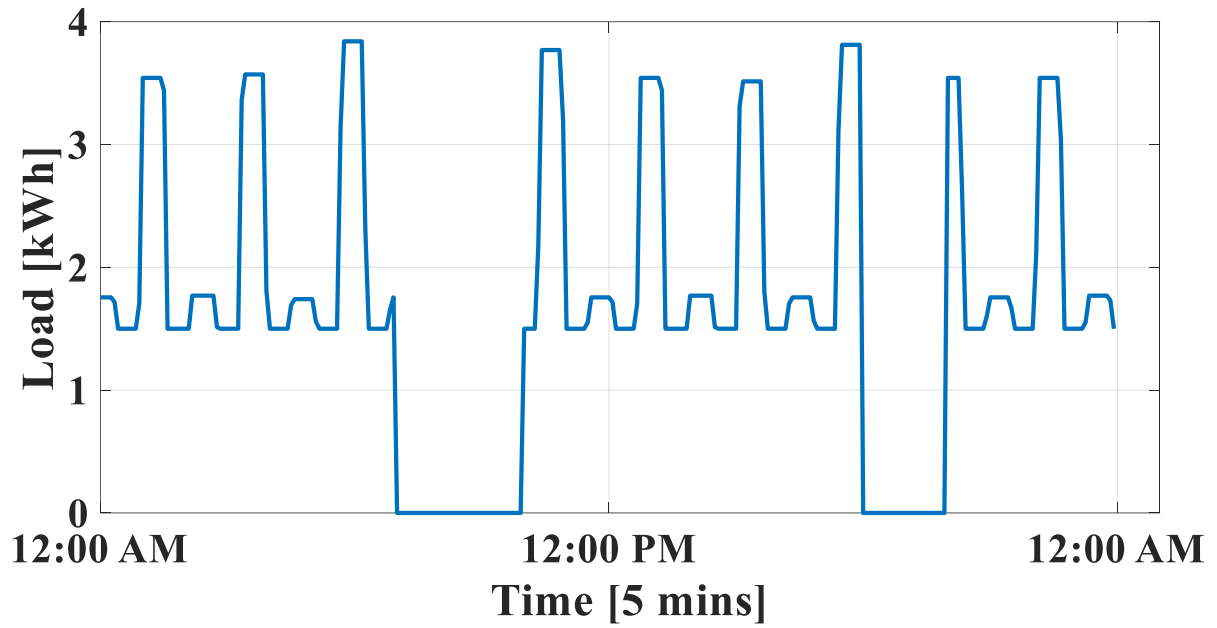


Figure 4.21: Five-minute interval pump input energy variation for a day for the proposed system

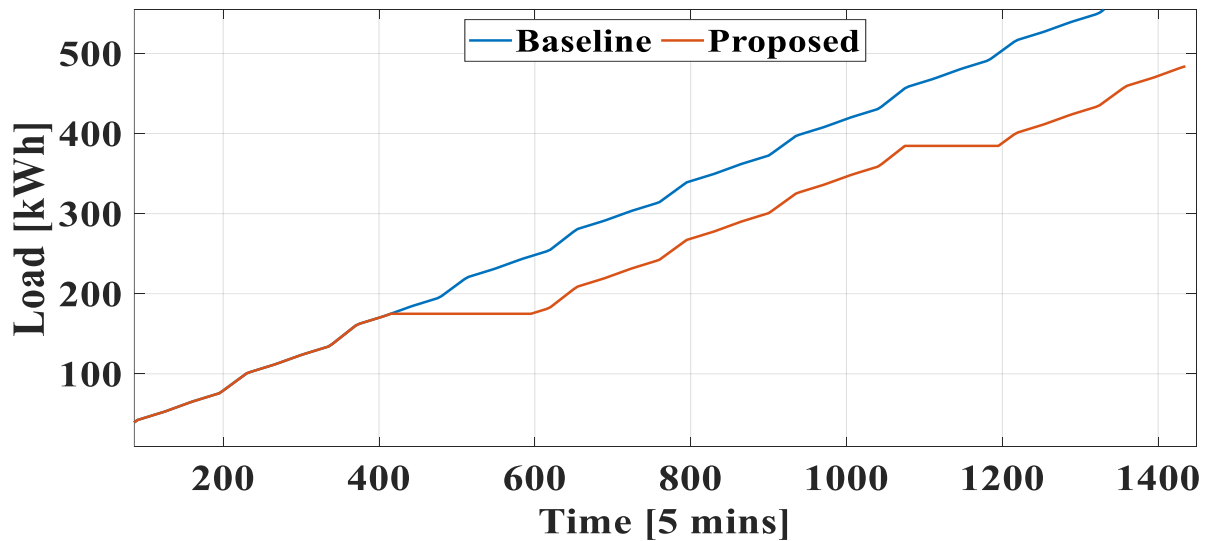


Figure 4.22: Five-minute interval cumulative input energy variation for a day for the proposed system

Referring to Figure 4.22, the input energy consumption was seen to reduce below the baseline after a certain period. Towards the end, a reasonable amount of energy was saved.

The net energy cost for the system for a day horizon was plotted in Figure 4.23. Optimal control of the system allowed for a reduction in operational costs, which is the main objective of optimising the system.

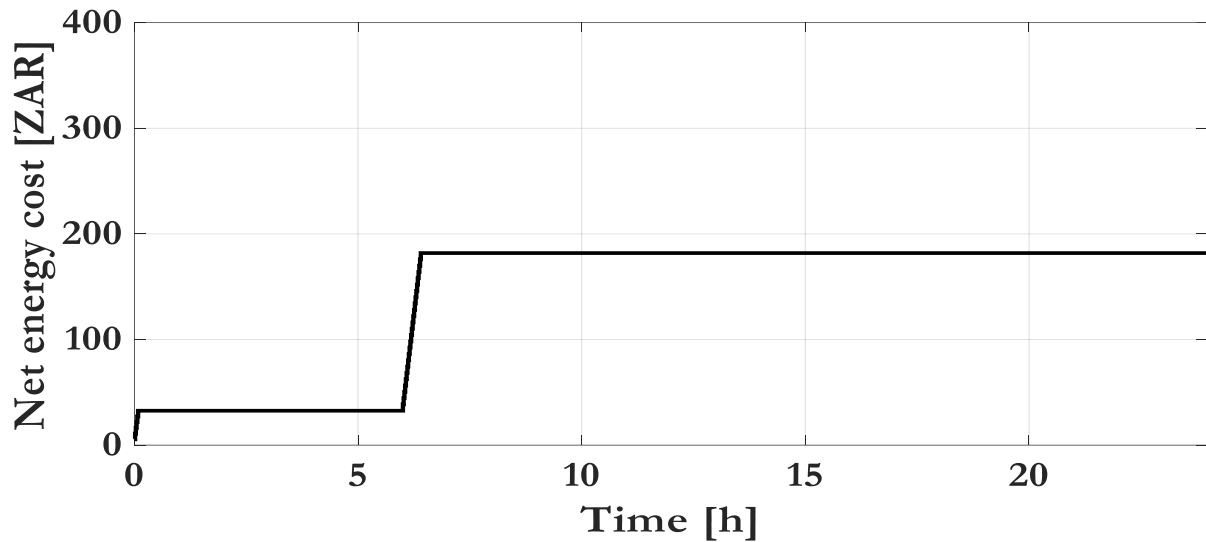


Figure 4.23: Net energy cost variation of the system

Figure 4.24 presents the monthly cost for the system. Months with zero costs indicate winter months. The ITES and ice-building chiller are switched off for these months, and the alternative cooling system is used if cooling is needed. The hospital utilises the second chiller in the system for heating purposes.

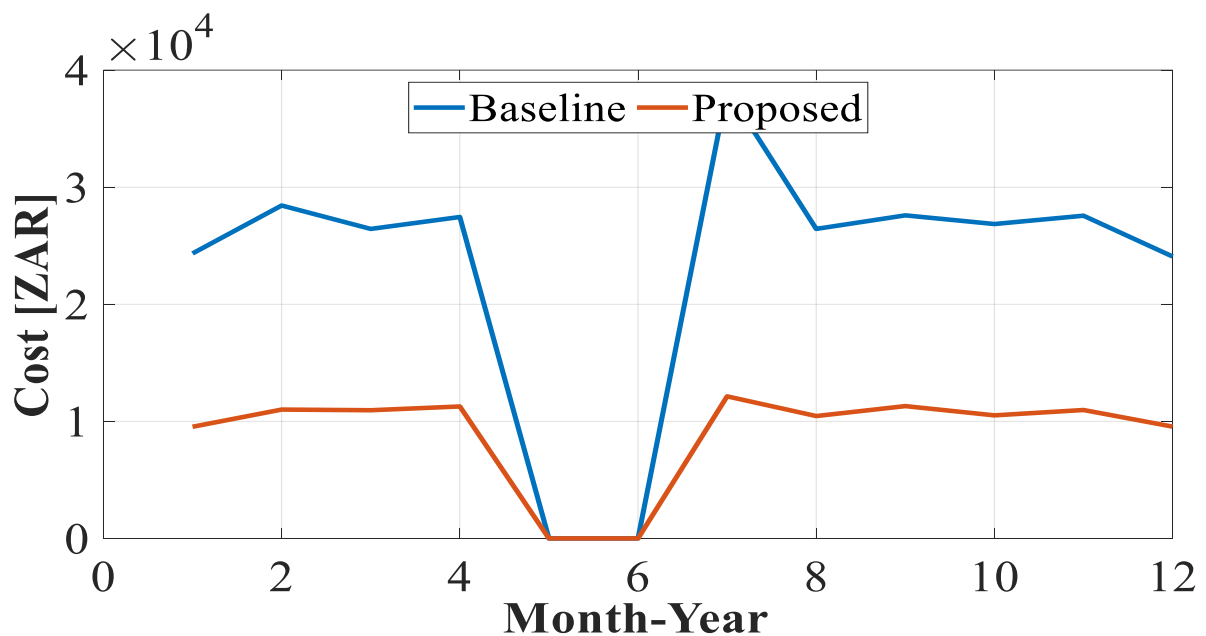


Figure 4.24: Monthly energy cost for the baseline and proposed systems

Figure 4.25 presents the monthly costs of batteries for the PV system. Including batteries may further reduce the energy costs but may attract more capital outlays.

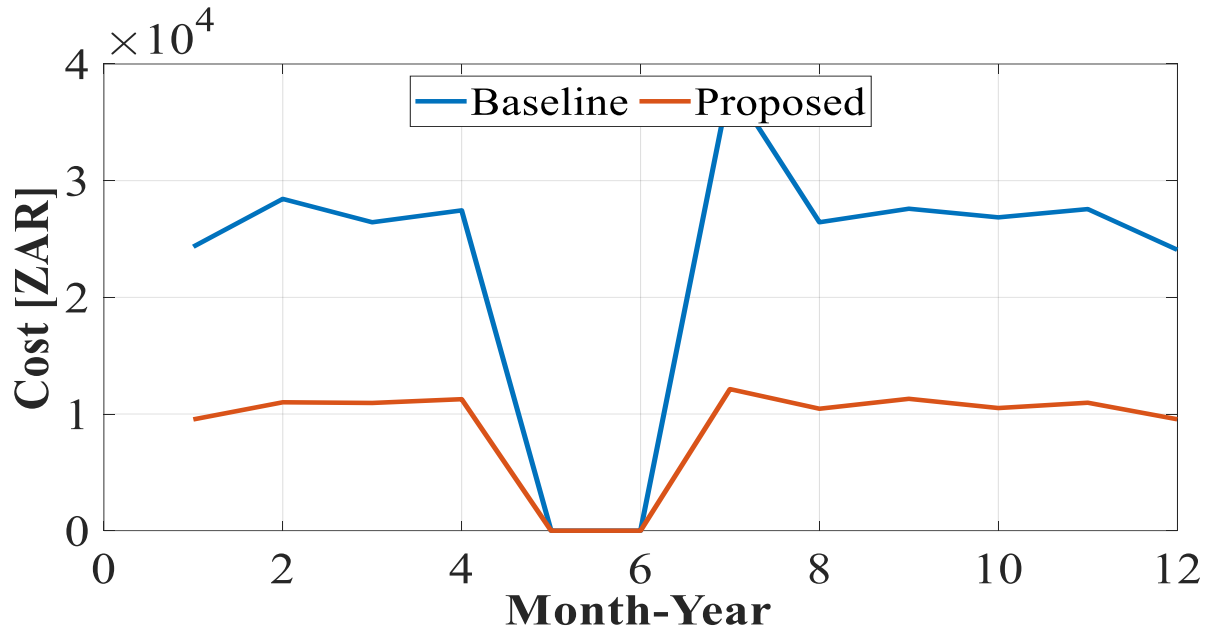


Figure 4.25: Monthly energy costs of the system with batteries

The system's optimal switching depends on the ToU tariff region, as shown in Table 4.4. Furthermore, service and capacity charges were considered for both the baseline and proposed system cases. Incorporating the tariff structure regarding price and period enables optimal switching control. However, the capacity charge attracted a higher cost of \$17 489, based on the energy consumed. The capacity charge may be reduced if the grid demand decreases.

The net summer cost for the year for the baseline system was estimated to be approximately \$34 259, while the optimal system was \$24 822, and the system with batteries was \$23 069. According to the estimate, approximately 27.5% cost savings may be achieved after optimisation, which are equivalent to \$9 437. Moreover, simulating the inclusion of batteries in the PV system showed that approximately 33% cost savings may be achieved after optimisation, which are equivalent to \$11 190. The optimisation, solar PV, and battery results showed potential to improve the cooling system further. The optimised values of the chiller power input (P_{chill}) and energy gain in the storage tank (Q_{chill}) indicate a significant improvement in efficiency. The objective function value (f_{val}) reflects the minimised cost achieved through the optimisation process. The binary switching variable (x) determines the optimal operational strategy under the given constraints and tariff structure. Table 4.5 presents a summary of the optimisation variables.

Table 4.5: Summary of optimisation variables

Variable name	Definition	Initial value	Optimised value	Units
Pchill	Chiller power input	95.6	90.3	kW
Qchill	Energy gain in storage tank from electric element	1 097 000	1 045 000	W
Alpha	Coefficient related to thermal dynamics	0.002	0.0021	-
Beta	Coefficient related to cooling effect	0.003	0.0032	-
Gamma	Coefficient related to solar gain	0.004	0.0043	-
Off-peak	ToU tariff during off-peak hours	1.207	1.207	(ZAR/kWh)
Standard	ToU tariff during standard hours	1.5703	1.5703	(ZAR/kWh)
Peak	ToU tariff during peak hours	2.0856	2.0856	(ZAR/kWh)
W1	Weighting factor for cost minimisation	0.4	0.4	-
W2	Weighting factor for thermal discomfort minimisation	0.3	0.3	-
W3	Weighting factor for PV usage maximisation	0.3	0.3	-
To	Initial temperature	-4	-4	°C
Tdesired	Desired temperature	0	0	°C
x	Switching variable	-	-	Binary
fval	Objective function value	616 662	446 796	ZAR
exitflag	Optimisation exit status	-	1	-
info	Optimisation information	-	SCIP	-

4.4.6 Results of the economic analysis

The average inflation cost and annual electricity price increase rate are 5% and 10% respectively. These are input parameters for the analysis. The average inflation cost represents the estimated rate at which the overall price of equipment and services is projected to increase over time. In this case, it is set to 5%, indicating an increase in the overall costs due to inflation. Figures 4.26 and 4.27 show the variations in the lifecycle costs of the proposed system.

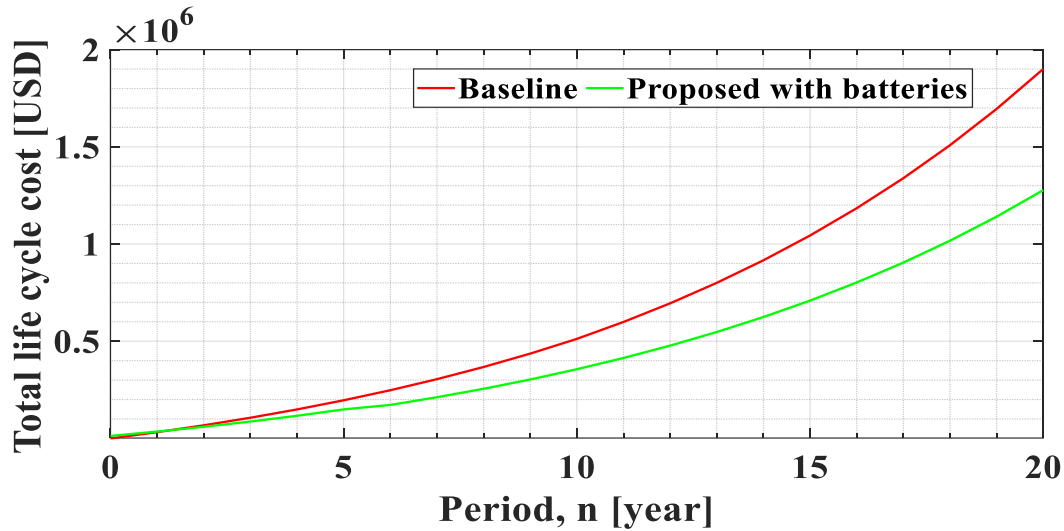


Figure 4.26: Lifecycle cost analysis for the baseline system and optimal system with PV

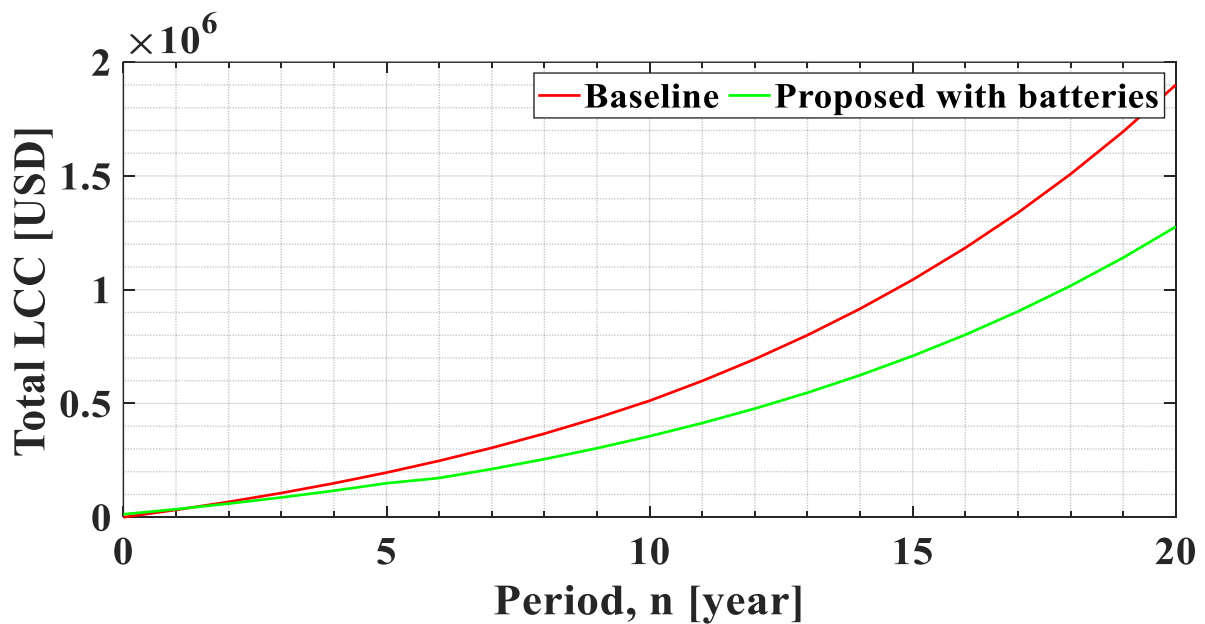


Figure 4.27: Lifecycle cost analysis including batteries

The annual electricity price increase rate refers to the expected growth in electricity expenses. A rate of 10% suggests that the cost of electricity is anticipated to increase by 10% every year, which will impact the cost of the system. These values are vital for predicting and evaluating the proposed system's consequences and are crucial in determining its economic viability and sustainability.

A projected lifetime saving of 30% was simulated, which is approximately \$601 264 savings over 20 years for the proposed system without batteries. The proposed system with

batteries has a projected lifetime saving of 35% and a 20-year saving of \$700 687. Based on the comparison between the baseline and both proposed systems, the breakeven for this system is a year from the start of the investment, which indicates a reasonable period for return on investment at an earlier stage.

4.4.7 Conclusion of the simulation results discussion

The input from the energy meter readings and the output load profile were based on the temperature of the water returning from the building, and the given flow rate was simulated for some summer days and months. Furthermore, environmental weather data, atmospheric temperature, and the solar irradiation were simulated for the plant's location.

Before the simulation, the higher demand region was expected to occur at the peak pricing period of the day; however, this was not the case. Increased demand for cooling load was further present during the off-peak pricing period for the day, while demand during the peak pricing period was moderate. Furthermore, the temperature of the storage for the baseline system and the proposed system was compared. It was seen that the solver was able to retain the desired temperature while saving energy costs.

Although the cooling load was constant for this simulation, it may be reduced by user management strategies. The energy input to the system for a duration was also considered. The monthly energy consumption was estimated for different configurations of the system. As a result, yearly energy consumption savings were calculated for both the baseline and proposed systems.

The simulation results may be used to develop more accurate and effective energy management strategies for buildings. Moreover, in some instances, the unexpected peak demand region during the late afternoon and early evening hours highlighted the importance of a flexible and responsive energy management system. This may involve implementing solutions such as batteries or thermal storage to shift the peak demand to a more convenient time or to reduce the overall energy consumption during peak demands.

4.5 CONCLUSION

This chapter modelled the optimal control of an ITES-based cooling plant for a commercial building (a hospital) in Sandton, Johannesburg, South Africa. The cooling system configuration includes a chiller and ITES, of which the latter stores the cooling

energy in the form of ice during the off-peak ToU tariff pricing period and discharges cooling energy using a glycol solution in the system. A heat exchanger transfers heat to the building and heat recovery chillers. Water is the medium for the heat transfer of fluid to and from the building. The optimal control strategy was implemented to improve operational efficiency, which may reduce energy cost savings and maintain the occupants' thermal comfort. Solar PV was proposed to assist the system in saving energy on pumping during peak demand.

The baseline system was the current system, without a PV system or optimal controller, while the proposed system included the two additions. Battery storage was further considered due to the unexpected cooling load profile of the system.

A comparison was made between the three system configurations to predict the energy cost savings potential of the proposed system, without negative impacts on the system. A binary switch, triggered by the optimal control function, shifted the load on the chiller and pumps as the primary devices that source power from the grid.

From the simulation of the proposed model, approximately 33% energy cost savings could be realised annually, with well-maintained thermal comfort. According to the size of the plant, the 25% energy cost savings are equivalent to \$11 190 in current assets for the yearly summer seasons.

Considering the lifecycle analysis, approximately 35% cost savings were estimated for 20 years, considering yearly inflation and an annual electricity price increase.

The result of optimisation and integration with solar PV is worth the investment in the system. Utilising an ITES system and additional efforts will generally be beneficial for the facility.

The simulation results provide valuable insight into the complex relationship between a building's energy consumption and the surrounding environment. By understanding these relationships, more efficient and sustainable energy management strategies for facilities may be developed, which may ultimately assist in reducing overall energy consumption and mitigating the impacts of climate change.

CHAPTER 5: GENERAL CONCLUSION

5.1 SUMMARY

This chapter concludes the research on the optimal energy management of ITES-based air conditioning systems for commercial buildings with a solar PV system.

Firstly, the major problem identified in this research was the higher cost implications of cooling buildings, which are primarily due to non-optimal operation and inaccuracies in operational control when applying ITES systems. The investigations highlighted a proposed stepwise objective to solve the current ITES challenge. This included developing and simulating models for conventionally and optimally controlled HVAC systems with ITES and different optimisation tools. Secondly, comparison, validation, and verification of the simulated models, with identification and improvement of the accuracy for the optimal controlled ITES, were conducted. Thirdly, the results from the final models of ITES for given commercial buildings from conducting case studies and analyses to verify the accuracies of the models were provided. A comparison of the model results revealed the potential cost savings of the optimal operation control strategy applicable to commercial buildings.

In further investigation, a systematic POET framework, applied at various levels, allowed structured and thorough guidelines for energy management to evaluate the energy-saving and efficiency-improvement potentials. After investigating multiple options, by adopting each level step of the POET framework, optimal control of the HVAC-ITES system combined with renewable energy was proposed for future solutions.

Chapter 3 of this study delved into how an ANN was effectively used in the ITES system. It involved testing different combinations of randomly selected input variables to forecast four key performance indicators. One hundred datasets were created, based on the energy balance foundation of the ITES cooling system. The regression values obtained during training, validation, testing, and overall evaluation for storage tank temperature, COP, cooling load, and chiller power, showed high precision, ranging from 0.98442 to 0.99987. These findings highlight the trustworthiness of ANNs in projecting system performance accurately. Furthermore, the minimal deviations between predicted and actual values confirmed the reliability, consistency, and resilience of the forecasting framework.

The proposed deterministic ANN strategy showed great potential for practical use in energy systems, particularly within HVAC and ITES systems. Engineers may utilise ANN forecasts to optimise their configuration decisions, which will lead to time and cost savings through avoiding physical experimental setups. Moreover, the superior performance of this method over further benchmarks emphasises its viability for real-world integration into energy systems, which will offer enhanced efficiency and financial benefits.

Chapter 4 focused on optimising the control of a cooling system that uses ITES in a hospital located in Sandton, Johannesburg, South Africa. The system consists of a chiller and ITES, of which the latter stores cooling energy as ice during off-peak ToU tariff periods and releases it using a glycol solution. Heat exchangers transfer heat to the building and a heat recovery chiller uses water as the medium for heat transfer. The main goal of implementing an optimal control strategy is improving operational efficiency, potentially reducing energy costs, while ensuring occupants' comfort. To achieve energy savings during peak demand, the introduction of solar PV was proposed.

To evaluate the effectiveness of the proposal, comparisons between the current system without a PV system and optimal controller (baseline) with the proposed system that includes these additions were carried out. Given the unpredictable nature of cooling load profiles, incorporation of battery storage was considered. A binary switch, controlled by the optimal control function, assisted in shifting the load, either on the chiller or pumps. However, in some cases, the primary devices that draw power from the grid may also be controlled.

Based on the simulation results from the proposed model, an annual reduction in energy costs by approximately 33%, while maintaining thermal comfort levels, was anticipated. For this particular sized plant, this translates to estimated yearly savings of \$11 190 during summer months.

Over a span of 20 years, taking into account inflation and increases in electricity prices, the results indicated projected cost savings of approximately 35%.

When considering the optimisation and integration of solar PV, it is evident that investing in ITES systems and related improvements can bring about significant advantages for the facility.

These simulation findings provide valuable insight into the complex interaction between a building's energy usage and the surrounding environment. Understanding these

connections may develop more effective and sustainable energy management strategies. This contributes to reducing overall energy consumption and addressing the challenges of climate change.

5.2 SUGGESTIONS FOR FURTHER RESEARCH

It is recommended that future research delves into the potential synergies between optimal control strategies for HVAC systems with ITES and the capabilities of innovative grid technologies to explore how these systems may seamlessly integrate with smart grids, enabling bidirectional communication, participating in demand response programmes, and efficient management of grid load. This investigation may further analyse the implications of such integration for energy efficiency, grid resilience, and overall sustainability in commercial buildings. The insights gained from this research may provide valuable knowledge about the evolving landscape of intelligent energy systems and their impact on optimising HVAC performance in real-world scenarios.

Additionally, it is crucial to assess how climate change may affect the performance and efficiency of HVAC systems, particularly those utilising ITES to identify strategies to enhance system resilience in response to changing climate conditions, extreme weather events, and temperature fluctuations.

Another aspect worth exploring is integrating occupant behaviour into modelling HVAC optimisation strategies. Adaptive and personalised HVAC control solutions may be created by developing feedback systems that consider occupants' preferences, behaviours, and thermal comfort requirements.

The potential integration of HVAC systems with ITES into microgrid networks to achieve energy independence can be examined. Research may involve the evaluation of the feasibility of creating commercial buildings that are independent of external energy sources by investigating the advantages of producing, storing, and distributing energy locally within a microgrid system.

Comprehensive approaches to managing building energy systems, beyond optimising HVAC, by researching integrating information technology and energy systems with further building components, such as lighting, ventilation and renewable energy sources, can be explored. The goal may be to develop synchronised and all-encompassing solutions for efficient energy usage.

The potential application of artificial intelligence (AI) in detecting and diagnosing faults in HVAC systems, by developing AI algorithms capable of proactively identifying issues in real time, as well as optimising system performance while minimising downtime, can be investigated.

The social and economic impacts associated with implementing sustainable HVAC on a long-term basis by examining how energy-efficient systems contribute to job creation, community wellbeing, and long-term financial sustainability can be assessed. The research may aim to provide a comprehensive understanding of the broader implications involved.

A thorough analysis throughout the lifecycle of emerging HVAC technologies can be conducted. This can include evaluating their manufacturing processes, installation procedures, operational efficiency during use, and decommissioning methods. Assessing these technologies' overall environmental impact and sustainability can help to inform decision making when selecting future HVAC systems.

The principles of designing buildings with the focus on human comfort and energy efficiency can be researched. How architectural and interior design features may work together with HVAC systems to ensure occupants' comfort while minimising energy usage can be explored.

The feasibility of utilising hybrid energy storage solutions for HVAC systems, combining ITES with advanced battery technologies, can be investigated. The advantages and disadvantages of these hybrid systems regarding efficiency, cost effectiveness, and environmental impact can be assessed.

The potential for community-level energy-sharing networks that involve multiple commercial buildings can be explored. How HVAC systems that are integrated with ITES can contribute to shared energy resources and creating resilient and sustainable communities may be investigated.

These diverse research directions aim to expand our understanding of sustainable HVAC systems by providing innovative solutions and valuable insights for future advancements in this field.

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APPENDIX A: ARTIFICIAL NEURAL NETWORK (ANN) CODES FOR CHAPTER 3 MODEL

```
% Solve an Input-Output Fitting problem with a Neural Network
% Script generated by Neural Fitting app
% Created 15-Feb-2024 10:57:46
%
% This script assumes these variables are defined:
%
% inputs - input data.
% Target - target data.

x = inputs';
t = Target';

% Choose a Training Function
% For a list of all training functions type: help nntrain
% 'trainlm' is usually fastest.
% 'trainbr' takes longer but may be better for challenging problems.
% 'trainscg' uses less memory. Suitable in low memory situations.
trainFcn = 'trainlm'; % Levenberg-Marquardt backpropagation.

% Create a Fitting Network
hiddenLayerSize = 10;
net = fitnet(hiddenLayerSize,trainFcn);

% Choose Input and Output Pre/Post-Processing Functions
% For a list of all processing functions type: help nnprocess
net.input.processFcns = {'removeconstantrows','mapminmax'};
net.output.processFcns = {'removeconstantrows','mapminmax'};

% Setup Division of Data for Training, Validation, Testing
% For a list of all data division functions type: help nndivide
net.divideFcn = 'dividerand'; % Divide data randomly
net.divideMode = 'sample'; % Divide up every sample
net.divideParam.trainRatio = 70/100;
net.divideParam.valRatio = 15/100;
net.divideParam.testRatio = 15/100;

% Choose a Performance Function
% For a list of all performance functions type: help nnperformance
```

```

net.performFcn = 'mse'; % Mean Squared Error

% Choose Plot Functions
% For a list of all plot functions type: help nnplot
net.plotFcns = {'plotperform','plottrainstate','ploterrhist', ...
    'plotregression','plotfit'};

% Train the Network
[net,tr] = train(net,x,t);

% Test the Network
y = net(x);
e = gsubtract(t,y);
performance = perform(net,t,y)

% Recalculate Training, Validation and Test Performance
trainTargets = t .* tr.trainMask{1};
valTargets = t .* tr.valMask{1};
testTargets = t .* tr.testMask{1};
trainPerformance = perform(net,trainTargets,y)
valPerformance = perform(net,valTargets,y)
testPerformance = perform(net,testTargets,y)

% View the Network
view(net)

% Plots
% Uncomment these lines to enable various plots.
%figure, plotperform(tr)
%figure, plottrainstate(tr)
%figure, ploterrhist(e)
%figure, plotregression(t,y)
%figure, plotfit(net,x,t)

% Deployment
% Change the (false) values to (true) to enable the following code blocks.
% See the help for each generation function for more information.
if (false)
    % Generate MATLAB function for neural network for application
    % deployment in MATLAB scripts or with MATLAB Compiler and Builder
    % tools, or simply to examine the calculations your trained neural
    % network performs.
    genFunction(net,'myNeuralNetworkFunction');
    y = myNeuralNetworkFunction(x);
end
if (false)
    % Generate a matrix-only MATLAB function for neural network code

```

```
% generation with MATLAB Coder tools.  
genFunction(net,'myNeuralNetworkFunction','MatrixOnly','yes');  
y = myNeuralNetworkFunction(x);  
end  
if (false)  
    % Generate a Simulink diagram for simulation or deployment with.  
    % Simulink Coder tools.  
    gensim(net);  
end
```

APPENDIX B: TARGET ANN PREDICTED TANK STORAGE TEMPERATURE VALUES AND DEVIATION FOR CHAPTER 3

Index	TSTORE Target	TSTORE ANN	Deviation (%)	Index	TSTORE Target	TSTORE ANN	Deviation (%)
1	268.9361	268.8543	0.0304	51	266.7847	266.8669	3.0783
2	270.7308	270.7766	1.6924	52	271.6435	271.235	15.0389
3	268.3738	268.1743	7.4324	53	270.0054	270.357	13.0056
4	271.067	271.0416	0.94	54	271.9065	271.5121	14.5035
5	265.455	265.7473	10.9999	55	268.0492	267.9047	5.3902
6	270.8162	270.5859	8.5036	56	267.4761	267.3503	4.7052
7	270.1432	270.1422	0.0387	57	267.9404	268.0945	5.7451
8	267.7541	267.6315	4.5796	58	268.6658	268.6241	1.5511
9	267.5802	267.4943	3.2113	59	268.3648	268.3682	0.1247
10	269.0194	268.4968	19.4287	60	268.5899	268.6822	3.4362
11	270.2713	270.5721	11.1155	61	271.3679	271.2054	5.988
12	270.5138	270.6428	4.7645	62	270.4852	270.3091	6.5118
13	271.665	271.8075	5.2408	63	270.139	270.4313	10.8089
14	270.1892	269.9673	8.213	64	270.1028	270.3586	9.4629
15	271.592	271.7629	6.2901	65	269.9508	270.0525	3.7651
16	270.9212	271.0977	6.5137	66	268.6109	268.5337	2.8739
17	271.3783	271.4187	1.486	67	267.7685	267.5861	6.8102
18	265.8693	266.1776	11.5843	68	271.5272	271.6546	4.6901
19	271.6088	271.7088	3.678	69	267.0676	266.9242	5.3712
20	267.0871	267.0792	0.2952	70	264.5457	265.27	27.3021
21	271.1909	270.8283	13.3722	71	267.5054	267.4798	0.9599
22	268.4627	268.4856	0.8554	72	270.1858	270.1046	3.0058
23	270.3074	270.6658	13.2406	73	270.1509	270.1165	1.2712
24	266.6076	266.7248	4.3906	74	266.9135	266.8534	2.2504
25	268.4178	267.9496	17.4436	75	272.0766	271.7559	11.7857
26	268.8829	269.1973	11.6794	76	269.3866	269.8194	16.0394
27	269.4217	269.554	4.9088	77	268.4153	268.6181	7.5502
28	269.3049	269.6675	13.4474	78	270.7507	270.9163	6.1122
29	272.0943	271.782	11.477	79	271.2057	271.239	1.2276
30	272.4173	272.0372	13.9513	80	271.0453	271.1641	4.3814
31	268.7136	268.9561	9.014	81	271.7672	271.6816	3.1501
32	267.8529	267.9813	4.791	82	266.3119	266.3913	2.9842
33	270.0844	270.4021	11.7493	83	268.0183	267.691	12.2133
34	270.6341	270.2382	14.6295	84	267.4188	267.2354	6.859
35	266.3197	266.1255	7.2924	85	266.3605	266.4144	2.0233
36	271.1338	271.382	9.1459	86	265.6569	265.7503	3.5159

Index	TSTORE Target	TSTORE ANN	Deviation (%)	Index	TSTORE Target	TSTORE ANN	Deviation (%)
37	268.5736	268.5685	0.1907	87	270.6748	270.8128	5.0962
38	271.3539	271.0228	12.2002	88	270.1599	270.2857	4.6518
39	266.8876	266.8574	1.1307	89	270.2586	270.7127	16.7716
40	269.9092	269.738	6.3405	90	269.0246	269.0466	0.8211
41	265.5901	265.8394	9.3804	91	272.2196	271.9881	8.5047
42	268.3408	268.6545	11.6782	92	269.1197	269.3384	8.1217
43	271.9412	271.7801	5.9244	93	270.7744	270.6431	4.8472
44	267.397	267.2303	6.2324	94	271.2429	271.3856	5.2592
45	269.7753	269.8375	2.3047	95	271.705	271.433	10.0129
46	271.3864	271.2731	4.1776	96	269.9936	270.0859	3.4167
47	270.4438	270.2026	8.9178	97	270.8912	270.6432	9.1549
48	271.3547	271.6786	11.9222	98	267.4291	267.5336	3.9076
49	270.13	270.5351	14.975	99	268.6675	268.6233	1.6426
50	270.548	270.2131	12.3777	100	270.0363	269.9539	3.0495

APPENDIX C: TARGET ANN PREDICTED TANK STORAGE COEFFICIENT OF PERFORMANCE (COP) VALUES AND DEVIATION FOR CHAPTER 3

Index	COP Target	COP ANN	Deviation (%)	Index	COP Target	COP ANN	Deviation (%)
1	4.03650	4.06350	0.66510	51	2.42480	2.44290	0.74140
2	1.45310	1.47330	1.36630	52	1.73230	1.76770	1.99810
3	1.22620	1.21980	0.52040	53	2.48340	2.46790	0.62510
4	3.37270	3.36790	0.14110	54	2.92040	2.92370	0.11310
5	3.10400	3.12140	0.55710	55	4.02460	4.04690	0.55100
6	1.67880	1.67440	0.26080	56	4.16450	4.11590	1.16640
7	1.59870	1.55900	2.48250	57	3.28080	3.28970	0.26990
8	1.70920	1.69390	0.89200	58	1.27220	1.26260	0.75220
9	2.52240	2.53240	0.39530	59	4.16840	4.15520	0.31800
10	3.55120	3.55010	0.03240	60	3.06400	3.07450	0.34110
11	3.43160	3.34550	2.50960	61	2.16640	2.18540	0.86860
12	2.69000	2.67610	0.51800	62	2.21560	2.19470	0.94440
13	1.73120	1.75980	1.62930	63	3.51600	3.51340	0.07260
14	1.41680	1.40720	0.68150	64	3.90180	4.00530	2.58520
15	1.97640	1.97140	0.25200	65	1.92860	1.90090	1.43650
16	3.02200	3.02630	0.14010	66	1.81770	1.84070	1.25030
17	2.20660	2.19190	0.66630	67	1.40240	1.43700	2.40460
18	3.85990	3.84230	0.45590	68	3.30710	3.27810	0.87630
19	1.61980	1.64590	1.58940	69	2.97150	2.98500	0.44990
20	2.33570	2.31980	0.67740	70	3.56380	3.55880	0.14030
21	1.45350	1.48820	2.33180	71	1.09080	1.09080	0.00160
22	1.34410	1.37180	2.01950	72	4.24890	4.26330	0.33700
23	2.96660	2.95160	0.50470	73	1.41250	1.39810	1.02300
24	2.63120	2.60270	1.08370	74	4.12890	4.14320	0.34630
25	1.15080	1.15150	0.05710	75	2.10990	2.10760	0.10610
26	4.56930	4.54900	0.44490	76	1.85780	1.88480	1.43470
27	4.50860	4.49810	0.23210	77	3.42710	3.38900	1.11170
28	3.57610	3.55690	0.53650	78	1.79590	1.87850	4.39940
29	3.10790	3.10380	0.13440	79	2.92700	2.94380	0.56930
30	1.91260	1.92800	0.79570	80	2.40840	2.41610	0.31740
31	1.39340	1.38180	0.83050	81	3.17280	3.14740	0.79940
32	3.38220	3.37930	0.08730	82	3.94500	3.89960	1.15110
33	3.89670	4.01020	2.83140	83	3.74740	3.74890	0.03930
34	1.46550	1.48900	1.58180	84	2.96710	2.87720	3.03000

Index	COP Target	COP ANN	Deviation (%)	Index	COP Target	COP ANN	Deviation (%)
35	2.57500	2.59800	0.88490	85	3.51620	3.56020	1.23530
36	1.18890	1.22480	2.93010	86	2.96830	2.91970	1.63940
37	2.01060	2.03130	1.02120	87	2.13590	2.14800	0.56190
38	1.38250	1.33940	3.12070	88	2.37090	2.36200	0.37520
39	3.50870	3.50040	0.23670	89	2.50970	2.48760	0.87890
40	1.72510	1.84570	6.53450	90	4.06300	4.05890	0.10080
41	3.15120	3.13580	0.48750	91	2.42830	2.40660	0.89470
42	2.47320	2.43450	1.56840	92	4.93040	4.85360	1.55900
43	2.65860	2.66530	0.25120	93	3.62290	3.61350	0.25920
44	4.15460	4.18600	0.74920	94	3.45830	3.47480	0.47440
45	3.66730	3.67060	0.08920	95	3.76700	3.80510	1.00070
46	1.16960	1.14640	1.98820	96	4.17850	4.20770	0.69450
47	3.02430	3.00120	0.76390	97	1.93900	1.93730	0.08780
48	1.40100	1.39770	0.23330	98	2.26270	2.26150	0.05300
49	3.99150	3.98310	0.21150	99	2.39120	2.41270	0.89280
50	3.12110	3.11490	0.19850	100	1.56980	1.57510	0.33880

APPENDIX D: TARGET ANN PREDICTED COOLING LOAD VALUES AND DEVIATIONS FOR CHAPTER 3

Index	CL Target	CL ANN	Deviation (%)	Index	CL Target	CL ANN	Deviation (%)
1	22362.16	24858.31	10.04%	51	89452.49	69939.17	21.81%
2	298162.6	296982.4	0.40%	52	85724.53	85535.43	0.22%
3	9051.381	9531.246	5.03%	53	113414.9	113433.4	0.02%
4	31147.14	35835.84	13.08%	54	157515.4	158012.8	0.31%
5	184137.7	182409.9	0.94%	55	12867.3	12535.54	2.58%
6	138966.9	138033.9	0.67%	56	1774.86	2047.389	13.31%
7	157962.6	158935.2	0.61%	57	46855.46	47285.9	0.91%
8	26622.32	23491.56	11.76%	58	32301.64	32665.4	1.11%
9	258762.1	257231.4	0.59%	59	93888.77	93243.91	0.69%
10	157962.6	158407.8	0.28%	60	190793.3	190142.4	0.34%
11	73209.84	72115.55	1.49%	61	42153.17	43538.66	3.18%
12	44014.83	43835.42	0.41%	62	115363	108251.4	6.16%
13	95845.94	97965.39	2.16%	63	103835.4	107707.6	3.60%
14	175709.4	174914.2	0.45%	64	65316.64	65981.14	1.01%
15	173042.6	172398.3	0.37%	65	103826.7	110061.2	5.66%
16	115187.3	115623	0.38%	66	114658.2	114225	0.38%
17	163994.1	163019.9	0.59%	67	74541.42	80651.99	7.58%
18	19966.74	24460.49	18.37%	68	71354.57	84820.71	15.88%
19	279527.4	277709.6	0.65%	69	219982.9	217224.6	1.25%
20	330106	324421.8	1.72%	70	43929.39	51236.1	14.26%
21	90514.58	91031.44	0.57%	71	156890.6	156420	0.30%
22	23961.48	28497.92	15.92%	72	34079.8	33758.99	0.94%
23	253438.7	252662.9	0.31%	73	50317.03	52302.14	3.80%
24	107378	107409.1	0.03%	74	144826	142674.9	1.49%
25	229300.1	226864.6	1.06%	75	148641.3	148084	0.37%
26	101163.4	110178.8	8.18%	76	283962.2	279666.5	1.51%
27	134177	131267.5	2.17%	77	175351.8	174679.8	0.38%
28	44725.67	48124.15	7.06%	78	139763.7	145372.5	3.86%
29	9318.355	11757.55	20.75%	79	185289.1	183661.4	0.88%
30	154407.2	154507.1	0.06%	80	25381.99	26609.08	4.61%
31	118289.9	123279.3	4.05%	81	89983.15	90725.6	0.82%
32	8076.089	8155.398	0.97%	82	57504.43	59910.82	4.02%
33	7099.635	6372.275	10.25%	83	69576.42	59831.32	14.01%
34	78445.3	69981.28	10.79%	84	33279.84	34075.34	2.33%
35	178367	177657.2	0.40%	85	27687.32	28604.27	3.21%
36	69572.35	70042.89	0.67%	86	58568.26	58114.91	0.77%
37	95664.02	94972.34	0.72%	87	161243.8	161132.1	0.07%

Index	CL Target	CL ANN	Deviation (%)	Index	CL Target	CL ANN	Deviation (%)
38	24846.88	26728.55	7.04%	88	93443.75	92069.59	1.47%
39	24849.21	21685.36	12.73%	89	178632	178090.9	0.30%
40	87851.81	87949.78	0.11%	90	21920.81	23911.59	8.33%
41	227619.4	227049.3	0.25%	91	126459.5	126401.2	0.05%
42	119977.5	116326.9	3.04%	92	66555.81	60939.55	8.44%
43	91942.06	94126.93	2.32%	93	40464.72	42086.79	3.85%
44	184312.1	185100.9	0.43%	94	117135.7	117939.4	0.68%
45	316973.7	311509.4	1.72%	95	12069.28	4905.94	59.35%
46	76674.89	78087.23	1.81%	96	75428.17	77836.84	3.09%
47	125123.1	124101.7	0.82%	97	159022.5	159973.1	0.59%
48	19523.27	20718.76	5.77%	98	87675.89	92402.02	5.11%
49	108176.2	117130.4	7.64%	99	72680.15	72237.6	0.61%
50	86972.22	88287.77	1.49%	100	69314.48	73675.22	5.92%

APPENDIX E: TARGET ANN PREDICTED CHILLER POWER INPUT VALUES AND DEVIATIONS FOR CHAPTER 3

Pchiller Target	Pchiller ANN	Deviation (%)	Pchiller ANN	Index	Pchiller Target	Pchiller ANN	Deviation (%)
1	96860	97038.29	0.18%	51	97327	97210	0.12%
2	94082	94400.35	0.34%	52	95781	95820	0.04%
3	91754	91688.16	0.07%	53	99024	98597	0.43%
4	99254	99113.19	0.14%	54	96684	96732	0.05%
5	94886	94491.67	0.42%	55	96288	96290	0.00%
6	97943	97903.97	0.04%	56	99868	100022	0.15%
7	92231	92073.76	0.17%	57	91024	90613	0.45%
8	91910	91950.23	0.04%	58	97853	98089	0.24%
9	91107	91122.9	0.02%	59	95719	95607	0.12%
10	92328	91977.97	0.38%	60	97022	96991	0.03%
11	90783	90182.67	0.66%	61	92026	92611	0.63%
12	97552	97280.71	0.28%	62	99798	99440	0.36%
13	91405	91295.06	0.12%	63	91768	90953	0.89%
14	94839	94368.6	0.50%	64	92563	92905	0.37%
15	92390	92410.27	0.02%	65	92225	92019	0.22%
16	99802	99048.5	0.75%	66	98520	97498	1.04%
17	92757	92955.27	0.21%	67	90639	90464	0.19%
18	91302	91537.53	0.26%	68	93083	92990	0.10%
19	97045	97176.11	0.13%	69	99985	99922	0.06%
20	97030	97117.91	0.09%	70	99103	98646	0.46%
21	94009	94177.69	0.18%	71	99523	99449	0.07%
22	99729	99599.42	0.13%	72	96065	96031	0.04%
23	91193	91347.57	0.17%	73	99079	98931	0.15%
24	95957	96096.38	0.15%	74	97362	97326	0.04%
25	91786	91508.51	0.30%	75	96486	96457	0.03%
26	93529	93717.05	0.20%	76	93385	93959	0.61%
27	99302	99067.79	0.24%	77	92703	92775	0.08%
28	93146	93073.31	0.08%	78	93920	94404	0.51%
29	97547	97203.21	0.35%	79	94704	95058	0.37%
30	97968	98186.42	0.22%	80	99404	99195	0.21%
31	91585	91526.91	0.06%	81	90144	90271	0.14%
32	94632	96546.56	1.98%	82	98782	98842	0.06%
33	99606	100020	0.41%	83	93532	93346	0.20%
34	92856	92772.81	0.09%	84	96518	97117	0.62%
35	96263	96667.3	0.42%	85	93990	93956	0.04%
36	95857	95760.97	0.10%	86	95664	95993	0.34%

Pchiller Target	Pchiller ANN	Deviation (%)	Pchiller ANN	Index	Pchiller Target	Pchiller ANN	Deviation (%)
37	90321	90131.12	0.21%	87	99802	98698	1.11%
38	93897	93794.1	0.11%	88	96958	96976	0.02%
39	98089	97833.21	0.26%	89	94162	94227	0.07%
40	91638	91336.41	0.33%	90	97446	97377	0.07%
41	95609	95620.11	0.01%	91	97910	97671	0.24%
42	93970	93882.78	0.09%	92	94808	94807	0.00%
43	97457	96410.07	1.07%	93	90208	90374	0.18%
44	98281	97997.12	0.29%	94	96996	97218	0.23%
45	97211	97305.46	0.10%	95	99628	99500	0.13%
46	92379	94445.63	2.19%	96	91854	91511	0.37%
47	90232	89704.36	0.58%	97	91566	91429	0.15%
48	90360	91082.01	0.79%	98	99882	99940	0.06%
49	97491	96945.28	0.56%	99	95208	94942	0.28%
50	92158	92327.43	0.18%	100	96622	95913	0.73%

APPENDIX F: ANN CODES FOR OPTIMISATION MODEL (CHAPTER 4)

```

clear;
%Time interval
days=1;
hours=24*days;
ts=1/12; %for 5-minute interval
N=hours/ts;
t=3600

%INPUT VARIABLES
fct=1/ts
Cd=fct*1000*[xlsread('JHB_DATA_5min V4.xlsx','5 min','Q20313:Q20600')]
Tgly=[xlsread('JHB_DATA_5min V4','5 min','L20313:L20600')]
Tdb=[xlsread('JHB_DATA_5min V4','5 min','V20313:V20600')]
GHI=[xlsread('JHB_DATA_5min V4','5 min','S20313:S20600')]
DNI=[xlsread('JHB_DATA_5min V4','5 min','U20313:U20600')]
DHI=[xlsread('JHB_DATA_5min V4','5 min','T20313:T20600')]
HXS=[xlsread('JHB_DATA_5min V4','5 min','R20313:R20600')]
HXR=[xlsread('JHB_DATA_5min V4','5 min','M20313:M20600')]
%xx=[xlsread('JHB_DATA_5min V4','5 min','AE20313:AE20600')]
Tst=[xlsread('JHB_DATA_5min V4','5 min','P20313:P34137')]
Cdib=[xlsread('JHB_DATA_5min V4.xlsx','Year load','AJ98211:AJ98498')]
Cdio=[xlsread('JHB_DATA_5min V4.xlsx','Year load','AP98211:AP98498')]
CdcB=[xlsread('JHB_DATA_5min V4.xlsx','Year load','AU98211:AU98498')]
Cdco=[xlsread('JHB_DATA_5min V4.xlsx','Year load','AS98211:AS98498')]
INTVSD=[xlsread('JHB_DATA_5min V4.xlsx','Year load','AV98211:AV98498')]

%SOLAR PV INPUT
PVSTC=0.31; %PV at maximum power point and standard test condition kWp
NPVS=8; %the number of PV panels in series
NPVP=2; %the number of PV panels in parallel
ALPHAT=0.0045; %the temperature coefficient of power in °C
NOCT=46; %nominal operating cell temperature in °C
RHO_r=0.2; %the reflectance of the surrounding area
BETA_tilt=30; %the tilted angle in degrees
THETA_inc=0; %the incidence angle of solar radiation on a tilted surface in degrees
Ta=25 ; %Standard

TI=DHI*cosd(THETA_inc)+DHI*((1+cosd(BETA_tilt)/2))+RHO_r*GHI*((1-
cosd(BETA_tilt)/2)); %total irradiance received by the PV cell
TC=Ta+TI*((NOCT-20)/800); % the temperature of the PV cell in °C

```



```

PPV=PVSTC*NPVP*NPVS*(TI/1000).*(1-ALPHAT*(TC-25));
t=3600;
PPV_F=PPV*300; %Power from solar source
GT=DNI*0+DHI*(1.866/2)+GHI*0.2*(0.134/2)
G=GT*t; %heat gain from solar irradiance in collector if Solar Absorption Refrigeration
system is considered
% CONSTANTS
cgly= 4145;%Specific heat capacity of glycol in kJ/kg K
QSCAP=4560000;%storage capacity in W; stored one- third of the full day
%S= 2*3.142*0.33*1.41+2*3.142*0.33^2 ;
S= 9.84*8; % Outer surface area in square metre
h = 6.3*8 ;
dx =0.035*8 ;
kc =0.055;
U=(dx/kc)+(1/h)
Pchill =96500;%Chiller capacity in kW
Qchill=Pchill*COP*300; %Energy gain in storage tank from electric element per 5 min
%Tdb =25;
%%To =10;
%Tup = 0 ;
%Tlow= -10;
Alpha= (S/(QSCAP*U))+(Cd./QSCAP) ;
Beta = (Qchill/QSCAP);
gamma =(S.*Tdb/(QSCAP*(U)))-(Cd(1:N).*Tgly(1:N)/QSCAP);

%City Power Johannesburg Schedule of Approved Electricity Tariffs for
%FY2022/23 (Summer Energy charges)
off_peak=1.207; % Rand/kwh
standard=1.5703; % Rand/kwh
peak=2.0856; % Rand/kwh

%p=ones(1:N)
%%TOU Regions
T=[off_peak*ones(1,6/ts),standard*ones(1,1/ts),peak*ones(1,3/ts),standard*ones(1,8/ts)
,peak*ones(1,2/ts),standard*ones(1,2/ts),off_peak*ones(1,2/ts)];

% Maximum demand;

A=[];
b=[];

%T05=y2(5); T06=y2(6); T20=y2(20); T21=y2(21); T24=y2(24)
%W1=0.4; % Weighting Factor for cost minimisation priority
%W2=0.3; % Weighting factor for thermal discomfort priority
%W3=0.3; % Weighting factor for PV usage priority

```

```

%%Objective function(cost minimisation + thermal discomfort minimisation)
Tdesired=0

% Objective function (cost minimisation) reduced to fit dissertation
f=@(x)(ts*sum(T(1:N)*x(1:N)))

% Objective function (cost minimisation and PV maximisation)
f=@(x)(ts*sum(T(1:N)*x(1:N))+ts*sum(T(1:N)*x(1:N)

%%Initial temperature
To=-4;
%%thermal discomfort minimisation
%%Objective function (cost minimisation and PV maximisation)
f=@(x)(W3*ts*sum(PPV_F.*T(1:N)'.*x(1:N)));

CS=To.*prod(1-ts.*Alpha(1:N))+ts.*sum((((gamma(1:N)).*prod(1-ts.*Alpha(1:N)))));
%constraint sum
CC=prod(1-ts.*Alpha(1:N));%constraint coefficient
OC=ts.*Beta; %Outside multiplier
AL=ones(1,N)';%Align with rhs

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Tu=0*ones(1,N);
Tl=-6*ones(1,N);

Less=-ones(1,N);
More=ones(1,N);
Ineq=Inf(1,N);

nlcon=@(x)[((CS+OC.*sum(((x(1:N)).*CC))).*AL);((CS+OC.*sum(((x(1:N)).*CC))).*AL)
];

cl=[Tl,-Tu];

cu=[Ineq,Ineq];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%INITIA
L GUESS AND BOUNDARIES%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

x0=zeros(1,N);
lb=zeros(1,N);
ub=ones(1,N);

```

%%
%%SOLVER PARAMETERS%%

xtype="";

for each=1:N

 xtype=[xtype,'B'];
end

MyOptions=optimset
('solver','scip','display','iter','maxfeval',10000,'maxtime',100000,'maxnodes',100000000,'solverOpts',scipset(),'derivCheck','on');

Opt=optim('fun',f,'nl',nlcon,cl,cu,'ineq',A,b,'eq',[],[],'bounds',lb,ub,'xtype',xtype,'options',MyOptions);

[x,fval,exitflag,info]=solve(Opt,x0');

info ;x=x';

%%Tank
Temp Dynamic Loops%%

y1=ones(1,N);
Sw=(x(1:N));

for k=1:N

 y1(k)=To*prod(1-ts*Alpha(1:k))+ts*Beta*sum(((Sw(1:k))*prod(1-ts*Alpha(1:k))))+ts*sum(((gamma(1:k))*prod(1-ts*Alpha(1:k))));
end

%%TOTAL POWER and
COST%%

POT=(Pchill/24).*Sw(1:N);

CPT=Pchill.*T(1:N).*Sw(1:N);

%%TOTAL
COST%%
%%

for k=1:N

POT(k)=ts*sum(POT(1:k).*T(1:k));

end

%Plot of TOU Tariff

```
figure(1)
stairs(T);
grid on
%title(['ToU Tariff Function'])
xlabel(['Time [5 min]'])
ylabel(['Cost [ZAR/kWh]'])
```

%Plot switching function

```
Off-peak=[0,1,0]; standard=[1,1,0]; peak=[1,0,0];
Sw=x(1:N)
figure(2)
fill([0 6 6 0],[-1 -1 2 2],off-peak,'HandleVisibility','on');
hold on;
fill([6 7 7 6],[-1 -1 2 2],standard,'HandleVisibility','on');
hold on;
fill([7 10 10 7],[-1 -1 2 2],peak,'HandleVisibility','on');
hold on;
fill([10 18 18 10],[-1 -1 2 2],standard,'HandleVisibility','off');
hold on;
fill([18 20 20 18],[-1 -1 2 2],peak,'HandleVisibility','off');
hold on;
fill([20 22 22 20],[-1 -1 2 2],standard,'HandleVisibility','off');
hold on;
fill([22 25 25 22],[-1 -1 2 2],off-peak,'HandleVisibility','off');
stairs(linspace(0,hours,N),x(1:N),'k','linewidth',2)
hold on
ylabel('Switch [On/Off]')
xlabel('Time [h]')
legend('off-peak','standard','peak','location','northoutside','orientation','horizontal');
axis([0 hours -0.1 1.1]);
hold on
set(0,'DefaultAxesFontName','Garamond');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off
```

% Plot Solar irradiance

```
figure(3)
stairs(GT)
grid on
%title(['Solar irradiance'])
xlabel(['Time [5 min]'])
ylabel(['Irradiance [W/m^2]'])
```

```
% Plot Specific Solar Power from PV
```

```
figure(4)
stairs(PPV_F)
grid on
%title(['Specific Solar Power Input '])
xlabel(['Time [5 min]'])
ylabel(['Solar Power [W/m^2]'])
```

```
% Plot cooling demand
```

```
figure(5)
stairs(Cd)
grid on
%title(['Cooling Demand'])
xlabel(['Time [5 mins]'])
ylabel(['kW'])
```

```
%%%for k=1:N
```

```
T0=1.3;
y1(k)=To.*prod(1-ts*Alpha(1:k))+ts.*Beta.*sum(((x(1:k)).*prod(1-
ts*Alpha(1:k))))+ts.*sum(((gamma(1:k)).*prod(1-ts*Alpha(1:k)))));
end
```

```
Unwanted=[1,0.2,0.2]
```

```
ChilledWater=[1,0.600,0.400]
```

```
Desired=[0,0.6,1]
```

```
% Plot ITES Storage Tank Temperature
```

```
y1=y1(1:N);
figure (5)
fill([0 25 25 0],[1.00 1.00 2.00 2.00],Unwanted,'HandleVisibility','on');
hold on;
fill([0 25 25 0],[1.00 1.00 0.00 0.00],ChilledWater,'HandleVisibility','on');
hold on;
fill([0 25 25 0],[0.00 0.00 -6.00 -6.00],Desired,'HandleVisibility','on');
hold on;
plot(linspace(0,hours,N),y1,'k','linewidth',2)
hold on
%title(['ITES Temperature Variation'])
ylabel('Temperature [°C]')%alt 248
xlabel('Time [h]')
legend('Unwanted','Water&Ice','Desired','location','north','orientation','horizontal');
axis([0 hours -3.00 2.00]);
hold on
set(gca,'linewidth',3,'FontSize', 30);
hold on
```

```
ax = gca;
ax.XTick = 1:24;
xticks([0 2 4 6 8 10 12 14 16 18 20 22 24])
hold on
set(0,'DefaultAxesFontName','Times New Roman');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off
```

%Plot variation of optimised versus baseline figure 8

```
figure (6)
y1=y1(1:N);
Tst=Tst(1:N);
fill([0 25 25 0],[1.00 1.00 9.00 9.00],Unwanted,'HandleVisibility','on');
hold on;
fill([0 25 25 0],[1.00 1.00 0.00 0.00],ChilledWater,'HandleVisibility','on');
hold on;
fill([0 25 25 0],[0.00 0.00 -6.00 -6.00],Desired,'HandleVisibility','on');
hold on;
plot(linspace(0,hours,N),y1,'g','linewidth',2)
hold on
plot(linspace(0,hours,N),Tst,'b','linewidth',2)
hold on
%title(['ITTES Temperature Variation'])
ylabel('Temperature [°C]')%alt 248
xlabel('Time [h]')
legend('Unwanted','Water&Ice','Desired','Optimised','Baseline','location','north','orientation','horizontal');
axis([0 hours -6.00 9.00]);
hold on
set(0,'DefaultAxesFontName','Garamond');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off
```

% Plot ITES Storage Tank Temperature

```
figure (7)
Tst=Tst(1:N);
fill([0 25 25 0],[1.00 1.00 9.00 9.00],Unwanted,'HandleVisibility','on');
hold on;
fill([0 25 25 0],[1.00 1.00 0.00 0.00],ChilledWater,'HandleVisibility','on');
hold on;
fill([0 25 25 0],[0.00 0.00 -6.00 -6.00],Desired,'HandleVisibility','on');
hold on;
plot(linspace(0,hours,N),Tst,'b','linewidth',2)
hold on
%title(['ITTES Temperature Variation'])
```

```
ylabel("Temperature [°C]")%alt 248
xlabel("Time [h]")
legend("Unwanted",'Water&Ice','Desired','location','north','orientation','horizontal');
axis([0 hours -6.00 9.00]);
hold on
set(gca,'linewidth',3,'FontSize', 30);
hold on
ax = gca;
ax.XTick = 1:24;
xticks([0 2 4 6 8 10 12 14 16 18 20 22 24])
hold on
set(0,'DefaultAxesFontName','Times New Roman');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off
```

%Plot variation of optimised versus baseline figure 8

```
figure (8)
y1=y1(1:N);
Tst=Tst(1:N);
fill([0 25 25 0],[1.00 1.00 9.00 9.00],Unwanted,'HandleVisibility','on');
hold on;
fill([0 25 25 0],[1.00 1.00 0.00 0.00],ChilledWater,'HandleVisibility','on');
hold on;
fill([0 25 25 0],[0.00 0.00 -6.00 -6.00],Desired,'HandleVisibility','on');
hold on;
plot(linspace(0,hours,N),y1,'g','linewidth',2)
hold on
plot(linspace(0,hours,N),Tst,'b','linewidth',2)
hold on
%title(['TTES Temperature Variation'])
ylabel("Temperature [°C]")%alt 248
xlabel("Time [h]")
legend("Unwanted",'Water&Ice','Desired','Optimised','Baseline','location','north','orientation','horizontal');
axis([0 hours -6.00 9.00]);
hold on
set(0,'DefaultAxesFontName','Garamond');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off
```

```
figure (9)
fill([0 25 25 0],[1.00 1.00 2.00 2.00],Unwanted,'HandleVisibility','on');
hold on;
fill([0 25 25 0],[1.00 1.00 0.00 0.00],ChilledWater,'HandleVisibility','on');
hold on;
```

```

fill([0 25 25 0],[0.00 0.00 -3.00 -3.00],Desired,'HandleVisibility','on');
hold on;
stairs(linspace(0,hours,N),y1,'Color',rand(1,3),'linewidth',2)
hold on;
ylabel("Temperature [°C]")%alt 248
xlabel("Time [h]")
legend('Unwanted','Water&Ice','Desired','location','north','orientation','horizontal');
axis([0 hours -6.00 2.00]);
hold on
set(gca,'linewidth',3,'FontSize', 30);
hold on
ax = gca;
ax.XTick = 1:24;
xticks([0 2 4 6 8 10 12 14 16 18 20 22 24])
hold on
set(0,'DefaultAxesFontName','Times New Roman');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off

figure(10)
fill([0 6 6 0],[-1 -1 2 2],off-peak,'HandleVisibility','on');
hold on;
fill([6 7 7 6],[-1 -1 2 2],standard,'HandleVisibility','on');
hold on;
fill([7 10 10 7],[-1 -1 2 2],peak,'HandleVisibility','on');
hold on;
fill([10 18 18 10],[-1 -1 2 2],standard,'HandleVisibility','off');
hold on;
fill([18 20 20 18],[-1 -1 2 2],peak,'HandleVisibility','off');
hold on
fill([20 22 22 20],[-1 -1 2 2],standard,'HandleVisibility','off');
hold on
fill([22 25 25 22],[-1 -1 2 2],off-peak,'HandleVisibility','off');
stairs(linspace(0,hours,N),x(1:N),'Color',rand(1,3),'linewidth',3)
hold on
hold on
ylabel("Switch [On/Off ]")
xlabel("Time [h]")
legend('ofp','std','pk','location','north','orientation','horizontal');
axis([0 hours -0.1 1.1]);
hold on
set(gca,'linewidth',3,'FontSize', 30);
hold on
ax = gca;
ax.XTick = 1:24;
xticks([0 2 4 6 8 10 12 14 16 18 20 22 24])

```



```

hold on
set(0,'DefaultAxesFontName','Times New Roman');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off

figure(11)
%Plot switching function
Off-peak=[0,1,0.6]; standard=[1,1,0.8]; peak=[1,0.4,0.4];
fill([0 6 6 0],[-1 -1 40 40],off-peak,'HandleVisibility','on');
hold on;
fill([6 9 9 6],[-1 -1 1000 1000],peak,'HandleVisibility','on');
hold on;
fill([9 17 17 9],[-1 -1 1000 1000],standard,'HandleVisibility','on');
hold on;
fill([17 19 19 17],[-1 -1 1000 1000],peak,'HandleVisibility','off');
hold on;
fill([19 22 22 19],[-1 -1 1000 1000],standard,'HandleVisibility','off');
hold on
fill([22 25 25 22],[-1 -1 1000 1000],off-peak,'HandleVisibility','off');
stairs(linspace(0,hours,N),POT(1:N),'k','linewidth',2)
ylabel('Cost [ZAR]')
xlabel('Time [h]')
legend('off-peak','standard','peak','location','north','orientation','horizontal');
axis([0 hours 0 20]);
set(gca,'linewidth',3,'FontSize', 30);
hold on
ax = gca;
ax.XTick = 1:24;
xticks([0 2 4 6 8 10 12 14 16 18 20 22 24])
hold on
set(0,'DefaultAxesFontName','Times New Roman');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off

Pchill=ones(1,N);

for k=1:N
    OPTIMAL_SUMMER(k)=ts*sum(Pchill(1:k).*T(1:k).*x(1:k));
end

DailyCost=OPTIMAL_SUMMER(k)

OPTIMAL_SUMMER=OPTIMAL_SUMMER(1:k)

```

% Plot Daily cost

```
figure (12)
stairs(linspace(0,hours,N),OPTIMAL_SUMMER,'k','linewidth',2)
hold on
ylabel('Net energy cost [ZAR]')%alt 248
xlabel('Time [h]')
axis([0 hours 0 25]);
hold off
```

% Plot cumulative load profile for a day

```
figure (13)
BLL1=[xlsread('JHB_DATA_5min V4.xlsx','Year load','AI98211')]
BLL=-BLL1+[xlsread('JHB_DATA_5min V4.xlsx','Year load','AI98211:AI98498')]
plot(INTVSD,BLL,'k','linewidth',2)
hold on
ylabel('Cumulative chiller [kWh]')%alt 248
xlabel('Time [h]')
axis([0 hours 0 25]);
hold off
```

% Baseline cooling and pumping 5 min interval load

```
figure(14)
plot(INTVSD,Cdib,'Linewidth',2);
xlabel(['Time [5 mins]']);
ylabel(['Baseline Load [ kWh]']);
%%legend('Baseline','Optimal','location','north','orientation','horizontal');
grid on;
```

% Proposed cooling and pumping 5 min interval load

```
figure(15)
plot(INTVSD,Cdio,'Linewidth',2);
xlabel(['Time [5 mins]']);
ylabel(['Proposed Load [ kWh]']);
%%legend('Baseline','Optimal','location','north','orientation','horizontal');
grid on;
%%title('Baseline and optimal cooling and pumping 5 min interval load');
```

% Baseline cooling and pumping 5 min cumulative load

```
figure(16)
plot(INTVSD,Cdcb,'Linewidth',2);
xlabel(['Time [5 mins]']);
ylabel(['Cumulative Baseline Load [ kWh]']);
%%legend('Baseline','Optimal','location','north','orientation','horizontal');
grid on;
```

% Proposed cooling and pumping 5 min cumulative load

```
figure(17)
plot(INTVSD,Cdco,'Linewidth',2);
xlabel(['Time [5 mins]']);
ylabel(['Proposed Load [kWh]']);
%%legend('Baseline','Optimal','location','north','orientation','horizontal');
grid on;
%%title('Baseline and optimal cooling and pumping 5 min cumulative load');
```

% Baseline vs. Proposed cooling and pumping 5 min instance load

```
figure(18)
plot(INTVSD,Cdib,INTVSD,Cdio,'Linewidth',2);
xlabel(['Time [5 mins]']);
ylabel(['Load [kWh]']);
legend('Baseline','Proposed','location','north','orientation','horizontal');
grid on;
%%title('Baseline and optimal cooling and pumping 5 min interval load');
```

% Baseline vs. optimal cooling and pumping 5 min cumulative load

```
figure(17)
plot(INTVSD,Cdcb,INTVSD,Cdco,'Linewidth',2);
xlabel(['Time [5 mins]']);
ylabel(['Load [kWh]']);
legend('Baseline','Proposed','location','north','orientation','horizontal');
grid on;
%%title('Baseline and optimal cooling and pumping 5 min cumulative load');
```

```
OPTIMAL_SUMMERD=OPTIMAL_SUMMER';
filename='DAILYCOST.xlsx';
xlswrite(filename,OPTIMAL_SUMMERD,'D2:D100')
```

%%SUMMER BASELINE AND PROPOSED COST

```
figure(18)
BLL=[xlsread('JHB_DATA_5min V4.xlsx','MNTCST','E3:E14')]
POT=[xlsread('JHB_DATA_5min V4.xlsx','MNTCST','F3:F14')]
MNT=[xlsread('JHB_DATA_5min V4.xlsx','MNTCST','G3:G14')]
plot(MNT,BLL,MNT,POT,'Linewidth',3);
xlabel(['Month-Year']);
ylabel(['Cost [ZAR]']);
legend('Baseline','Proposed','location','north','orientation','horizontal');
grid on;
```

% Plot Ambient Temperature

```
figure(19)
stairs(Tdb)
grid on
%title(['Ambient Temperature'])
```

```

xlabel(['Time [5 min]'])
ylabel(['Temperature [C]'])

% Plot Ice Bank® Temperature
figure(20)
stairs(Tst)
grid on
%title(['Ice Bank® Temperature'])
xlabel(['Time [5 min]'])
ylabel(['Temperature [C]'])

% Plot cooling load from building
figure(21)
stairs(Cd)
grid on
%title(['cooling load'])
xlabel(['Time [5 min]'])
ylabel(['Cooling load [kW]'])

% Plot building return Temperature
figure(22)
stairs(HXR)
grid on
%title(['Buiding return Temperature'])
xlabel(['Time [5 min]'])
ylabel(['Temperature [C]'])

% Plot Storage supply Temperature
figure(23)
stairs(HXS)
grid on
%title(['Storage supply Temperature'])
xlabel(['Time [5 min]'])
ylabel(['Temperature [C]'])

%Plot Building return temperature variation with ToU
Off-peak=[0,1,0]; standard=[1,1,0]; peak=[1,0,0];
HXS=HXS(1:N)
figure(24)
fill([0 6 6 0],[5 5 15 15],off-peak,'HandleVisibility','on');
hold on;
fill([6 7 7 6],[5 5 15 15],standard,'HandleVisibility','on');
hold on;
fill([7 10 10 7],[5 5 15 15],peak,'HandleVisibility','on');
hold on;
fill([10 18 18 10],[5 5 15 15],standard,'HandleVisibility','off');

```

```
hold on;
fill([18 20 20 18],[5 5 15 15],peak,'HandleVisibility','off');
hold on;
fill([20 22 22 20],[5 5 15 15],standard,'HandleVisibility','off');
hold on
fill([22 25 25 22],[5 5 15 15],off-peak,'HandleVisibility','off');
stairs(linspace(0,hours,N),HXS(1:N),'k','linewidth',3)
hold on
ylabel('Temperature [C]')
xlabel('Time [h]')
legend('off-peak','standard','peak','location','northoutside','orientation','horizontal');
axis([0 hours 5 15]);
hold on
set(0,'DefaultAxesFontName','Garamond');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off
```

%Plot of cooling load variation with ToU

```
Off-peak=[0,1,0]; standard=[1,1,0]; peak=[1,0,0];
Cd=Cd(1:N)
figure(25)
fill([0 6 6 0],[-100 -100 200 200],off-peak,'HandleVisibility','on');
hold on;
fill([6 7 7 6],[-100 -100 200 200],standard,'HandleVisibility','on');
hold on;
fill([7 10 10 7],[-100 -100 200 200],peak,'HandleVisibility','on');
hold on;
fill([10 18 18 10],[-100 -100 200 200],standard,'HandleVisibility','off');
hold on;
fill([18 20 20 18],[-100 -100 200 200],peak,'HandleVisibility','off');
hold on;
fill([20 22 22 20],[-100 -100 200 200],standard,'HandleVisibility','off');
hold on
fill([22 25 25 22],[-100 -100 200 200],off-peak,'HandleVisibility','off');
stairs(linspace(0,hours,N),Cd(1:N),'k','linewidth',3)
hold on
ylabel('Cooling load [kW]')
xlabel('Time [h]')
legend('off-peak','standard','peak','location','northoutside','orientation','horizontal');
axis([0 hours -100 200]);
hold on
set(0,'DefaultAxesFontName','Garamond');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off
```

```
%Plot ITES temperature variation with ToU
Off-peak=[0,1,0]; standard=[1,1,0]; peak=[1,0,0];
Tst=Tst(1:N)
figure(26)
fill([0 6 6 0],[-5 -5 10 10],off-peak,'HandleVisibility','on');
hold on;
fill([6 7 7 6],[-5 -5 10 10],standard,'HandleVisibility','on');
hold on;
fill([7 10 10 7],[-5 -5 10 10],peak,'HandleVisibility','on');
hold on;
fill([10 18 18 10],[-5 -5 10 10],standard,'HandleVisibility','off');
hold on;
fill([18 20 20 18],[-5 -5 10 10],peak,'HandleVisibility','off');
hold on;
fill([20 22 22 20],[-5 -5 10 10],standard,'HandleVisibility','off');
hold on
fill([22 25 25 22],[-5 -5 10 10],off-peak,'HandleVisibility','off');
stairs(linspace(0,hours,N),Tst(1:N),'k','linewidth',3)
hold on
ylabel("Temperature [C]")
xlabel("Time [h]")
legend('off-peak','standard','peak','location','northoutside','orientation','horizontal');
axis([0 hours -5 10]);
hold on
set(0,'DefaultAxesFontName','Garamond');
set(0,'DefaultTextFontSize',30);
set(0,'DefaultAxesFontSize',30);
hold off
```