BOTSWANA INTERNATIONAL UNIVERSITY OF SCIENCE & TECHNOLOGY

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Department of Mechanical, Energy and Industrial Engineering

DESIGN, MODELLING, AND SIMULATION OF SOLAR PHOTOVOLTAIC DRIVEN AIR-CONDITIONING SYSTEMS FOR HERBARIA COLLECTION IN BOTSWANA

by

TABOKA LAME BAKANG MOTLHABANE

Student ID number: 14001768

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Supervisor(s): Professor Pradeep Sahoo & Professor Tobias Bader

Department of Mechanical, Energy, Industrial Engineering

Faculty of Engineering and Technology, BIUST

E-mail Address: sahoop@biust.ac.bw & tobias.bader@th-deg.de

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Abstract

The demand for cooling has grown exponentially over the past century to meet economic development, availability, comfort and social needs, accounting for over 10% of the global electricity consumption and growing. Rising global temperatures have also contributed to the growing need for cooling in buildings. Cooling, is a very energy-intensive process that can account for 20% to 75% of a building's energy, depending on the building use. Solar photovoltaic (PV) driven air-conditioning offers a great cost-effective and environmental alternative for adoption in both residential and non-residential buildings to offset grid electricity, particularly in countries with high irradiation, such as Botswana.

This thesis explores the potential of a grid-assisted solar PV air-conditioning system for Peter-Smith Herbarium at the University of Botswana (PS-HUB) Okavango Research Institute (ORI) in Maun, Botswana. Tourism and economic development in the Okavango region have contributed to the environmental strain and the loss of botanical species, some unique to the area and the world. The herbarium plays a critical role in collecting and preserving botanical collections for reference and research with data dating over 100 years. The herbarium requires special thermal comfort settings in terms of temperature and humidity to preserve the botanical collections and thus requires huge amounts of energy for cooling.

At the start of this study, the thermal comfort demand could not be substantiated in the herbarium storage. In fact, with recurrent power interruptions, and an inadequately designed air-conditioning system housed in a prefabricated structure, PS-HUB experiences severe challenges in keeping its primary operation mandate. This bares the risk that valuable plant specimen with immense importance faces severe deterioration over in time, which would be a great loss.

Therefore, this study explores the design, model, simulate and evaluation of the potential of a solar PV variable air volume (VAV) air-conditioning system in an energy-efficient herbarium building in Botswana using the DesignBuilder software and PVsyst. The PS-HUB is a case study for the research. Due to the herbarium's specific needs, it operates throughout the day and year, in attempts to maintain a constant herbarium temperature of $16°C$. The research involved design of the building envelope and dynamic annual cooling load calculation using a typical meteorological year (TMY), and a supply air temperature of 14°C to meet the specified temperature needs. The variable-air- volume HVAC system was designed with a system rating of 30 kW to meet these needs.

The results of the study showed that the HVAC system accounted for 68.9% of the building's total electricity at 293 509.60 kWh annually. To offset the grid electricity, a 175.1 kWp nominal power rated PV system requiring 416 modules to match the required power, covering an area of 928 m^2, which spanned the roof and carport areas to meet the HVAC system annual needs. The PV system produced a total of 329 535.61 kWh annually to meet the herbarium HVAC electrical demand, of which the extra electricity produced was fed into the grid at a fixed feed-in tariff of 0.45BWP/kWh determined by the Botswana Power Corporation.

An economic assessment using PVsyst found that for an installation priced with average solar PV prices in Botswana totalled to be 1 014 841.00 BWP, with annual operating costs of 33 000 BWP/year. With self-project financing, the project is estimated to have recouped its initial investment within 8.8 years. The PV system has able to meet the HVAC electrical load.

Keywords: photovoltaic cooling; design; energy modelling; simulation, efficient buildings

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On a personal note, I would like to thank my parents, Dr and Mrs Motlhabane, my sisters and friends for the continual support, patience, and inspiration.

List of Abbreviations

AC	Air-Conditioning
AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
BMS	Building Management System
BOM	Bill of Materials
BPC	Botswana Power Corporation
CARNOT	Conventional And Renewable eNergy systems Optimization Toolbox
COP	Coefficient of Performance
DBT	Dry Bulb Temperature
DC	Direct Current
FiT	Feed-in Tariff
GHG	Green House Gas
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
MATLAB	MathWorks high-performance language software package for technical computing
NOCT	Nominal Operating Cell Temperature
PSH	Peak Sunshine Hours
PV	Photovoltaic
RETs	Renewable Energy Technologies
STC	Standard Testing Conditions
THB	Thermo Hydraulic Bus
TRY	Test Reference Year
VCC	Vapour Compression Cycle
WDB	Weather Data Bus
WDT	Wet Bulb Temperature

Nomenclature

A	Area, m^2
C_p	Specific Heat Capacity
κ	Thermal Conductivity
I	Electric Current, *Amps*
LCOE	Levelized Cost of Electricity
ρ	Density
$\dot{Q}$	Heat transfer energy, *W*
V	Electric Voltage

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Chapter 1: Introduction

1.1 Research Background

The demand for energy service provision has grown significantly over the past century, subsequently causing a rise in atmospheric greenhouse gas (GHG) emissions, resulting in one of the biggest challenges the present and future generations faces; climate change (Edenhofer *et al.*, 2011). Key drivers contributing to the global increase in energy demand include economic growth, improved access, and demographic factors such as population growth and urbanisation (International Energy Agency, 2018).

The demand for cooling and air-conditioning has also grown exponentially over the past century to meet current social and economic development needs. As an alternative to conventional air-conditioning systems and means to decarbonise power generation by reducing space air-conditioning related GHG and CO2 emissions, solar cooling can be used to reduce the peak energy demand for cooling in non-residential buildings (Daut *et al.*, 2013). Principally, cooling is required mainly during the hottest hours of the day, when solar insolation, irradiation and solar electricity production are at their highest (Laine *et al.*, 2019). The exploitation of solar energy has become increasingly popular thanks to the potential saving on energy costs and its widespread environmentally friendly benefits (Chesi *et al.*, 2013; Campaniço *et al.*, 2019).

Similarly, due to the increased global activity, plant biodiversity is constantly threatened with extinction due to economic and human activity, population growth and the changing climate, which is of great global concern. Areas rich in biodiversity, such as the Okavango Delta, face threats of significant degradation (Mladenov *et al.*, 2007); hence plant species need to be well documented and their information preserved in herbaria for future reference. These provide a reference point for present and future research (Bahei-El-Din and Hassan, 2016; James *et al.*, 2018; Lang *et al.*, 2019). Herbaria provide otherwise scarce long-term data crucial to track ecological and evolutionary changes over these centuries of global change (Lang *et al.*, 2019) and are expected to continually be a significant part of research and historical biodiversity reference point.

The Okavango Research Institute (ORI) hosts one of the very few herbaria in Botswana and Southern Africa, the Peter-Smith Herbarium (PSHUB). The herbarium houses approximately 30,000 specimens and an estimated variety of more than 16,000 species from all over Botswana, dating back over 100 years (Murray-Hudson, Madome, *et al.*, 2018). The majority of the species at PS-HUB are native to the northern part of Botswana, particularly around the

Okavango Delta, a UNESCO world heritage site, with some samples being the last remaining samples of their kind. However, many species are no longer found at their original documented coordinates and are also threatened by extinction in their natural habitats and the herbarium if changes with the current conditions.

The current herbarium collection is currently housed in a prefabricated building and is under threat of deterioration. The herbarium, which requires controlled temperature and humidity conditions, also functions as a meeting room with frequent foot traffic and the inability to monitor its required climatic environment. The specimen stored in the herbarium is also threatened by insect and rodent infestation, increasing the collection's deterioration risk. Given the rarity and value of the specimen in the herbarium, it must be preserved and stored fittingly.

1.2 Research Problem

The problem statement that justifies the purpose of the research is as follows:

“The room air conditioning at the Peter-Smith herbarium at the University of Botswana (PS-HUB) is currently not controlled and sustained to temperature and humidity levels as required for preservation in herbaria. The current conventional air-conditioning system presents an energetically inefficient solution contributing significantly to greenhouse gas emissions. In addition, unfettered human traffic into the herbaria poses a risk of damaging the stored rich botanical national treasure dating back over a hundred years.”

1.3 Research Aim

The research aims to:

“Evaluate the potential and performance of a solar photovoltaic (PV) powered air-conditioning systems and building energy model for the Peter Smith Herbarium at the University of Botswana ORI campus using an experimental proposed design of the building under semi-arid climatic conditions.”

1.4 Objectives

The purpose of this research is to address the following objectives:

- Conduct a comprehensive literature review of current and past studies on energy-efficient building principles for the southern hemisphere and solar PV cooling systems.

- Design building model to match floor plan requirements of a proposed building by the ORI management using DesignBuilder. Define building material, direction, design, equipment, occupancy and operational parameters of the overall building energy use and herbarium cooling load.
- Conduct building simulations to evaluate the energy performance of the building, cooling load required to maintain the herbarium at the recommend temperature and energy consumption patterns.
- Model, size and simulate the solar PV system to effectively meet the air-conditioning system load with grid-connection for the herbarium.
- Compile simulation results and report findings.

1.5 Thesis Structure

Chapter 1 outlines the research background carried out, the research problem and the aim. It presents the objectives and research strategies employed.

Chapter 2 presents a comprehensive review of relevant literature and market research on solar PV cooling systems. It also examines building principles commonly used in Botswana and energy-efficient principles, analyses standards used in herbaria, and reviews grid-connected solar PV cooling systems projects.

Chapter 3 the research methodology, the research background, descriptions, site location, considerations and key performance indicators to the research's success are also considered. The validation and verification of the software used compared to a previous study to ensure proper software functionality. An overview of the software used, design of the model, system sizing and other factors central to the system functionality. It also highlights the planned outcomes of the simulations.

Chapter 4 presents the results and discussions of the building and herbarium simulation, solar PV system, bill of quantities and financial analyses of the solar PV systems powering the air-conditioning system.

Chapter 5 conveys the conclusion from the research and results presented in the thesis and outlines future work.

Appendix presents essential information which aided to the research, additional results and a detailed overview of the MATLAB/Simulink Carnot toolbox model, the initial software used to build the model. Unfortunately, the software used was changed to DesignBuilder due to technical problems. However, a detailed model was modelled and completed.

1.6 Research Strategy

The overall research strategy is displayed below, exhibiting in sequential order steps taken to fulfil the research objectives.

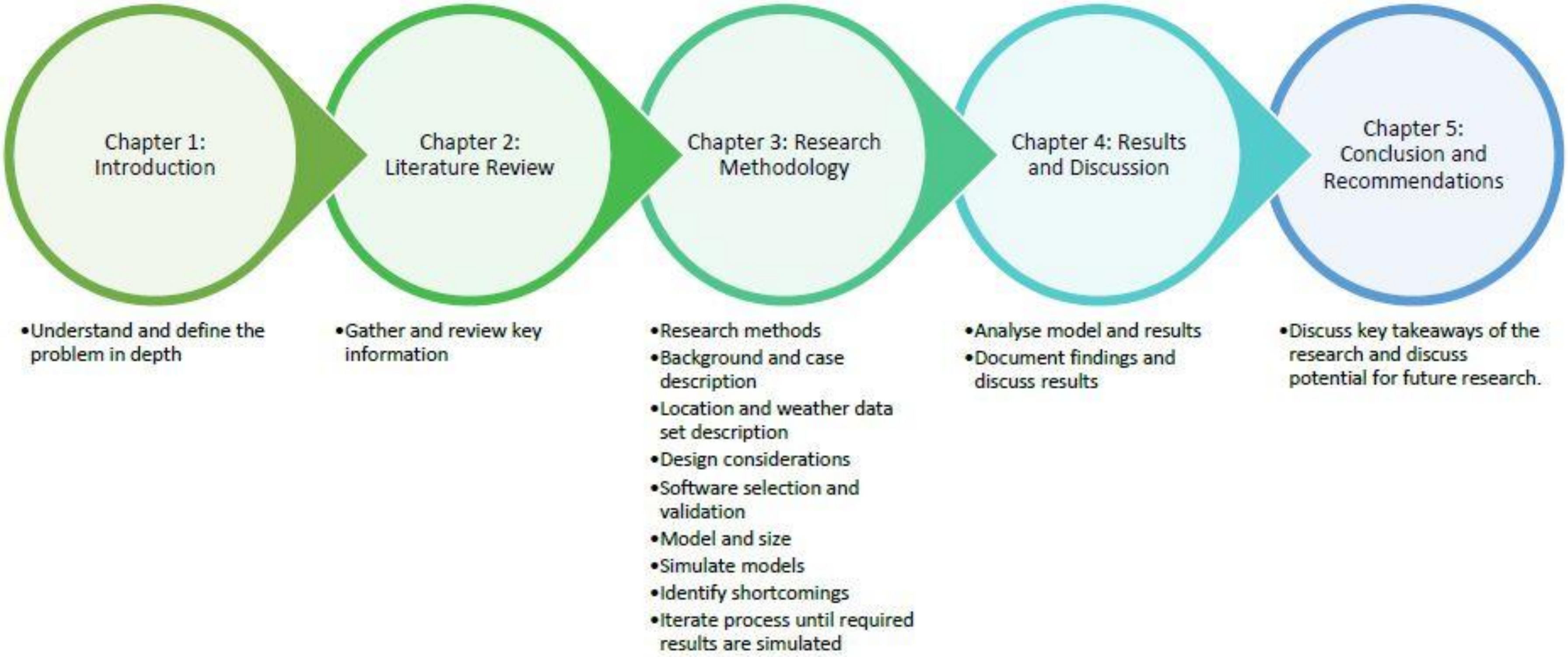

Figure 1 Research Strategy

1.7 Research Knowledge Acquired and Outputs

The following training and programs were carried out to realise the objectives of the study.

- Exchange trip to the Technische Hochschule Ingolstadt (THI) University in Ingolstadt, Germany, through the Academic Initiative for Renewables (AIR), to gain considerable knowledge on renewables, solar cooling and the use of the CARNOT toolbox. The trip also afforded a look into solar cooling and other major renewable energy projects.
- Invited to participate in the International Energy Agency (IEA) Energy Efficiency Training Week for Emerging Economies in Sub-Saharan Africa, in Pretoria, South Africa. Attended the buildings track training aimed at equipping professionals with policy and project development skills for energy-efficient and net-zero buildings for Sub-Saharan Africa. Contributed with country knowledge to the GlobalABC Roadmap for Buildings and Construction for Africa.
- Attended the first German Training Week on PV Project Development organized by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). The training focused on pre-and post-project development for solar PV projects in Botswana and equipping citizens with the necessary skills.
- Also attended a solar PVsyst training organised by the Jamataka solar project team for in-depth understanding and gaining expertise on using the PVsyst software.
- In addition, paid-for courses on Udemy, YouTube and textbooks to gain supplementary knowledge.

The additional quest for knowledge stated above helped in shaping this project. Research outputs include:

- Poster presentation: BIUST RDAIS conference 2019: Review of solar cooling and air-conditioning.
- Conference paper presentation: ICRAME 2022. NIT SILCHAR, India: Design of Herbarium Unit Air-Conditioning System in Botswana with DesignBuilder Software.

Chapter 2: Literature Review

2.1 An Overview of the Energy Landscape in Botswana

The Republic of Botswana is a landlocked country located at the centre of the Southern African region, with a landscape defined by the Kgalagadi desert and the Okavango Delta. Bordered by South Africa, Zimbabwe, Zambia, and Namibia, it has a population of approximately 2.3 million people (World Bank, 2019).

Botswana's primary energy sources are coal, wood, liquefied petroleum gas (LPG), diesel and petroleum (UNDP, 2012). According to an Energy Profile of Botswana by IRENA, the total electricity generation in 2018 was 3502 GWh, of which 3497GWh was attributed to non-renewable sources, while solar energy contributed 5GWh to the total generation (IRENA, 2019). The country operates two coal-fired power plants, Morupule A and Morupule B, with a collective generation capacity of 732MW. However, both operate at a capacity lower than the planned generation capacity. It also has two diesel power plants in Matshelagabedi and Orapa, operating at 70 and 90 MW. Electricity is required all year round, for residential and non-residential buildings and properties and industry, mainly for lighting, heating water, powering air-conditioning (AC) units, and cooking and powering machinery. However, Botswana cannot sufficiently cater to all its energy needs and imports a significant portion of its electricity through the Southern Africa Power Pool (SAPP), mainly from South Africa.

In 2020, the Integrated Resource Plan (IRP) was launched, in line with Vision 2036 and the 11th National Development Plan (NDP) to diversify the national energy mix, reduce the country’s carbon footprint and increase its generation capacity for self-sufficiency and export potential.

Botswana has abundant renewable energy potential, particularly in solar, which remains largely untapped. The country receives over 3,200 hours of sunshine per year, and an average global irradiation of 21 MJ per m^2/day throughout the country, one of the world's highest levels of solar irradiation (GET.invest, 2020).

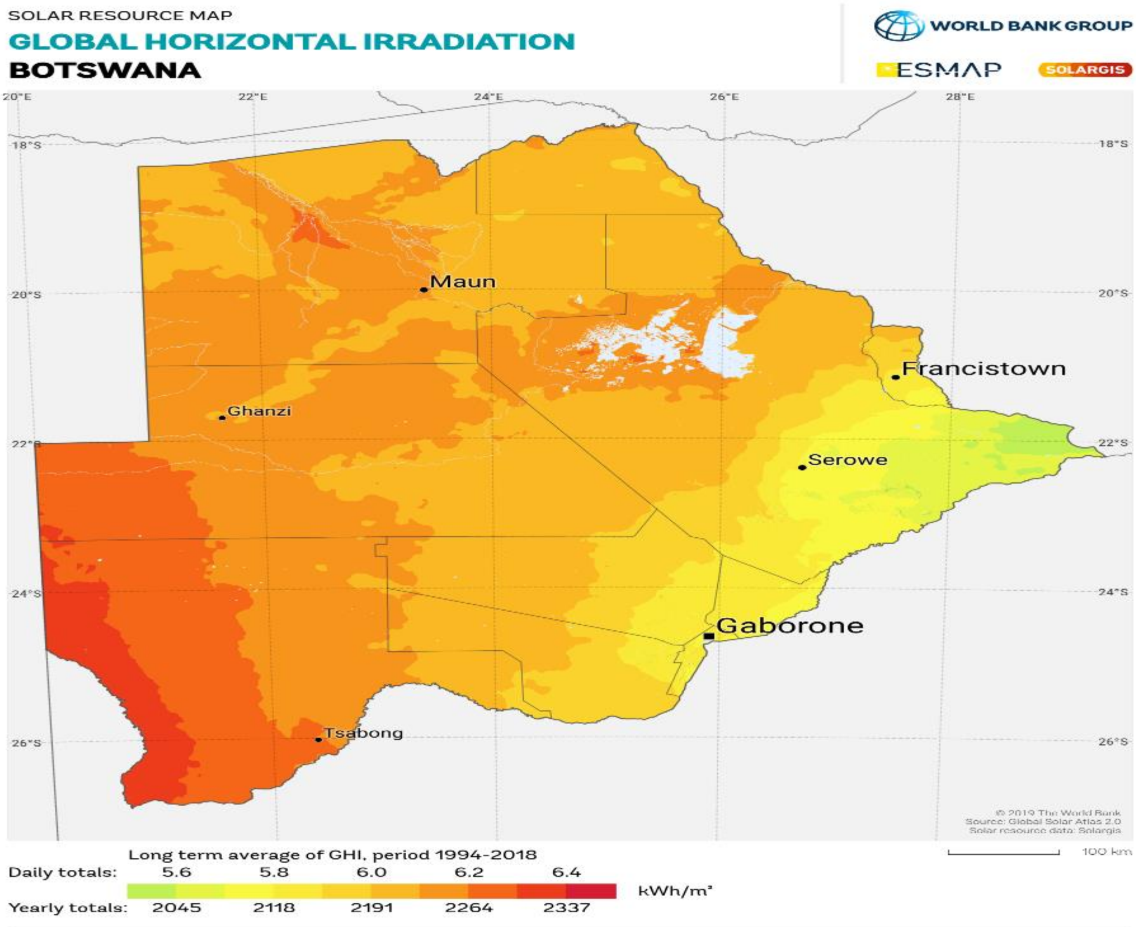

Figure 2 Solar Global Horizontal Irradiation map of Botswana (Global Solar Atlas, 2021)

2.2 Solar Photovoltaic Energy Use in Botswana

Botswana has a high potential of adopting and tapping into solar energy (Sustainable Energy for All and UNDP, 2015). However, its adoption has been relatively low owing to a few factors such as limited knowledge, previously high investment costs and limited government interventions supporting solar PV adoption, among many other factors.

Mbaiwa *et al.* (2018) examined the use and adoption of energy in the tourism sector in Botswana, particularly in the north-western part of the country. The Okavango Delta, which receives approximately 150,000 tourists annually, has experienced growth in tourist numbers and facilities, infrastructure, aircraft operations, and tourism services, resulting in increased energy consumption. While fossil fuels have predominantly been used in lodges and camps, there has been a recent drive towards more sustainable and renewable energy sources to achieve sustainable and environmentally friendly tourism.

A few solar PV installations have also been carried for industrial purposes, such as the 2.2MW rooftop solar plant in Airport Junction Mall, Gaborone, the 1.3MW solar farm in Phakalane and 200kW Botho University solar installation, to name a few. Furthermore, rural electrification using solar has also been carried out in villages like Mmokolodi (Kiravu *et al.*, 2015) and Jamataka. In addition, the adoption of solar PV rooftop systems for feeding into the grid on a small scale for residential and small to medium organisations has recently been approved by the Ministry of Mineral Resources, Green Technology and Energy Security through the Rooftop Guidelines Programs.

2.3 Overview of Solar Cooling Technology

Ever-increasing comfort requirements in buildings have resulted in a raised cooling demand and a growing cooling market. The increasing demand for air-conditioning has led to a dramatic increase in peak electricity demand globally and an increase in the cost of electricity.

Comfort, a leading factor in air-conditioning usage, can no longer be viewed as a luxury but a necessity. As the number of conventional vapour compression cooling machines grows, so do carbon dioxide (CO_2) and greenhouse gas emissions. An obvious counter to this trend is to use the same energy for the generation of cooling that contributes to creating the cooling demand—solar energy (Mugnier, 2016).

The utilisation of solar power for cooling is categorised in two ways, through the use of solar photovoltaic (PV) or solar radiation to generate heat which then drives a thermal chiller unit (Oppelt *et al.*, 2013).

Figure 3 below provides an overview of the different solar cooling approaches.

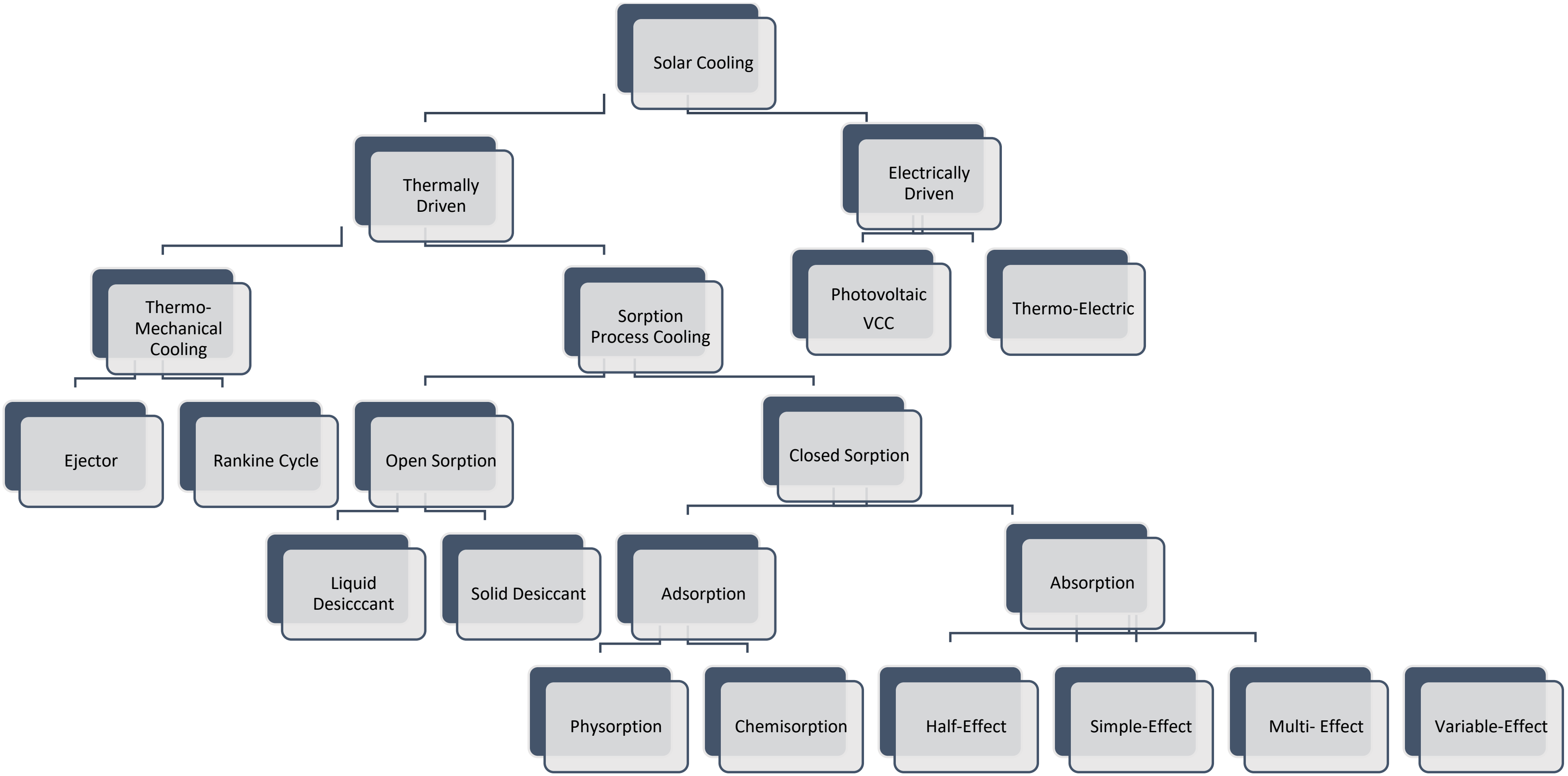

Figure 3 Schematic of Solar Cooling Technologies

In the first case, solar PV panels generate electricity, which drives a conventional electric compression system. In contrast, for solar thermo-electric cooling systems, electrons are used as a heat carrier, extracting heat from cooling loads instead of refrigerants, using a temperature gradient through a phenomenon called the reversed Seebeck or Peltier effect (Sarbu and Dorca, 2018).

In the second case, thermal solar collectors generate hot water, which drives a thermal refrigeration cycle. In this case, the hot water produced in periods without cooling can be used for building heating and domestic hot water needs, most notably during the winter. However, cooling systems driven by solar thermal collectors, compared to PV solar collectors, are more complex, less standardised, less developed and currently more expensive than PV systems (Oppelt *et al.*, 2013).

Various methods can be employed to capture the solar energy which are suitable for thermal cooling.

- Flat Plate Collectors (FPCs),
- Evacuated Tube Collectors (ETCs),
- Parabolic Trough Collectors (PTC) and
- Fresnel Collectors (FCs).

2.4 Solar Photovoltaic Cooling

Unlike solar thermal cooling, solar PV cooling has historically not been as widely researched and adopted due to its previously low PV efficiencies and high initial investment cost, which were a drawback of their adoption (Ge *et al.*, 2018). However, because of the improving PV efficiencies and sharp fall in PV module price, the initial investment in PV cooling systems has decreased over the years. The main advantage of PV cooling systems consists of their practical and simple design (Allouhi *et al.*, 2015) and their superior capacity to stand out among other solar cooling systems.

Solar PV cooling systems can either be off-grid or on-grid system configurations. In off-grid/ stand-alone systems, a battery needs to be used to cover periods with low or no sunshine and where grid-connected electricity is not available. Off-grid PV systems can be used with minimal oversizing for smaller applications and gadgets as they do not require a large current. In comparison, larger applications such as air-conditioners may require oversized inverters and batteries to cater for the start-up load (high starting current/surge current) (Howley and Fleischer, 2015). However, in systems connected to the grid, battery storage makes no technical or economic sense. The power from the grid offers a constant, reliable supply for periods with low irradiation. The Okavango Research Institute, where the herbarium is hosted, has an accessible grid connection making it logical to have a grid-connected PV cooling system.

Figure 4 below shows a grid-connected PV solar cooling system with a rechargeable battery bank for extra backup.

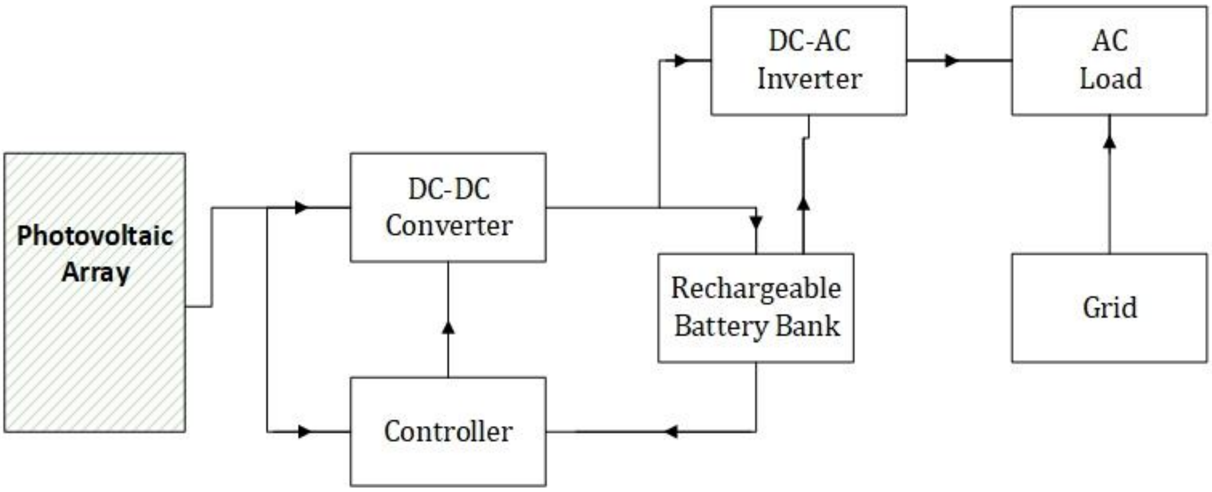

Figure 4 Block diagram of the PV-AC system

The block diagram above displays the configuration of a solar PV-AC cooling system. Depending on the power available from the PV array, the system can switch to grid power.

However, in off-grid applications, the solar air conditioner needs to be powered by a stand-alone PV system with battery storage for backup energy needs during cloud cover or at night, as shown in Figure 5. The system consists of PV panels, a controller, an inverter, a lead-acid battery bank and an air conditioner (Li *et al.*, 2015).

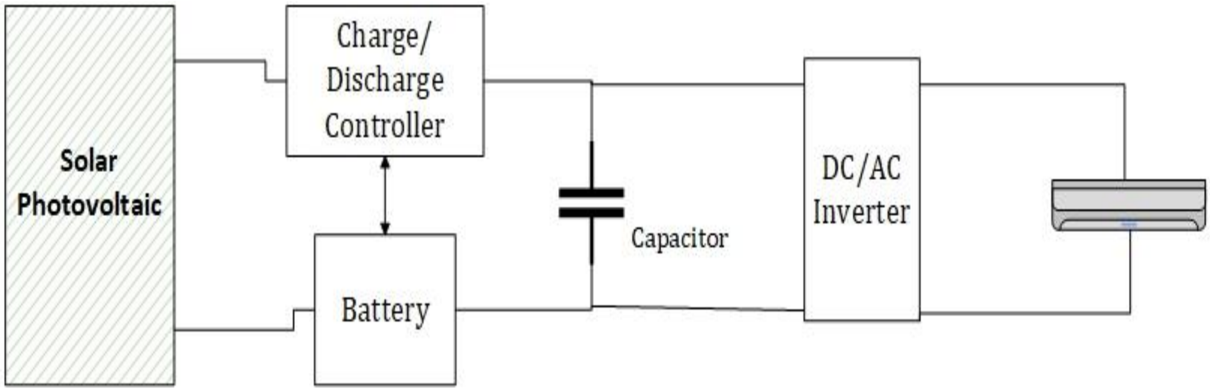

Figure 5 Schematic diagram of solar air conditioning system

When designing a solar PV air-conditioning system, it is essential to consider the following factors: the collection of meteorological data- of a typical meteorological year (TMY) and processed data solar radiation data (hourly, monthly, and annual values); cooling load calculations- calculations reliant on room/ load size, type of building/ space, room use, external weather conditions and sizing of the air conditioning system; and the design and sizing of the photovoltaic system (Tsoutsos *et al.*, 2010; Daut *et al.*, 2013).

Solar PV cooling systems can be designed to meet different demands, including a small PV cooling system for room (e.g., split room AC), a small central PV cooling system (e.g., variable refrigerant flow AC), and a large central PV cooling system for commercial use (e.g., centrifugal PV chiller) (Ge *et al.*, 2018).

2.5 Review of Solar PV Air-Conditioning Installations with Grid-Connection

In an experimental study, Aguilar, Aledo and Quiles (2017) analysed the performance of a photovoltaic powered air-conditioner supported by the grid in Alicante, Spain. The air-conditioning unit used in the experiment had a nominal cooling capacity of 3.52kW with an EER of 4.09 cooling operation to condition an office with a size of 35m^2 for 12hours daily usage (from 8 am to 8 pm). Three PV panels with a total peak power of 705Wp are connected directly to the unit at 24V_{dc}. The high DC voltage was then connected internally to the DC point in a frequency converter, where the energy from the grid and the PV panels are summed. The grid energy is absorbed once PV energy levels are insufficient.

The experimental study was focused on the summer months to establish seasonal results in cooling conditions. The technical characteristics of the air-conditioner and photovoltaic panels used are as follows.

Table 1 Technical characteristics of the air-conditioner

Kaysun suite solar 3D	Unit	Min.	Nom.	Max.
Cooling capacity	kW	0.95	3.52	4.15
Cooling power supply	kW	0.19	0.86	1.18
EER	-		4.09	
Refrigerant	-	R410A		

Table 2 Technical Characteristics of the photovoltaic panels

Eurener 235	Unit	Nom.
Nominal Power, $P_{N,PV}$	W	235
Panel surface area, A_{PV}	m^2	1.67

Efficiency, $Eff,_{PV}$	%	13.74
Short circuit current, I_{sc}	A	8.25
Open circuit voltage, V_{OC}	V	37.08
Nominal current, $I_{N,PV}$	A	7.66
Nominal voltage, $I_{N,PV}$	V	30.01

The air-conditioner's solar power consumption is calculated as:

$$P_{PV,UNIT} = I_{PV,UNIT} * V_{PV,UNIT} \quad (1)$$

Where the total power consumption of the air-conditioner is derived from the following sum:

$$P_{TOT,UNIT} = P_{PV,UNIT} + P_{GRID,UNIT} \quad (2)$$

The power is taken from the grid, P_{GRID} Was measured using a wattmeter. The total energy consumed by the unit is calculated as follows:

$$E_{TOT,UNIT} = E_{PV,UNIT} + E_{GRID,UNIT} \quad (3)$$

Where

$$E_{PV,UNIT} = \sum P_{PV,UNIT} * \Delta t \quad (4)$$

$$E_{GRID,UNIT} = \sum P_{GRID,UNIT} * \Delta t \quad (5)$$

The solar contribution, which is the ratio between the energy produced by the solar panels and the total energy consumed by the equipment, was calculated as:

$$SC(\%) = 100 * \frac{E_{PV,UNIT}}{E_{TOT,UNIT}} = 100 * \left(\frac{E_{PV,UNIT}}{E_{PV,UNIT}+E_{GRID,UNIT}}\right) \quad (6)$$

The annual results showed that the unit fulfilled a cooling demand of 3478.4 (99.4 kWh/m^2), taking in 239.3kWh (6.8 kWh/m^2) of electricity from the grid. The solar contribution obtained in cooling mode from May to October was 64.5%, while the production factor was 65.1%.

Li *et al.* (2018) conducted a study to comprehend the performance of a grid-connected, PV-powered, bi-directional central air-conditioner for an office building with an area of 14220 m^2 cooled using a centrifugal water chiller in Southern China. The PV array was installed on the building roof at a tilt angle of 20° and an azimuth angle of 10° southwest. The capacity of the PV system was designed to be greater than the chiller rated power to match the energy production with consumption. As a result, the PV array offered a maximum power rating of 390.5kW$_{p,}$ while the cooling power of the chiller was rated at 362kW.

Table 3 Technical characteristics of the photovoltaic modules

Parameters	Units	Value
Material type	-	Polycrystalline silicon
Maximum power	W_p	250
Maximum power voltage	V	30.4
Maximum power current	A	8.24
Open-circuit voltage	V	38.4
Short-circuit current	A	8.79
Efficiency (STC)	-	15.3
Temperature coefficient of P_{max}	%/ °C	-0.45
Temperature coefficient of V_{oc}	%/ °C	-0.33
Temperature coefficient of I_{SC}	%/ °C	0.06

Table 4 Technical characteristics of the air-conditioning system

Name	Parameter	Number
Direct-driven inverter water chiller	Rated power: 362kW, Rated cooling capacity: 2461kW, Rated COP: 6.80, IPLV: 9.56, Refrigerant: R410A	1
Cooling water pump (fixed frequency)	Flow rate: 720m^3/h, Lift: 28m, Rated power: 75kW	2 (one backup)
Chiller water pump (fixed frequency)	Flow rate: 552m^3/h, Lift: 34m, Rated power: 75kW	2 (one backup)
Cooling tower	Flow rate: 360m^3/h, Rated power: 18.5kW	2

Driven by direct current (DC) from the PV array and alternating current (AC) from the utility grid, the power management box containing an inverter and converter controls the chiller's power flow.

The load power, P_L, and the load energy, E_L, used by the air-conditioner are calculated as:

$$P_L = P_{PV} - P_G \quad (7)$$

$$E_L = E_{PV} - E_G \quad (8)$$

The performance of the solar PV air-conditioning system is evaluated using an index called the solar fraction, SF.

$$SF = \frac{E_{PV\_L}}{E_L} = \frac{E_L - E_N}{E_L} = 1 - \frac{E_N}{E_L} \quad (9)$$

E_{PV_L} is the portion of PV generated electricity that is used to drive the air-conditioning system. At the same time, SF is the ratio of the electrical energy provided by solar energy to the total electrical energy used to drive the air-conditioner.

The performance analysis was carried out in three typical weather pattern days: sunny, cloudy & rainy days, together with a monthly and year performance analysis. Operating for approximately eight months in the year, the PV generated electricity exceeded the required cooling load for two months (September and November), with other months requiring grid assistance. The maximum generated PV electricity was in August at approximately 43000kWh.

In a techno-economic analysis, Opoku, Mensah-Darkwa and Samed Muntaka (2018) studied the performance of a hybrid solar PV-grid powered air-conditioner for daytime cooling in Kumasi, Ghana. The office floor area measured at 30m^2, in a building with three sides sharing walls with adjacent offices and a set air-conditioning temperature of 20°C. The solar PV system to power the daytime cooling was rated at 1040Wp, with a 200Ah, 24V battery configuration for an air-conditioning unit with a nominal cooling capacity of 2.5 kW and power consumption of approximately 1.19 kW. The tables below show the size of the components used and the PV module specifications.

Table 5 Size of System Components

Component	**Size**
Solar Panels	1040 Wp
Inverter	2.0 kVA (1.6 kWac output)
Battery	200 Ah, 24 V system, deep cycle
Utility Grid	230V AC, 50Hz

Table 6 Solar PV module specifications

Maximum power	260 Wp
Maximum power voltage (V_{mp})	31.4 V
Maximum power current	8.44 A
Open circuit voltage (V_{oc})	38.6 V
Short circuit current (I_{sc})	9.03 A
Nominal operating cell temperature	45 ± 2°C

Maximum system voltage	1000 V_{DC}
STC conditions	1.0 kW/m^2; 25°C; AM 1.5

The annual energy generation of the PV system was around 1211kWh, with the maximum monthly output occurring in April at approximately 125kWh and minimum in August at around 88kWh.

Aguilar, Quiles and Aledo, (2014) also conducted an experimental analysis for a grid and photovoltaic connected hybrid air-conditioner. An inverter heat pump with a nominal cooling capacity of 3.52 kW and heating capacity of 3.81 kW was connected to three 235Wp solar PV panels. The system was conditioned to operate for 12 hours, from 8 am to 8 pm. The total power consumed by the air-conditioner was the sum of the power from the electrical grid and that produced by the PV panels. For a single day in June, the maximum power produced by the PV panel was approximately 500 W, while for a day in February, it was approximately 610 W.

2.6 Overview of Building Construction in Botswana

Buildings in Botswana are mainly constructed using bricks, with inner walls are made up of one layer of 115 mm bricks and outer walls of one layer of 115mm bricks, which means a total thickness of 230 mm, with a thin layer of cement plastering. Alternatively, thicker hollow cement bricks, clay or sand-oven baked bricks are used. Building wall structures in Botswana are usually non-insulated.

The roof is the only part of the building structure that is usually insulated. The roofing type can range from clay tiled, corrugated steel or flat cement roofing depending on the building use. The Botswana Building Draft Regulations 2007 detail specific requirements to be met depending on the building construction type and use (Ministry of Works and Transport and Wanjohi Consulting Engineers, 2007).

Figure 6 Building construction in Botswana

Ngowi (2010) examined the possibility of incorporating a hybrid approach to house construction using traditional and industrialised housing construction concepts in Botswana. The study, based in the village of Tsabong, examined four different housing styles, namely; mud walls with the thatched roof supported on the wall or poles independent of the wall; vertical poles with mud in-fill supporting a thatched or corrugated iron sheet roof; sun-dried brick wall supporting thatched/corrugated iron sheet roof and; concrete brick wall supporting thatched corrugated iron sheet or clay tile roof. Their investigation concluded that both traditional and industrial means of construction would continue to play an important role in housing development. However, aspects of the durability of structures and management of resources can be transferred from the industrialized housing system to the traditional system.

Douglass and Frew (2005) assessed a low-energy building structure for a predominantly hot and dry climate three years post-construction. The Botswana Technology Centre (BOTEC) building, now known as the Botswana Institute for Technology Research and Innovation (BITRI) headquarters in Gaborone, was designed and built using low-energy architecture, thermal comfort design and post-occupancy performance. The study results concluded that the building was performing reasonably well but could improve if certain modifications such as detailed thermal analysis, equipment calibration and maintenance were addressed.

Draft building construction regulations, conservation of energy in buildings technical guidelines and energy efficiency building design guidelines (Groth, Department of Energy and Ministry of Minerals, 2007) in Botswana exist and are yet to be enacted into legislation.

2.7 Climate Controlled Rooms

The specimen in herbaria are stored and preserved in herbarium cabinets which protect the specimen from light, insects, rodents, dust and water. Also crucial to the safekeeping of the specimen is a low temperature to avoid degradation of the stored samples. A climate or environmentally controlled room allows for researchers to study stored specimens in a thermally controlled space without potentially damaging them due to harsh temperature and humidity settings.

Figure 7 Herbarium Cabinets (South West Solutions Group, 2020)

Herbarium design standards exist to guide the maintenance of appropriate and recommended room settings. In 2012, Brown University's herbarium thought to include more than 100,000 specimens of plants, fungi and other natural treasures dating back to 1818, moved into a new herbarium space that can meet the temperature needs required of a herbarium (Orenstein, 2012).

Drobnik (2016), in a paper on modern techniques of herbarium protection, highlight that to protect herbaria against pests and mould, low temperatures must be maintained and monitored at 18 °C to prevent the complete metamorphosis of all herbarium insects or chilled to as low as 13 °C to prevent even the hatching of insects from eggs.

In addition, Bromberg (2020), in a recent and in-depth review of best practices for the conservation and preservation of herbaria, states that some of the main threats to herbaria may be damaged and destroyed by water and fire, fluctuations in temperature and relative humidity, light, pollutants, pests and improper storage. Bromberg further states that specimens should be stored in secure and climate-controlled buildings, with a stable temperature of about 20°C and relative humidity of 50% and that fluctuations in temperature and relative humidity can damage fragile plant specimens. Also, the storage facility's central HVAC (heating, ventilation and air conditioning) system should be set up with appropriate filters to reduce and control the volume of dust and other pollutants in the environment.

In Peru, the CIP institute has a large herbarium, which is invaluable because many of them were collected before their habitats disappeared due to population pressures affecting various flora and fauna in the world. According to Vargas (no date), “the herbarium has an environmentally controlled area with monitoring (24 hours a day) for temperature control (19-21°C) and relative humidity (45-50%) of which the specimens are placed in a cold chamber at -20 ° C for two days to kill the insects and fungi before storage”.

2.8 Modelling methods for HVAC systems

HVAC system modelling is an artificial reflection of indoor thermal behaviour due to air-conditioning unit operation (Homod, 2013). Generally, three types of modelling approaches are used: data-driven, physics-based, and the grey box approach.

The data-driven approach is also referred to as black-box or inverse approach. In this approach, system performance data is collected under normal use or real practice. Then, a relationship between the input and output variables is established using mathematical techniques, i.e. statistical regression or artificial neural network (ANN) (Afram and Janabi-Sharifi, 2014). This type of modelling is suitable for existing system performance improvement where sufficient data is available. Examples of data-driven modelling types include data mining algorithms, fuzzy logic, frequency domain, and statistical model.

The physics-based approach also referred to as the white box or forward approach, is derived using the governing laws of physics and the detailed knowledge of underlying processes. They are developed based on the fundamental laws of energy-mass balance, heat transfer, momentum, and flow balance, from where a set of mathematical equations can be derived and solved (Afroz *et al.*, 2018). This approach requires significant effort to develop and calibrate. They usually take the form of time-domain differential equations but can be converted to frequency domain transfer functions or time-domain state-space representations (Afram and Janabi-Sharifi, 2014). This approach is used primarily at the design stage where it is necessary to predict and analyse the performance of HVAC system components through simulation. Major physics-based applications are zone modelling, heating/cooling coil dynamics, duct and pipe model, and mixing box model. In zone models, the zone temperature is sustained by adding or removing the heat to balance the internal and external gains and losses. The zone model is attained by an energy balance of the room at a steady state.

The grey-box approach is administered using the physics-based methods, and the model parameters are determined using parameter estimation algorithms on the measured data of the system. It is regarded as a combination of white and black box models developed by overcoming the shortcomings of these models.

For this research project, the physics-based approach with zone modelling was used.

2.9 Cooling systems

The last few years have shown that climate change contributes to long-running heatwaves and generally high outdoor temperatures. The rising outdoor temperatures creep indoors, creating an uncomfortable thermal indoor environment. If outdoor temperatures consistently remain between 25-40°C, buildings can no longer whisk away this indoor heat of their own accord (Muller, 2019). The energy costs of a building are therefore a function of the annual energy consumption of HVAC system configuration and the system type (Catalyst Team, 2018).

Various types of heating, ventilation and air-conditioning systems exist, such as central, split-type, wall-mounted, constant air-volume (CAV) or variable air-volume (VAV) depending on the type of building and its needs. CAV and VAV systems are viable, energy-efficient options for HVAC systems, depending on a specific building or facility needs.

CAV systems deliver a fixed rate of air, varying the building or zone temperature supply rate. For buildings with different cooling zones, the air supply in CAV systems is cooled at a central location to meet the zone with the highest demand (Graham, 2016).

VAV systems, unlike CAV systems, vary the amount of air supplied to a zone, holding constant the supply of air temperature. This strategy saves fan energy, making VAV systems slightly more efficient as less energy is used to recondition the air temperature than CAV systems (Graham, 2016).

For this research, a VAV system is used.

2.10 Herbaria Thermal Comfort Setting Standards

Microclimatic conditions of herbaria, like that of data centres, museums and libraries, require constant monitoring and control to limit fluctuations which can be damaging. A herbarium is a collection of dried plant specimens and an important data source used by researchers in many plant-related sciences (Victor *et al.*, 2004). In addition, herbaria are an important reference library that has traditionally served to assist in plant identification and future taxonomy

(Conservation and Collections Care, 2014). However, their use is evolving to include current scientific advances and societal priorities (Besnard *et al.*, 2018).

The carefully controlled operation to maintain ideal conditions in herbaria is vital for their preservation purpose building type. (Rabeler *et al.*, 2019), suggest temperatures between 15°C-18°C and relative humidity of about 50%, prevents the proliferation of pests. In the herbarium handbook, Bridson & Forman (Royal Botanic Gardens, 1992) state that ideal temperatures should be at constant lows of about 20°C-23˚C and humidity below between 40%-55%. The benchmark standards on the care of botanical materials recommend temperatures of 18˚C -20˚C and RH 40%-50% for general herbarium (NHM: CSIP Standards Conservation and Collections Care, 2014). The table below demonstrates the comparison of standards and recommended temperature and humidity and ranges for herbaria.

Table 7 Standards and recommendations for different herbaria.

Application	**Standard/ Recommendation**	**Temperature Range**	**Humidity Range**	**Reference**
Herbaria	American Society of Plant Taxonomists	15˚C- 18˚C	≤50%	(Rabeler *et al.*, 2019)
	Royal Botanical Garden	20˚C -23˚C	40% -55%	(Royal Botanic Gardens, 1992)
	NHM Standards in the Care of Botanical Materials	18˚C -20˚C	40%- 50%	(NHM: CSIP Standards Conservation and Collections Care, 2014)
	British Standards Institute	13˚C -20˚C	35% -60%	(Bahei-El-Din and Hassan, 2016)

Psychrometric charts present air's physical and thermal properties in graphical form and understand the relationship between different parameters. The herbarium standards are presented in graphical form below.

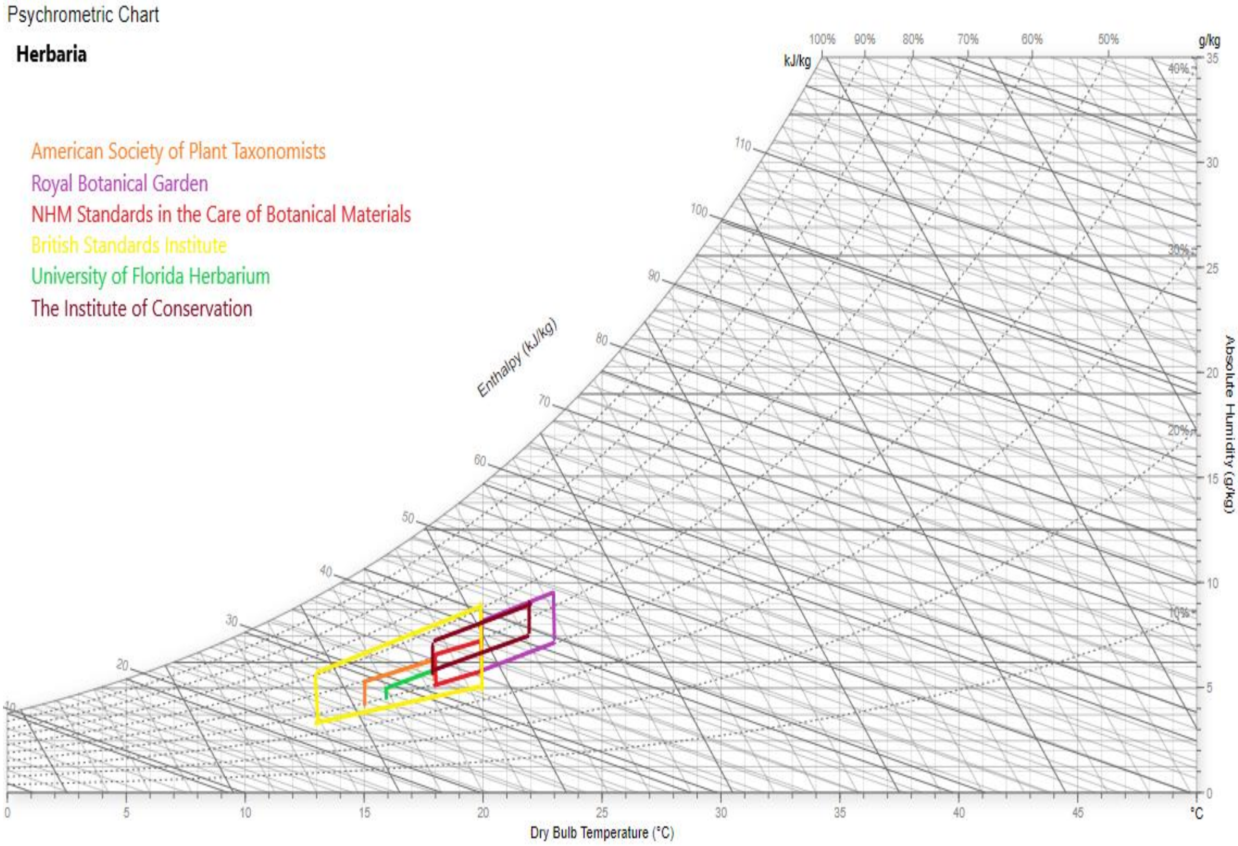

Figure 8 Herbaria Psychrometric Chart

Chapter 3: Research Methodology

A model and simulation of a climate-controlled room utilising solar PV energy and grid connection to power the chiller are carried out. The research design included collecting baseline information about the herbarium. Data collection methods used included interviews and desk research. Details surrounding the case; meteorological data, geographical data and the suggested floorplan for the proposed herbarium were also considered. A broad aspect of the research involved an exhaustive review of literature.

The energy model of an energy-efficient building was designed, modelled, and simulated through the DesignBuilder simulation environment. The energy consumption of the HVAC system, herbarium room temperature and heat balance were also determined. The HVAC model was designed to be powered by solar PV with grid support. The HVAC system was sized considering the cooling load and room size, which was then used to size the PV.

The proposed model can be replicated for other functional uses than herbaria and in different geographical locations.

The building energy model and chiller model requires the following steps to be fulfilled:

1. Characterisation of the proposed building geometry and orientation
2. Definition of the structure and construction material
3. Definition of heat sources and gains like light, power, hot water, etc.
4. Definition of boundary conditions (adjacent zones such as the ground and neighbours)
5. Definition of thermal zones
6. Formation of the building model (energy model and cooling load)
7. Simulation of building energy model and load estimation
8. Defining of the HVAC/chiller system
9. Design and sizing of the chiller system
10. Definition of the solar PV system
11. Creation and sizing of the solar PV system and grid connection
12. Post-processing (analysis) of the results
13. Validation of the simulation results

The flow process below depicts the steps taken in achieving the desired outcome in this project. The metrics to gauge the success of this project are determined by achieving the stages in this diagram.

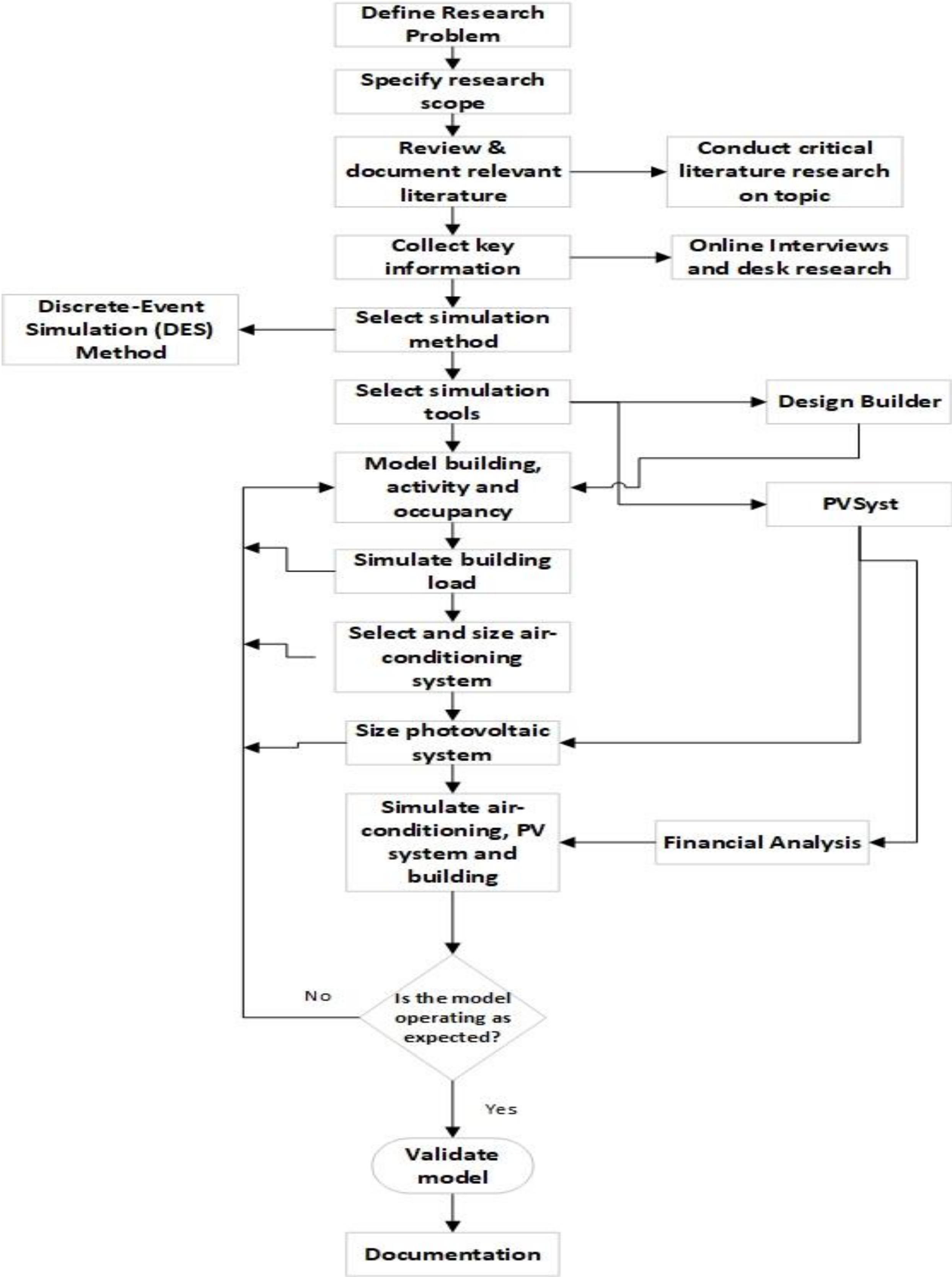

Figure 9 Methodology workflow

3.1Background and Description of Case Study

3.1.1 Current Herbarium Setup

The current PS-HUB setup consists of two separate buildings, namely the library and herbarium accommodated in prefabricated structures on the ORI campus. The library incorporates a collection of books that are related to the herbarium. It is partially air-conditioned; however, the internal climate is not controlled according to parameters such as temperature and humidity as prescribed by thermal comfort standards for libraries.

The herbarium is equipped with one vapour compression type chiller tuned at a constant inlet temperature set at 17°C. The actual inlet or room temperature and humidity in the room are not controlled or monitored. The required room comfort conditions for the herbarium are not known and are currently not set to the appropriate standards/guidelines. The PS-HUB collection consists of more than 30,000 known specimens, of which there are over 16,000 species of stored botanical and natural collections (Murray-Hudson, Bader, *et al.*, 2018). New species are constantly being identified from the collection that was not previously known. A major challenge in the current herbarium is the infestation of termites, heat, moisture, rats, and squirrels that access the herbarium by surrounding trees and threaten the stored collection. The trees currently provide passive shading benefits.

An extension plan was proposed in 2010 to build a complete faculty for the natural management and tourism, including the herbarium and library; however, no action has been taken since then. This research project has refined the plan to study the potential of a sustainable and energy-efficient building with solar PV cooling for semi-arid climates such as in Botswana.

Photo documentation of the current state of the herbarium can be considered below (Murray-Hudson, Bader, *et al.*, 2018).

Figure 10 Current Herbarium prefabricated building structure (left) and herbarium entrance (right)

Figure 11 Sample of extensive book and journal collection to complement herbarium in the library at ORI

Figure 12 Termite damaged herbarium documents (not recent)

Figure 13 Termite hill (directly in front of herbarium)

Figure 14 Internal view of the herbarium from the entrance (left) and towards the entrance (right)

Figure 15 Herbarium entrance area

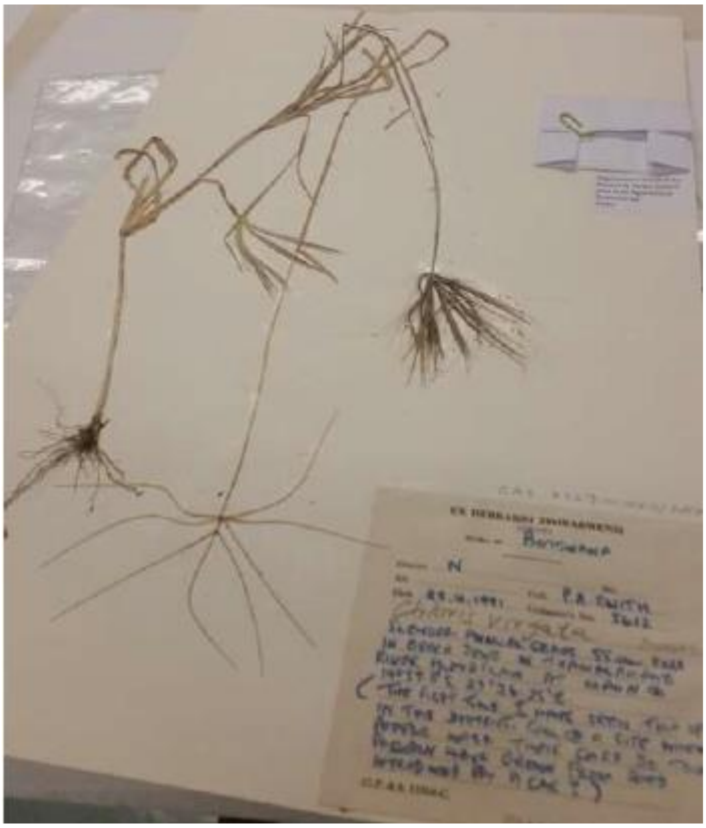

Figure 16 Example of a specimen

Figure 17 Vapour compression chiller used to condition the herbal archive in the herbarium (left) and the specs plate showing a 7.3kW cooling capacity (right)

3.1.2 Location & weather data set description

The Okavango Research Institute (ORI) is situated in the North-Western part of Botswana in a town called Maun at a Latitude of 19.98° South and a Longitude of 23.42° East as shown in Figure 7. Maun is around 955 metres above sea level, with a hot semi-arid climate (BSh) has an ASHRAE climate zone of 2B.

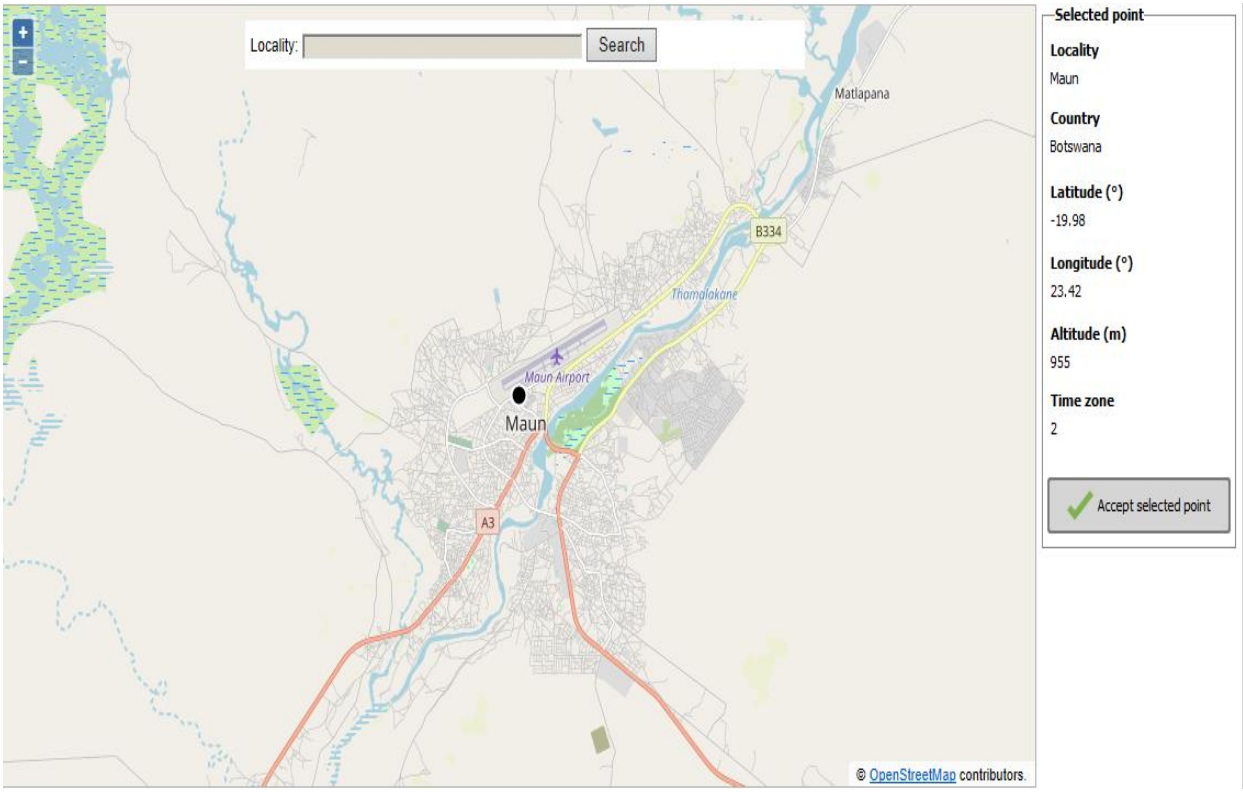

Figure 18 Satellite view of Maun, Botswana- PVsyst.

Meteorological data greatly influences the performance of the building energy model and PV cooling system. The weather data was taken as a typical meteorological year (TMY), a typical ten-year average, registered per hour. For the simulation, daily values in hourly increments will be used.

Report: **Input Verification and Results Summary**

For: **Entire Facility**

Timestamp: **2021-10-27 16:52:41**

General

	Value
Program Version and Build	EnergyPlus, Version 8.9.0-40101eaafd, YMD=2021.10.27 16:52
RunPeriod	ORI PS-HUB (01-01:31-12)
Weather File	Maun AP NW BWA ISD-TMYx WMO#=680320
Latitude [deg]	-20.0
Longitude [deg]	23.43
Elevation [m]	942.70
Time Zone	2.00
North Axis Angle [deg]	0.00
Rotation for Appendix G [deg]	0.00
Hours Simulated [hrs]	8760.00

Figure 19 DesignBuilder Input Verification

The psychrometric chart below shows the annual weather distribution in Maun, plotted against the recommended herbarium standards.

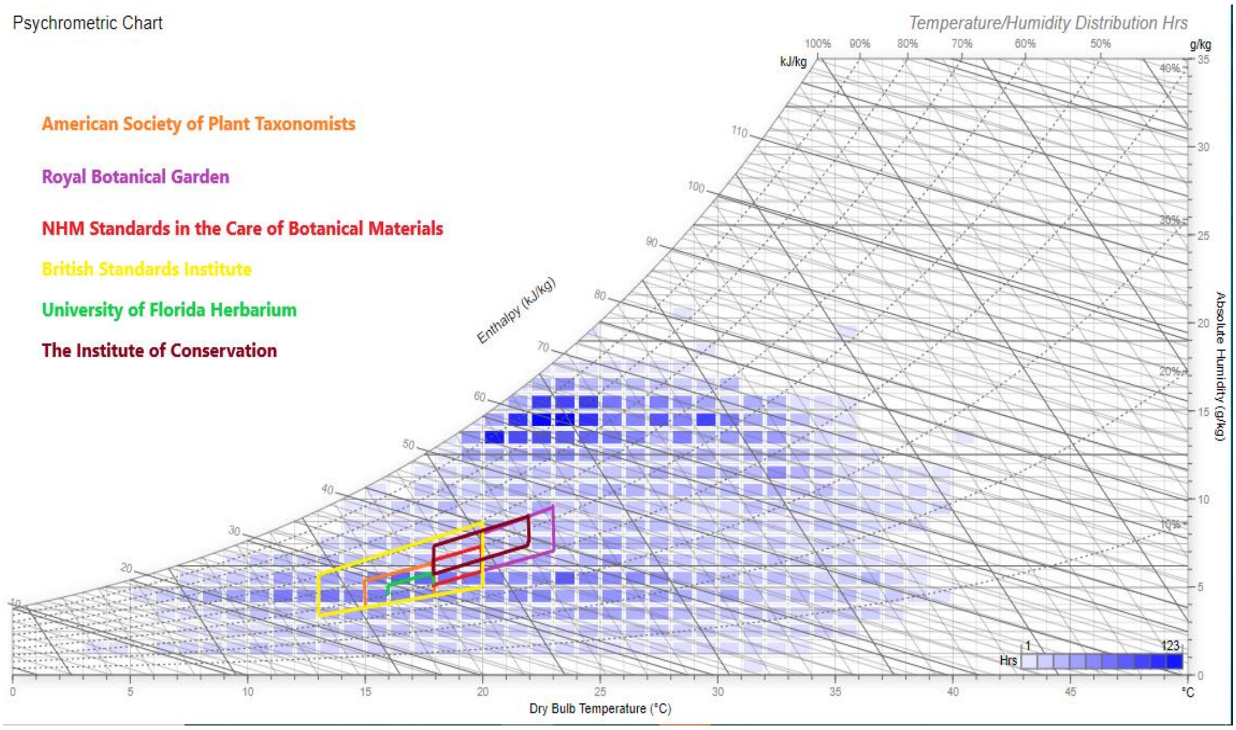

Figure 20 Weather data plotted on a Psychrometric chart

3.2 DesignBuilder Model Validation

This section shows the experimental validation of the proposed methodology and existing data. The DesignBuilder software is a validated modelling and simulation software based on EnergyPlus as its core computation engine. Two separate datasets were used for the experimental validation.

Due to limitations, the electrical bill for the Okavango Research Institute was not available for examination. However, using data provided by the herbarium management, the annual electrical end usage was deduced and compared to the same conditions modelled with DesignBuilder.

The data under study focused solely on the herbarium internal equipment, lighting, and the HVAC system to validate the methodology.

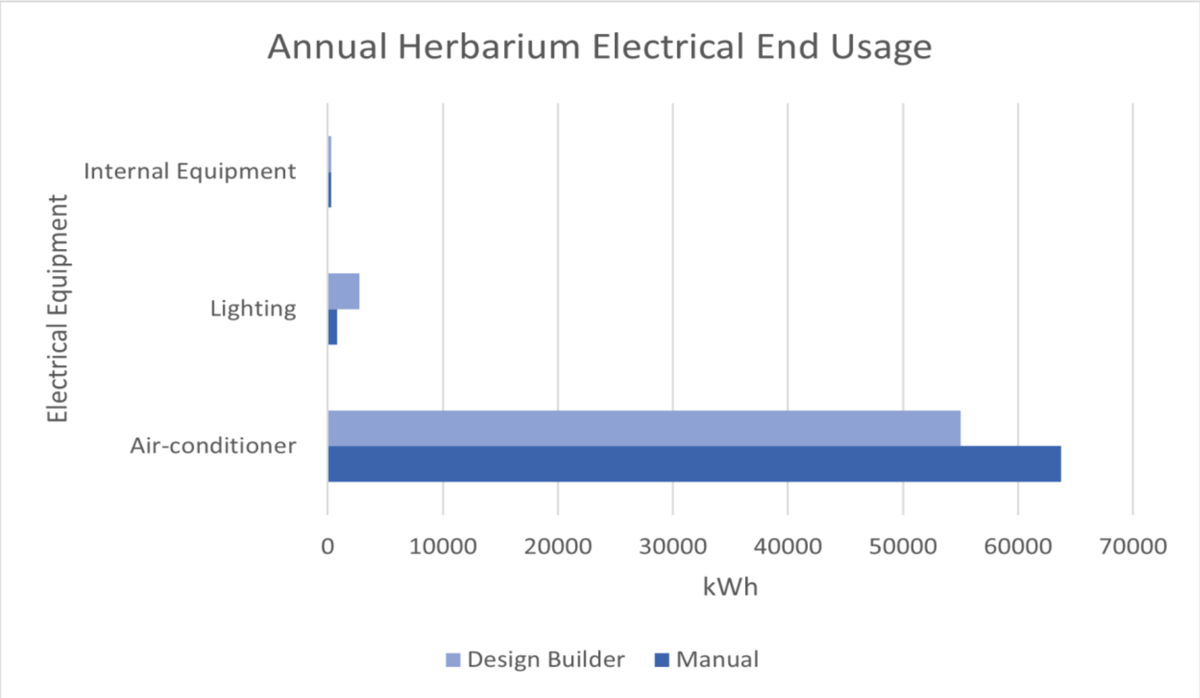

Figure 21 Methodology and dataset validation

The results indicate that the manual calculation for the split type air-conditioner was sizeably larger than the results modelled using DesignBuilder. The lighting showed the DesignBuilder simulation results being considerably larger than the manual calculation. At the same time, the internal equipment, mainly two desktop computers and a scanner, were almost equal for the manual calculation and DesignBuilder. As shown in Figure 21, the results indicate that the difference between the two methods was 10.5% for the building understudy, which falls under a considerable error range. The difference may have been due to several factors;

- Influences such as radiant factor, power fraction were considered in the DesignBuilder simulation
- The air-conditioner was considered as auxiliary energy (kWh/m^2) in the DesignBuilder simulation which may have resulted in a significant difference compared to the manual calculation.
- Building square footage and occupation were factored into the DesignBuilder model.

3.3 Design of Building Model

Building design is a complex intellectual process that involves creativity and judgement. Architectural creativity necessitates new building designs, while engineering judgement eliminates or modifies some of these due to project requirements and constraints.

A building is made of different components and systems. Minor changes and adjustments in the characteristics of any components or system can have a considerable effect on the other components or the building performance. For example, selecting how to orient a building on a site has a coherent effect on the building or room solar gains and day-light intake, lighting needed fresh air intakes in the building and overall energy balance. Also, small considerations such as window glazing properties can dramatically affect HVAC system cooling equipment sizes, ductwork, and piping network sizes. Building energy modelling allows the user to predict how a building, its associated systems and components operate post-construction from an energy usage and performance standpoint (Khazaii, 2016).

This thesis uses the DesignBuilder computational tool to design and model the building's load and energy use characterisation according to the project requirements.

3.3.1 DesignBuilder Software

The DesignBuilder software used in this project is a graphical user interface that utilises the EnergyPlus simulation engine to provide advanced tools to model and simulate a building's performance. In addition, the software can be used to model dynamic energy simulations and evaluate building designs.

When modelling in DesignBuilder, the building needs to be stipulated to the actual location, weather type, and the thermal zones of the building defined. In addition, the data concerning the construction, zone activity, and occupancy must also be logged for more accurate simulation outputs. The following workflow for modelling from scratch can be followed.

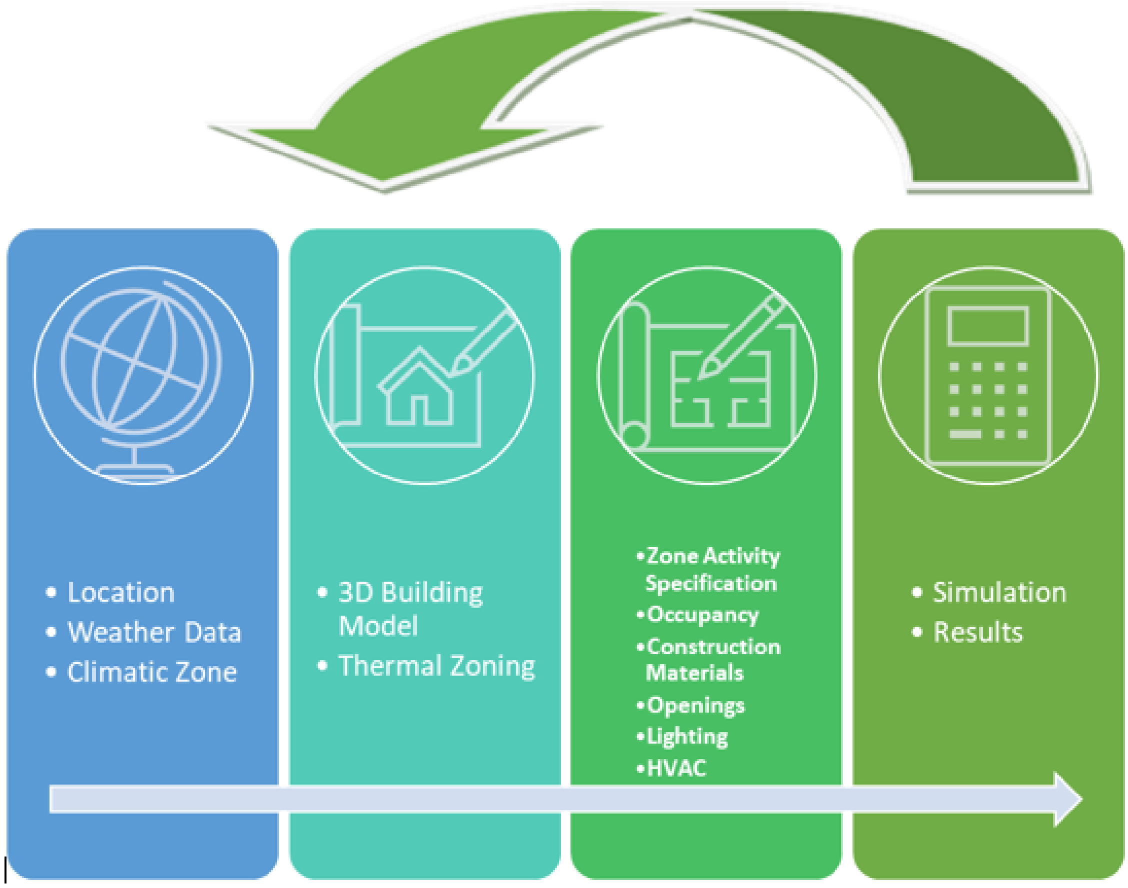

Figure 22 Building design model workflow

Each tab requires a considerable amount of input data for each specific building. Where information is not available, estimates or default values can be used. DesignBuilder can also be used for building energy and comfort analysis, providing data such as energy consumption, room comfort, and zone temperature distribution.

The room of interest, the herbarium, was designed on the ground floor to minimise the direct effect of the sun on the room, thus reducing the cooling demand. The focus of the study is understanding the overall building performance with a single HVAC zone- herbarium and understanding the cooling electricity demand to be powered with a solar PV system.

3.3.2 Load and Energy Balance

When designing a building, it is crucial to consider the hemisphere in which the building is located, its orientation, construction materials, and climatic conditions, among other factors. The building, located in the southern hemisphere, was modelled to face North towards the equator to enhance the efficiency of the building. The load calculation and overall building energy balance were then calculated, taking into account the building materials. The load calculation and building energy balance consist of external and internal gains, which are expounded in Table 8.

The total cooling load or heat to be removed from the building is a sum of the loads mentioned.

$$Q_{total\ cooling} = Q_{transmission} + Q_{product} + Q_{internal\_gains} + Q_{equipment} + Q_{infiltration} \quad (10)$$

Gain Type	Description	%	Equations	
Transmission Load	Heat flows from hot to cold. The interior of the herbarium is a lower temperature than its surroundings, so heat is always trying to enter. The transmission load is higher if the room is exposed to direct sunlight.	5-15%	Q = U x A x (Temp out – Temp in) x 24 ÷ 1000	(11)
Product Load	Accounts for the heat introduced into the herbarium when new products enter. If only cooling the products is needed, then only a sensible heat load should be considered. However, the packaging needs to be accounted for as it is inherently also cooled.	55-75%	Q = m x Cp x (Temp enter – Temp store) / 3600 3600 = convert from kJ to kWh	(12)
Internal Load	Refers to the heat given off by people working in the herbarium, lighting, and computers. The equipment used by the staff members, how much heat they and the equipment give off, and the daily duration also need to be considered.	10-20%	Q = people x time x heat / 1000 Q= lamps x time x wattage / 1000	(13) (14)
Equipment Load	Refers to the refrigeration equipment in the room, which will account for around 1-10% of the total cooling load. For this, we want to know the rating of the fan motors and estimate how long they will run for each day.	1-10%	Q= computer x time x wattage / 1000	(15)
Infiltration Load	The infiltration load refers to the heat energy that enters the herbarium if and when the doors and windows open. The other consideration is ventilation.	1-10%	Q = changes x volume x energy x ($Temp_{out}$ – $Temp_{in}$) / 3600	(16)

Table 8 Energy gain types

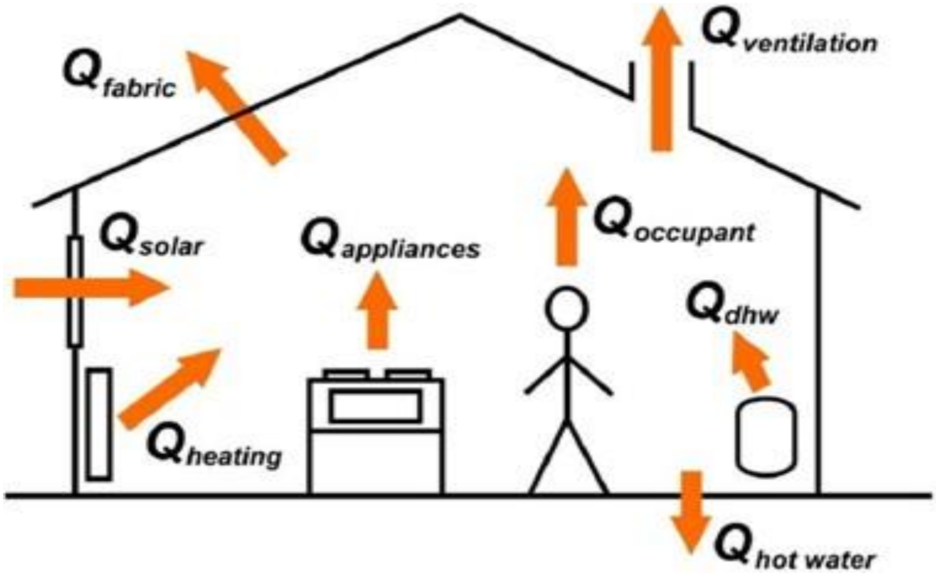

Figure 23 Illustration of Energy Balance and Gains (Simon, 2017)

Factors such as ventilation losses introduced by open doors, foot traffic (occupancy), and other internal gains were considered in the model. The herbarium model excludes windows. The amount of air changes per hour (ACH), which is a measure of the air volume added to or removed from a space, is a controllable aspect of the model which was considered. The Ventilation for Acceptable Indoor Air Quality standard by ASHRAE (ASHRAE, 2004) recommends an estimated outdoor air exchange rate (R_{ae}) for storage rooms to equal or greater than 2.16 l/h for the proposed room floor area.

3.3.3 Building Model

The building was modelled with energy-efficient principles suitable for hot, semi-arid locations such as Botswana. The model below represents a multi-functional, two-story building that houses offices, laboratories, storage facilities and the herbarium, with a total floor area of 903.0 m^2 and volume of 2664.9 m^3. The ground floor of the building houses the herbarium, laboratories, and preparation rooms, while the first floor is an office area. The model is divided into 22 zones, with the zone of interest being zone 2 of block 1.

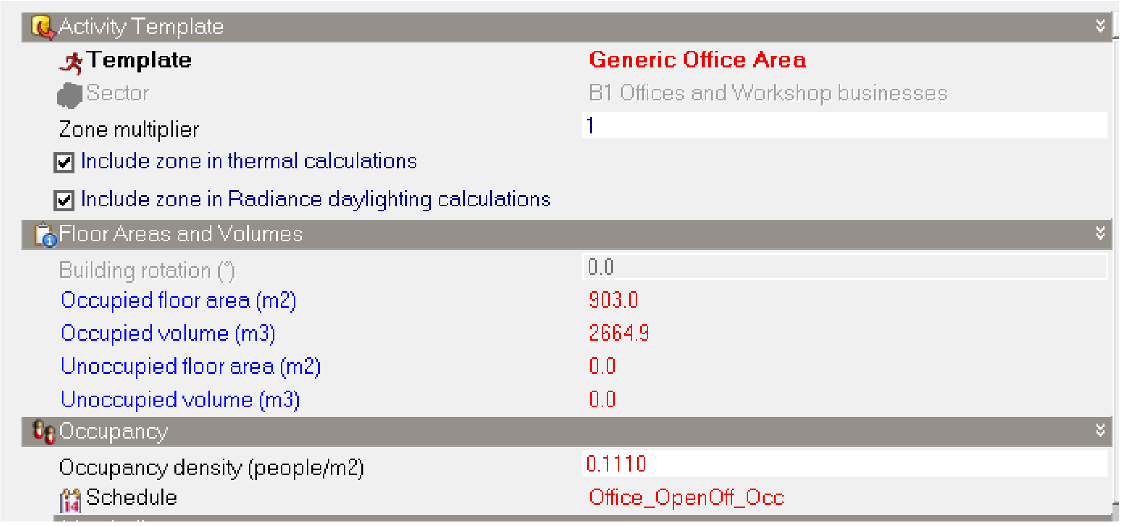

Figure 24 Building activity settings

The generic building activity was configured to operate as a generic building, with each zone set to its specific activity functions, occupancy, lighting, equipment, and other factors.

The herbarium was positioned to the west of the building and designed on the ground floor to minimise direct sunlight on the roof. The entrance of the building is north facing, with the internal door of the herbarium facing east with no windows to minimise heat gain. The herbarium has a length of 18.0m, a width of 13.1m, and a height of 3m.

Below is a representation of the proposed building.

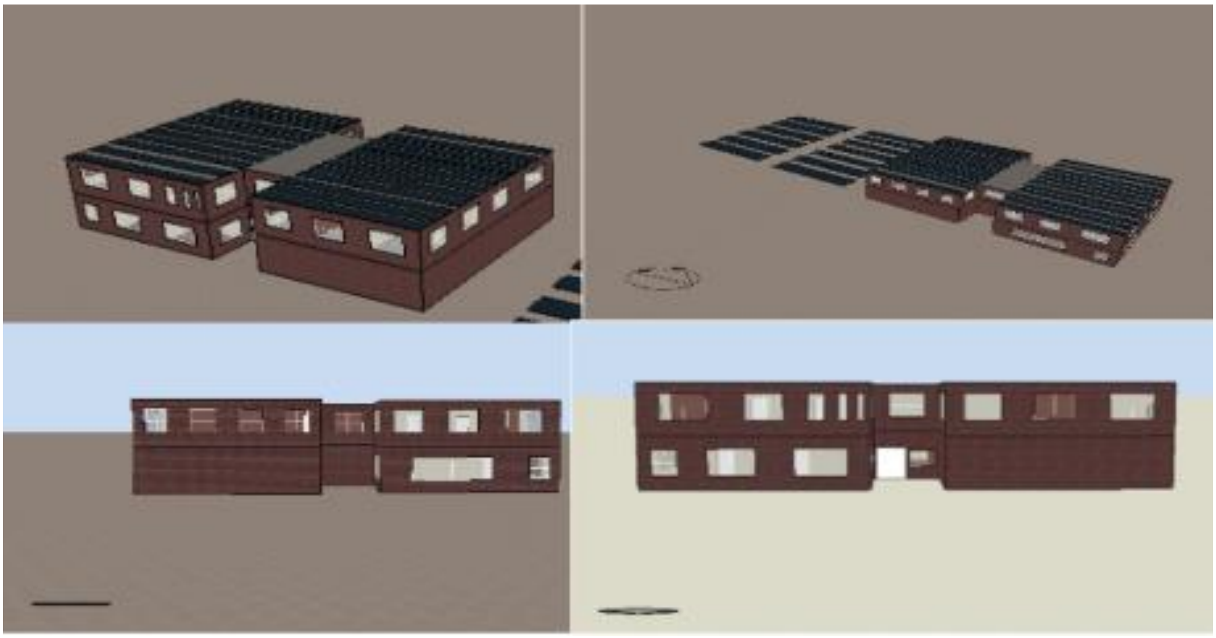

Figure 25 Proposed building illustration

The herbarium, workshops and laboratories are placed on the ground floor to reduce the direct effect of the suns ray on the roof and as a passive cooling strategy.

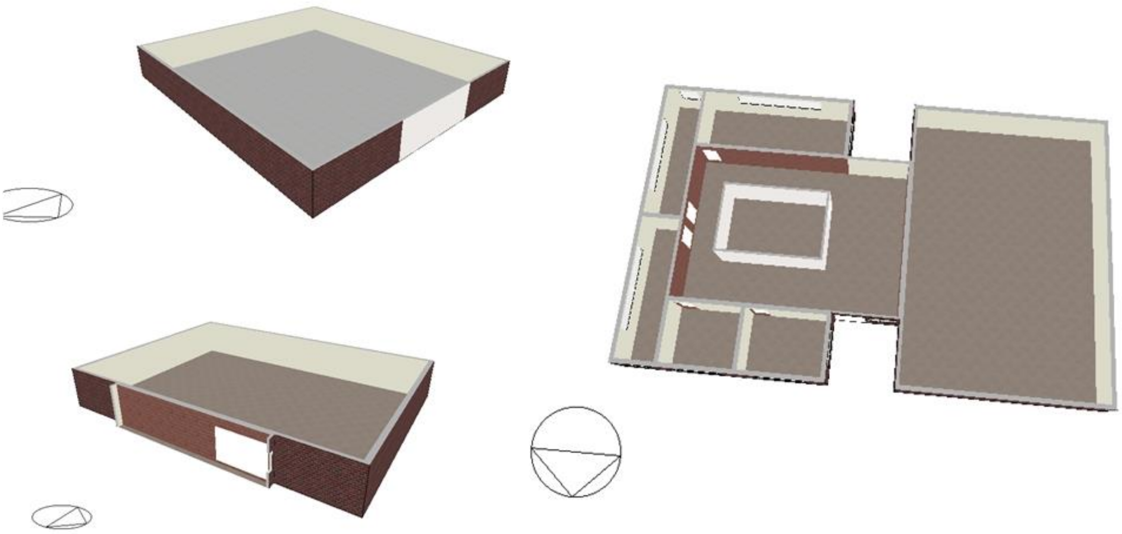

Figure 26 Ground Floor Illustration

The offices and main activity areas of the herbarium are positioned on the first floor of the research institute.

Figure 27 First Floor Office Layout Illustration

The table below shows the materials used for the construction of the model.

Table 9 Model construction materials and properties

Surface	Surface Layer	Material	Conductivity (W/m-k)	Density (kg/m^3)	Specific Heat (J/kg-K)	Emissivity	Absorptivity	Thickness (m)
External wall	1	Red/ Clay Brickwork Outer	0.8400	1700	800	0.900	0.700	0.1150
	2	Stock Brick/ Brickwork Inner	0.6200	1700	800	0.900	0.700	0.1150
	3	Cement Plaster	0.7200	1860	840	0.900	0.600	0.0500
Internal wall/ Partitioning	1	Cement Plaster	0.7200	1860	840	0.900	0.600	0.0500
	2	Stock Brick/ Brickwork Inner	0.6200	1700	800	0.900	0.700	0.1150
	3	Stock Brick/ Brickwork Inner	0.6200	1700	800	0.900	0.700	0.1150
Ceiling	1	Aerated Concrete Slab	0.1600	500	840	0.900	0.600	0.2000
	2	Insulation/ Glass wool	0.0400	12	840	0.900	0.600	0.1000
	3	Air Gap	-	-	-	0.900	0.700	0.025
	4	Plasterboard	0.2500	2800	896	0.900	0.500	0.0130
Roof	1	Asphalt	0.7000	2100	1000	0.900	0.850	0.0100
	2	Aerated Concrete Slab	0.1600	500	840	0.900	0.600	0.2000

	3	Insulation/ Glass wool	0.0400	12	840	0.900	0.600	0.1000
	4	Air Gap	-	-	-	0.900	0.700	0.025
	5	Plasterboard	0.2500	2800	896	0.900	0.500	0.0130
Floor	1	Cast Concrete Slab	1.400	2100	840	0.900	0.600	0.100
Doors	Internal	Painted Oak	0.1900	700	2390	0.900	0.500	0.0350
	External	Painted Oak	0.1900	700	2390	0.900	0.500	0.0350
		Window to wall %	**Window height (m)**	**Glazed**	**Window Spacing (m)**	**Sill height (m)**		
Windows		30	1.50	30%	5	0.80		

The building occupancy, equipment and activity were modelled according to zones to cater to the specific zones requirements.

A visual representation of the external and internal cross-section of the walls and partitioning, respectively, can be seen below.

Figure 28 External wall cross-section

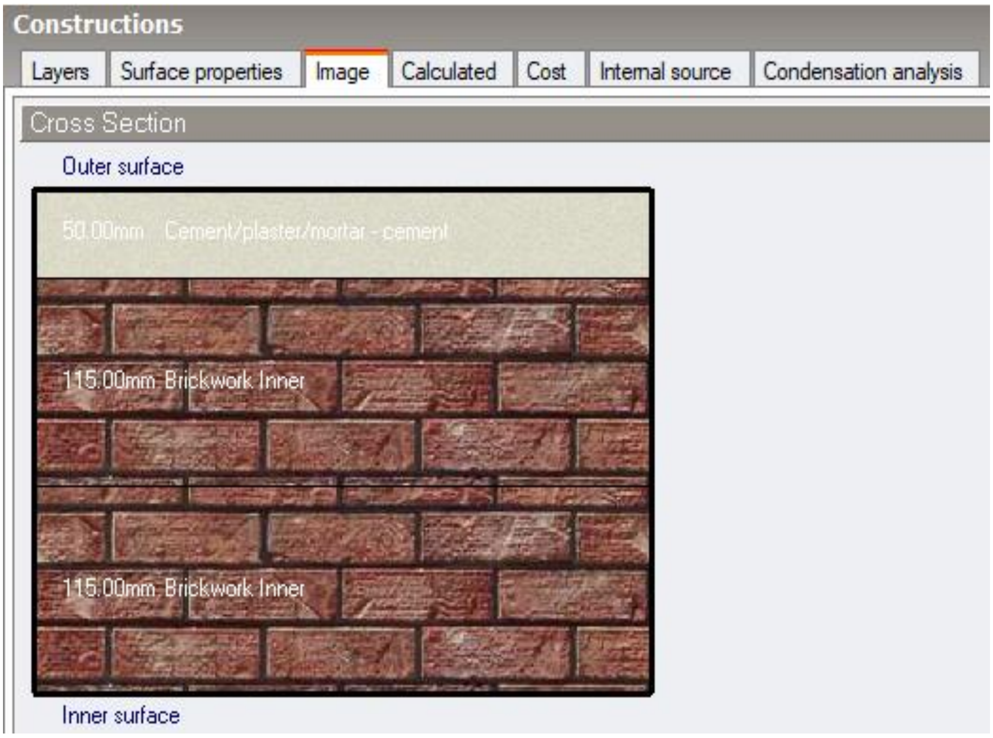

Figure 29 Internal partition wall cross-section

The herbarium zone was modified and defined to mimic real herbarium operations, providing minute details to the zone operations as seen in the figure below.

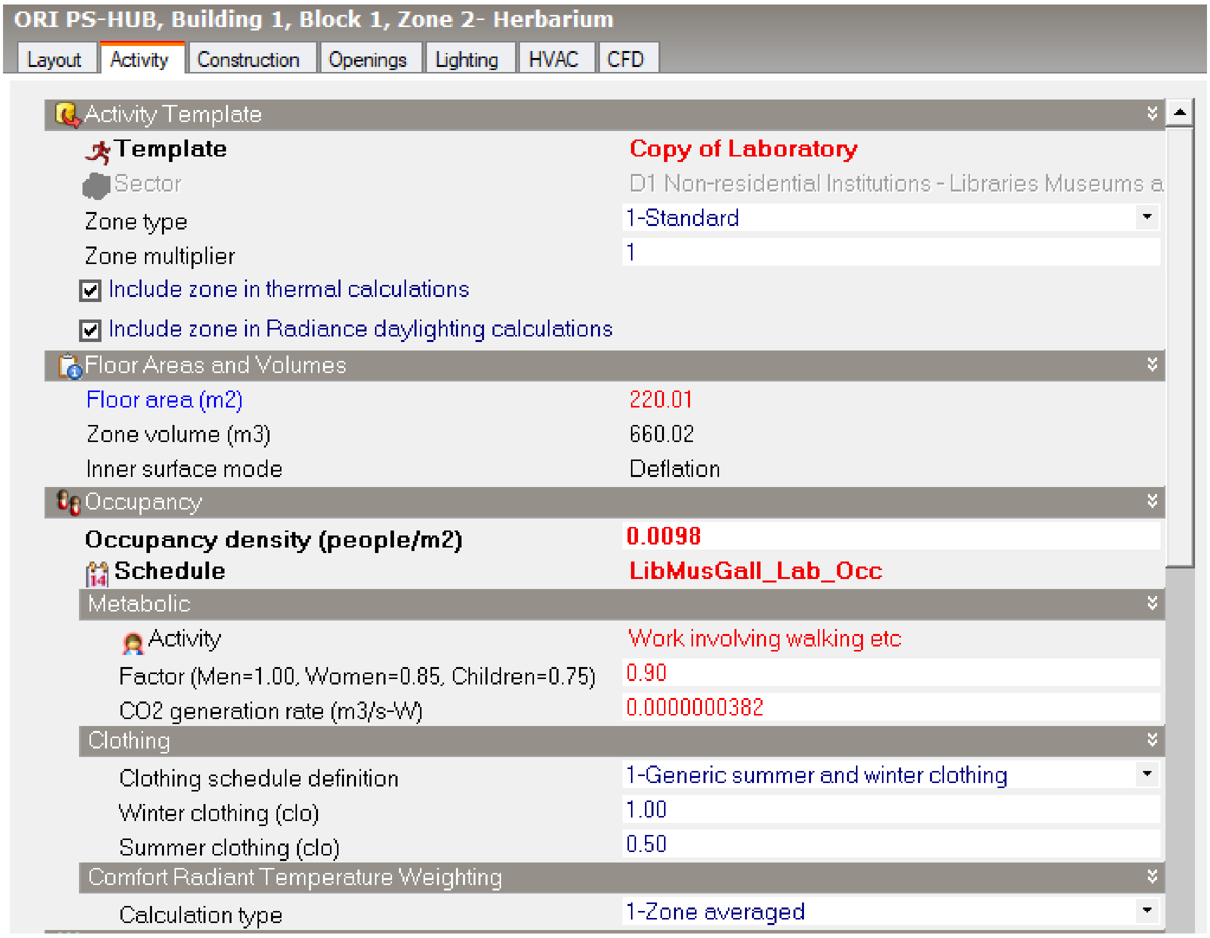

Figure 30 Herbarium activity configuration

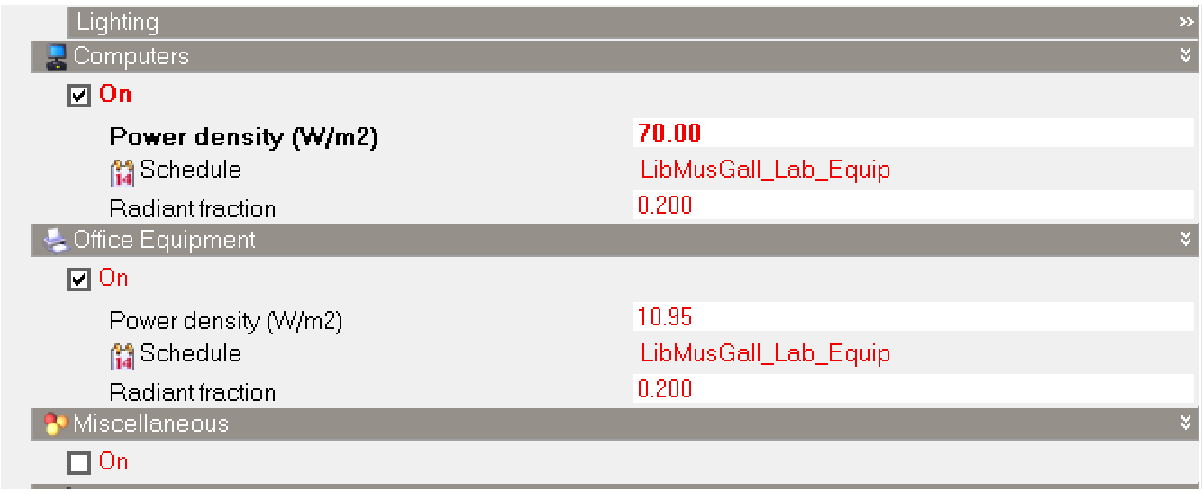

Figure 31 Herbarium Equipment configuration

The computer power density was set to 70 W/m^2 with an operating schedule of a typical museum or library laboratory equipment unit. At the same time, the office equipment was set as 10.95 W/m^2.

3.4 Design of Chiller Model

The HVAC system for the herbarium zone is a crucial component for maintaining the indoor temperature of the herbarium. A variable air-volume system was selected for the herbarium using detailed HVAC design in DesignBuilder.

Table 10 HVAC Parameters for Herbarium Zone

Building element	Value
Temperature Setpoints	Cooling (°C): 16 Cooling set back (°C): 20
Air Flows	Variable Air Volume
Supply Air Temperature Setpoint	Constant 14°C Supply air temperature
Zone	Block1: Zone2XHerbarium
AHU Schedule	Always on

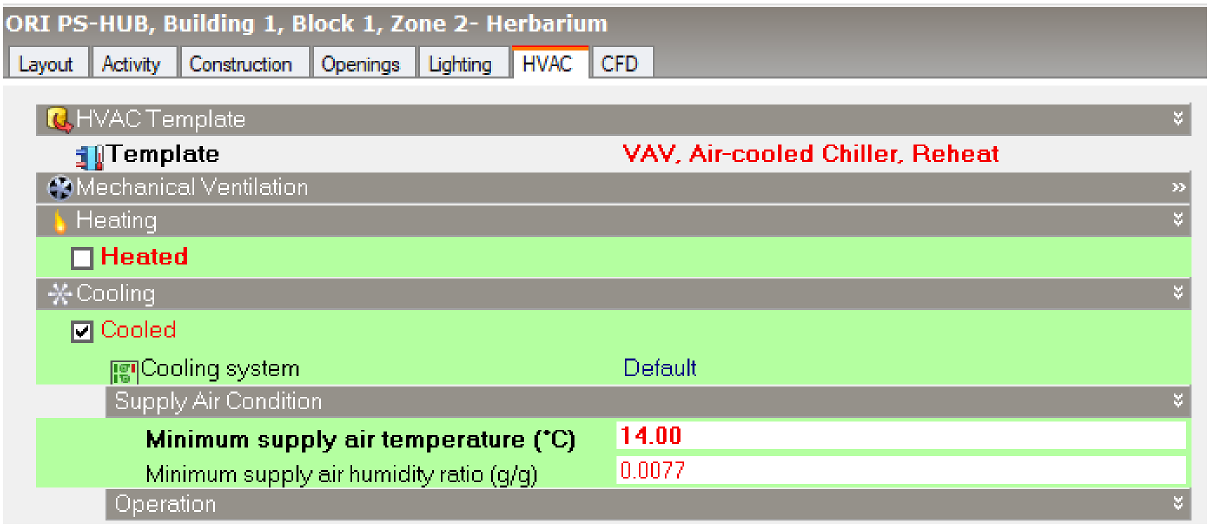

Figure 32 Herbarium HVAC settings

The HVAC system minimum supply air temperature was defined to supply the zone at 14°C. Therefore, the choice in the HVAC system was mainly from a technical or specification point, rather than a financial standpoint. As seen below, a typical HVAC system consists of a supply air system and returns air duct system.

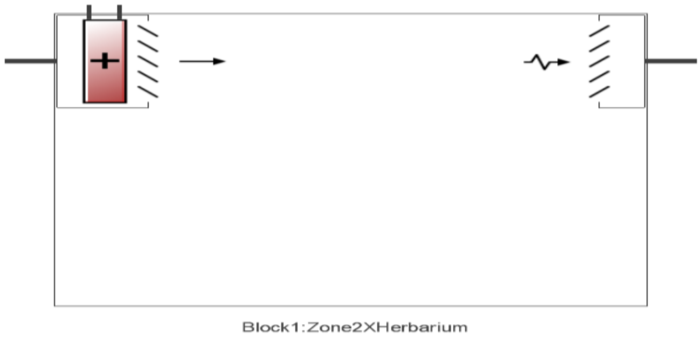

Figure 33 Herbarium Zone Airflow Operation

The supply air fan and return air duct fan in the air handling unit are used to move air, and the speed at which they operate is used to control the air flow rate. In addition, the heat exchanger in the air handling unit allows for some energy to be salvaged for the supply air fan, thus improving the system's energy efficiency. Also, in the air handling unit, the supplied air is heated or cooled by the heating loop or cooling loop respectively to help maintain the indoor temperature at the desired level. The figure below shows the modelled HVAC system.

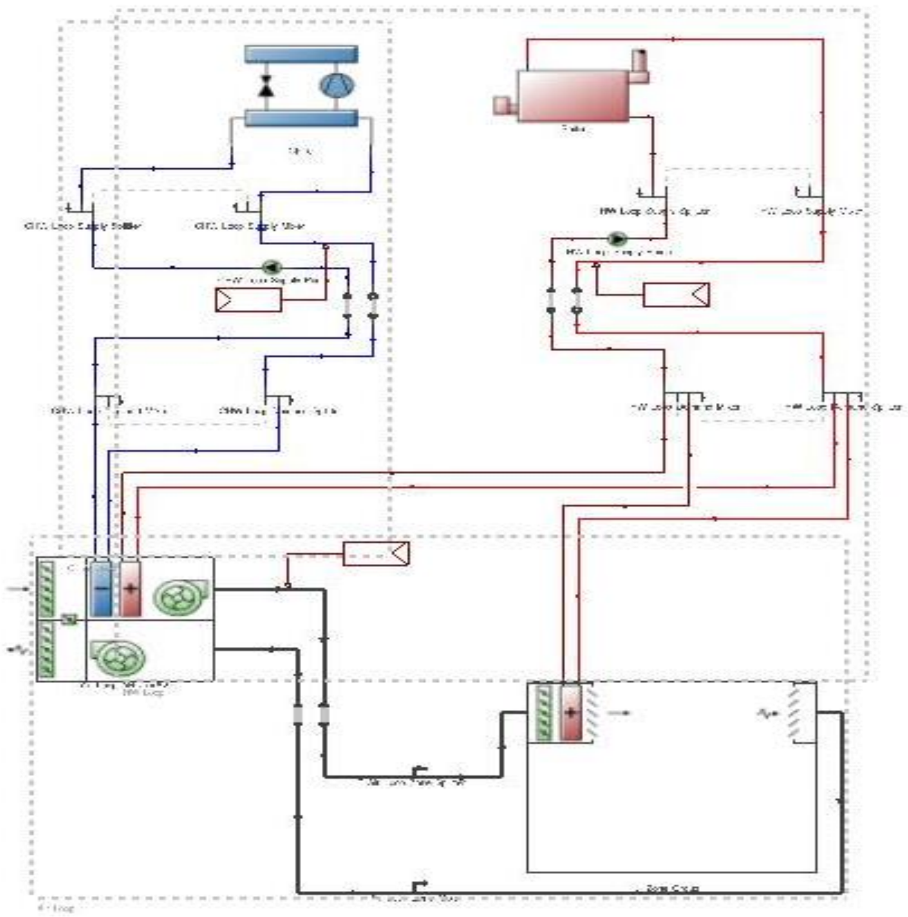

Figure 34 VAV HVAC system

The air handling unit in the model supplies the same amount of airflow to the herbarium zone regardless of the cooling load in the room at a constant temperature.

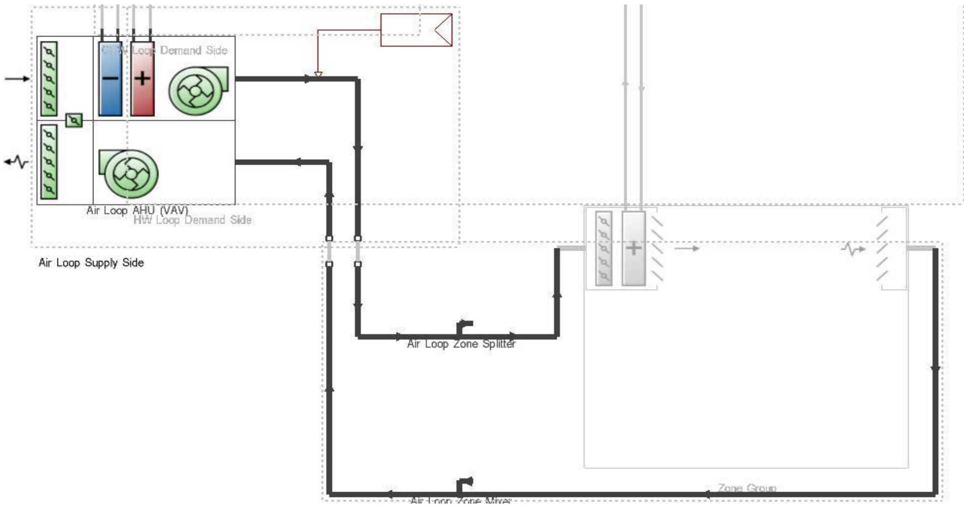

Figure 35 Air Handling Unit Operation

The chiller system comprises of an evaporator that functions as a heat exchanger, an expansion valve, a condenser that expels the heat and a compressor. The chiller is the unit that generates the cool air supplied to the room and maintains it at the desired temperature.

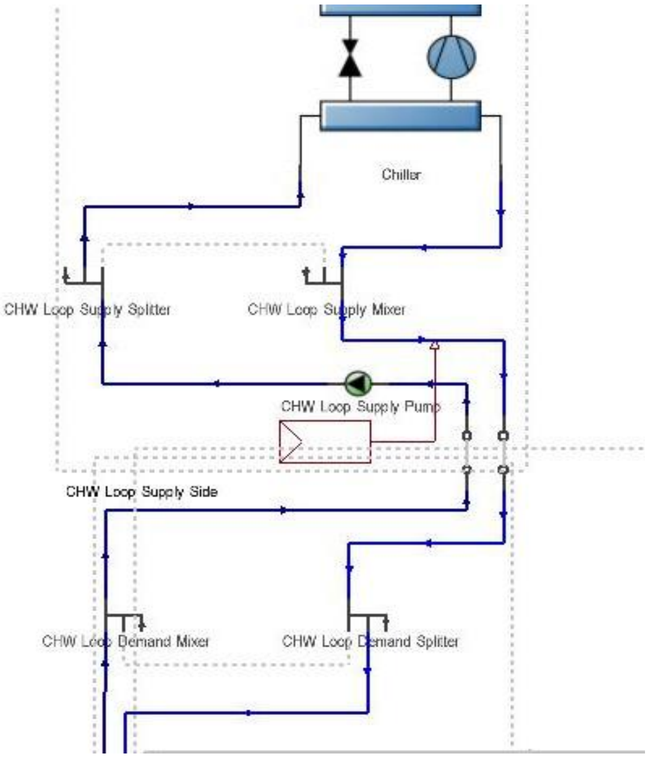

Figure 36 Chiller Operation

The herbarium zone model is considered a single thermal zone with a constant temperature. The building total energy gain is the sum of the internal gains, the thermal gain/loss through the heat convection between the wall and ceiling surfaces and the thermal heat transfer from the HVAC system. The internal gains are generated by human occupancy and the equipment in the herbarium.

$$Q_{total} = Q_{internal} + Q_{convection} + Q_{HVAC} \quad (17)$$

The total energy consumed by the VAV HVAC system is the sum of all the components and is given as:

$$E_{total} = E_{supply\_fan} + E_{return\_fan} + E_{pump} + E_{cool} + E_{heat} \quad (18)$$

E_{heat} is considered negligible since the HVAC system will only be providing cool air into the room.

3.5 Design of PV Model

One of the main goals of this project is to power the HVAC used to cool the room using energy generated from solar PV panels. The PV model and simulation aspect of the research required knowledge of the HVAC total energy consumption throughout the year to proper design and size the system. The PV system was modelled using PVsyst and DesignBuilder both at fixed roof-top and with grid connection due to the proximity of ORI to the BPC power lines.

3.5.1 PV system parameters

The selected parameters for tilt and azimuth angle for the PV system at the Okavango Research Institute were chosen to output the best possible results for optimum fixed tilted plane PV performance in Maun, Botswana. Initial system sizing and parameterisation was done in the PVsyst simulation software.

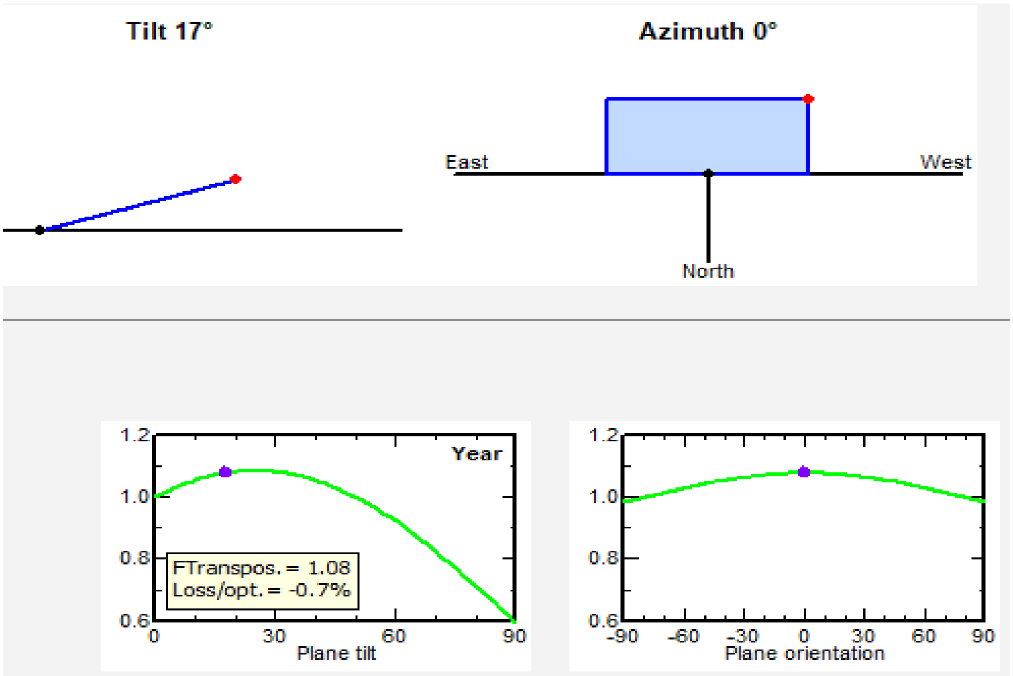

Figure 37 Tilt and azimuth selection in PVsyst

The fixed tilt angle was calculated using the latitude (*L*) to collect high irradiation during summer (Kalogirou, 2014). The optimum tilt angle, β, for annual yield can be approximated by:

$$\beta = 0.764L + 2.14°, \quad (19)$$

$$for\ L \leq 65°$$

$$\beta = 0.224L + 33.65°, otherwise. \quad (20)$$

For the system at a latitude of -19.99°, the fixed tilt angle was calculated at 17.41°.

The PV model output and performance are usually calculated based on module characteristic parameters at Standard Test Conditions (STC) and Nominal Operating Cell Temperature (NOCT) conditions.

For this research project, a Longi LR4-72HPH 430M solar module technical data was modelled. The panel has an STC condition of 430 (Pmax/W) and NOCT condition of 321.1 (Pmax/W). The electrical characteristics of the solar panel can be seen below.

Table 11 Solar Panel Electrical Characteristics

Module Type: Longi LR4-72HPH 430M		
Material type	-	Monocrystalline silicon
Testing Condition	STC	NOCT
Maximum Power (P_{max}/W)	430	321.1
Open Circuit Voltage (V_{OC}/V)	48.5	45.5
Short Circuit Current (I_{SC}/A)	11.31	9.15
Voltage at Maximum Power (V_{MP}/V)	40.7	37.9
Current at Maximum Power (I_{MP}/A)	10.57	8.47
Module efficiency (%)	19.8	
Temperature Ratings (STC)		
Temperature Coefficient of I_{SC}	+0.048%/°C	
Temperature Coefficient of V_{OC}	-0.270%/°C	
Temperature Coefficient of P_{MAX}	-0.350%/°C	

STC: AM1.5 1000W/m^2 25°C NOCT: AM1.5 800W/m^2 20°C 1m/s test uncertainty for P_{max}:±3%

Inverters convert direct current (DC) from the solar PV generator into alternating current (AC) usable for the HVAC system. Different types of solar inverters exist in the market, such as the string inverter, microinverters, hybrid solar, central and battery-based inverter/ charger (Cyanergy, 2021).

Multiple strings originating from the solar panels are attached to one inverter with string inverters, and the DC electricity is collectively transformed into AC. While with microinverters, small inverters are installed for each panel and the output AC electricity is sent to the building. Hybrid solar inverters are multi-mode inverters that allow electricity state conversion between the grid, home appliances, the battery, and the solar panels. Central inverters resemble the string inverter; however, the strings of panels are joined together and put into a combiner box which is protected. The combiner box receives the DC electricity and sends it to an inverter, which converts it to AC. The protected combiner box makes it less vulnerable to physical and natural damage. The battery-based inverter/ charger is ideal for off-grid solar systems as it can provide a little energy required to supplement deficits during winter or acute shading.

For the project, a string inverter was used. The size of the solar PV array determines the appropriate size for the inverter; its capacity needs to handle all the power the solar array produces. Generally, as a rule of thumb, the inverter size should be similar or equal to the solar PV array size (EnergySage and Thoubboron, 2018).

The string inverter modelled in this research is the HUAWEI Smart String Inverter. The inverter has the following technical specifications.

Table 12 Inverter Technical Data Sheet

Inverter Type: SUN2000-17/20KTL	
Strings	6
Max. Input Voltage	1, 000 V
Max. Short Circuit Current per MPPT	18 A
Number of MPPT Trackers	3
Rated. Input Voltage	620 V
Max. efficiency	98.6%
Rated AC Active Power	20,000 W
Rated AC Grid Frequency	50 Hz/ 60 Hz

The electrical system network in Botswana operates on a supply voltage of 230V for a single-phase and grid frequency of 50Hz (Botswana Power Corporation, 2001) for non-industrial connections. The inverter settings are seen below.

Table 13 Inverter Settings

Parameter	**Value**
Number of Phases	1
Grid Voltage	230V
Grid Frequency	50Hz
Standby Power	1W
Max. AC Power Output	17kW

3.5.2 PV sizing

The PVsyst simulation software was used to size the PV system. PVsyst is computer software developed by Geneva University in Switzerland for the study of photovoltaic systems. The PVsyst software is capable of simulating grid-connected, stand-alone, and solar-powered pumping systems. It is made up of four sections: preliminary design, project design, databases, and tools.

The annual PV yield was sized/ dimensioned according to the total energy (kWh) used by the HVAC system components over a year.

$$Annual\ HVAC\ electricity \left(\frac{MWh}{yr}\right) = Cooling\ elec. \left(\frac{kWh}{yr}\right) + fans \left(\frac{kWh}{yr}\right) + pumps \left(\frac{kWh}{yr}\right) \quad (21)$$

The table and graph below show the distribution of the electrical component end uses for the entire building. The cooling is solely concentrated on the herbarium and accounts for roughly 1/3 of the electricity end-use annually.

	Electricity [kWh]
Heating	0.00
Cooling	154219.79
Interior Lighting	40033.30
Exterior Lighting	0.00
Interior Equipment	150370.74
Exterior Equipment	0.00
Fans	138740.73
Pumps	481.16
Heat Rejection	0.00
Humidification	0.00
Heat Recovery	0.00
Water Systems	0.00
Refrigeration	0.00
Generators	0.00
Total End Uses	483845.72

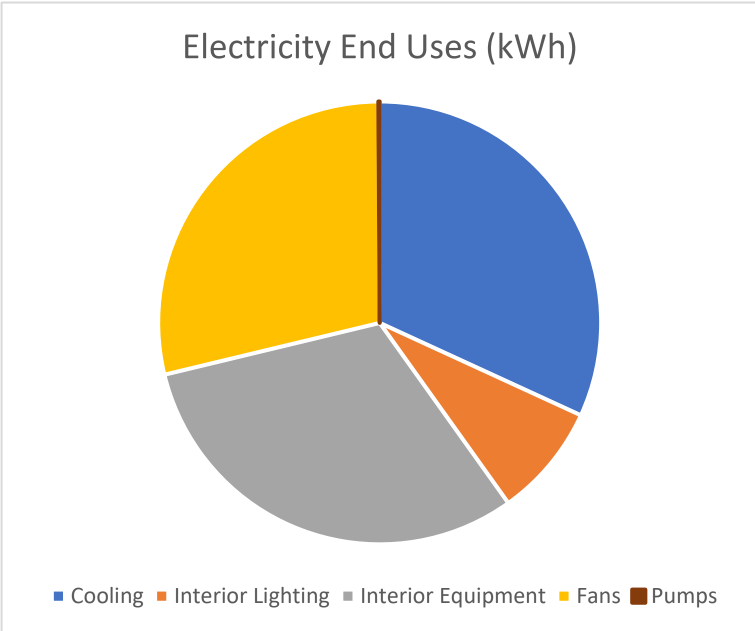

Figure 38 Electrical End Uses and Figure 39 Chart of total end-use electricity

The total HVAC system includes the cooling, fans and pump systems.

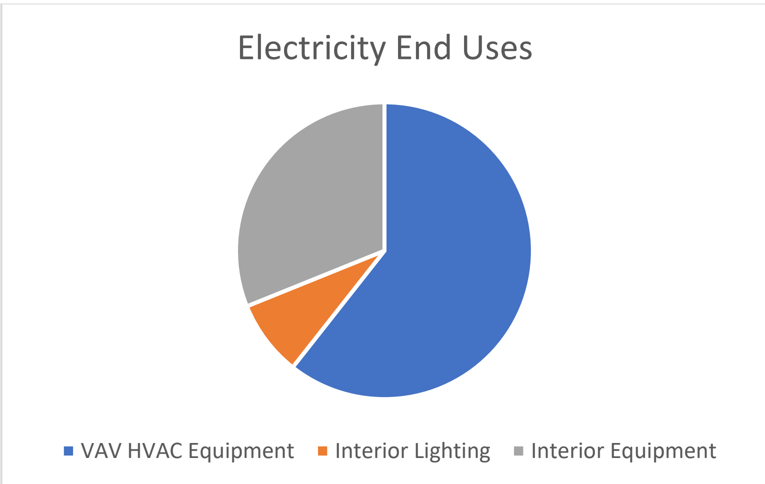

Figure 40 Total electricity end uses

$$Annual\ HVAC\ electricity \left(\frac{MWh}{yr}\right) = 154254.7 \left(\frac{kWh}{yr}\right) + 138773.62 \left(\frac{kWh}{yr}\right) + 481.28 \left(\frac{kWh}{yr}\right) \quad (22)$$

$$Annual\ HVAC\ electricity\ \left(\frac{MWh}{yr}\right) = 293509.6\frac{kWh}{yr} = 293.5MWh/yr \quad (23)$$

The PV annual yield was designed to match that the annual HVAC consumption of electricity.

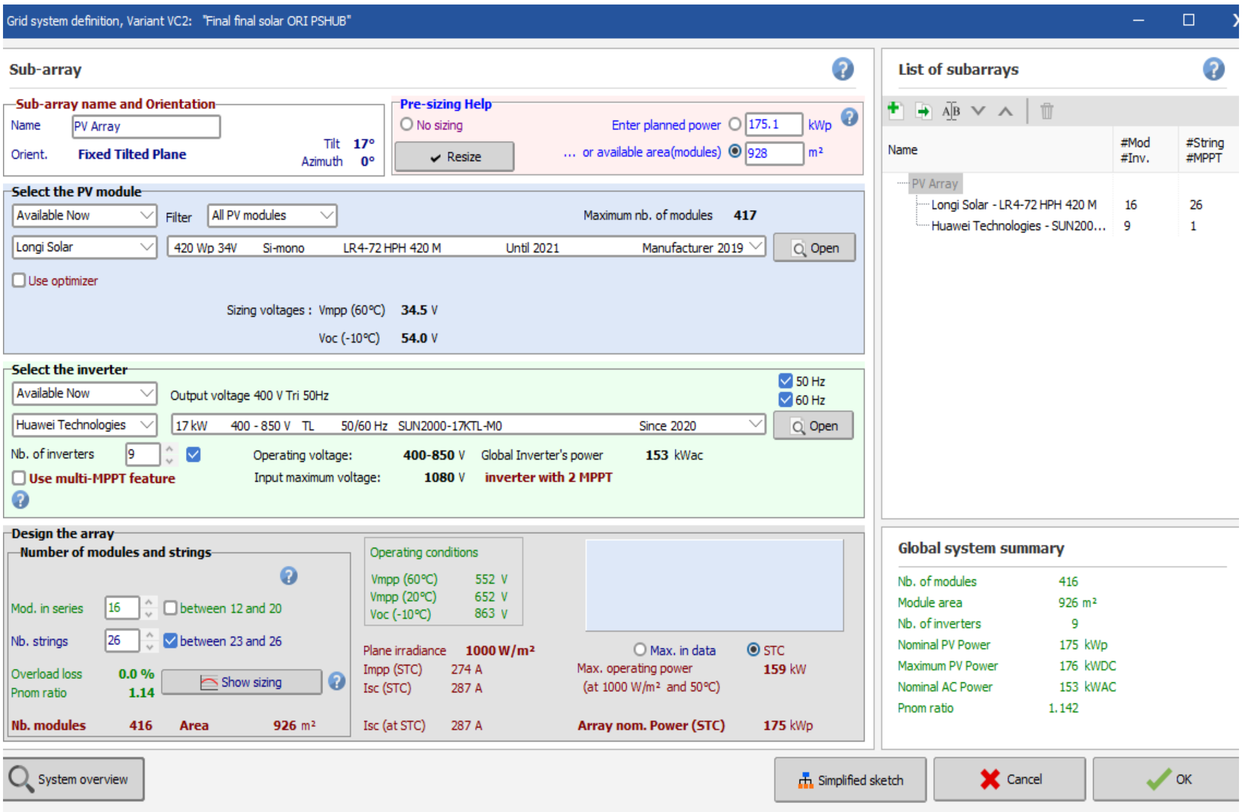

Figure 41 PV system sizing parameters

A 175.1 kW_p grid-connected PV system was designed, requiring a module area of 928 m^2 to be covered by 416 modules. The system sizing parameters used for the simulations are shown in Figure 41.

3.5.3 PV Design

The DesignBuilder PV system was sized according to the specifications mentioned above with the grid connection to determine the PV yield and grid electricity contribution. Find below figures of the PV system sizing.

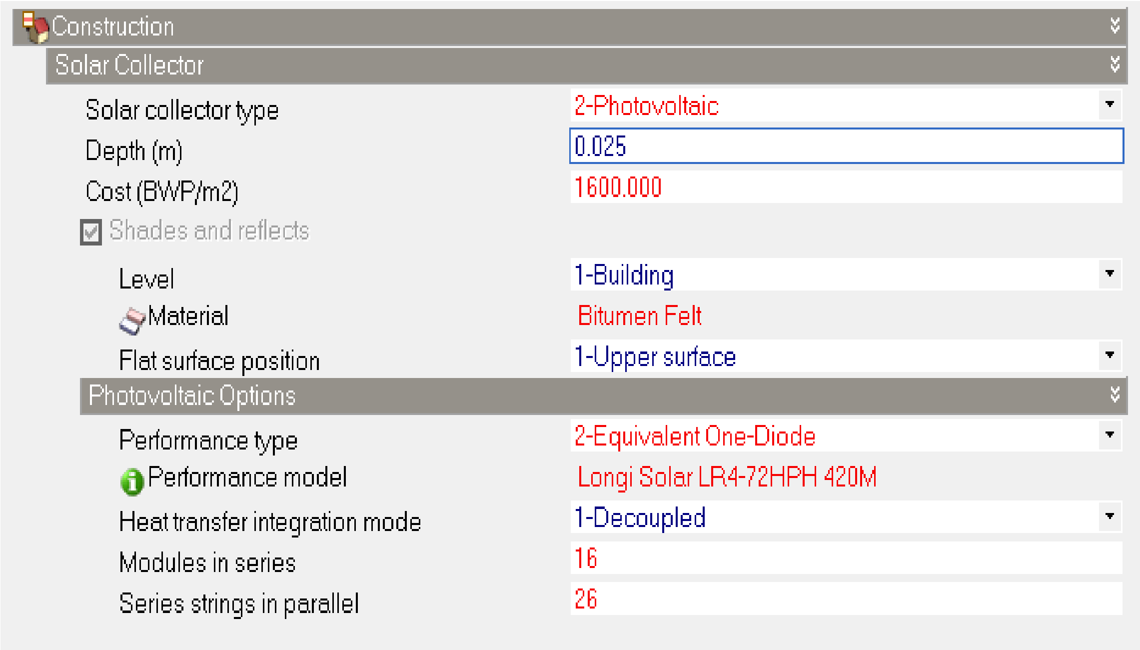

Figure 42 PV construction tab

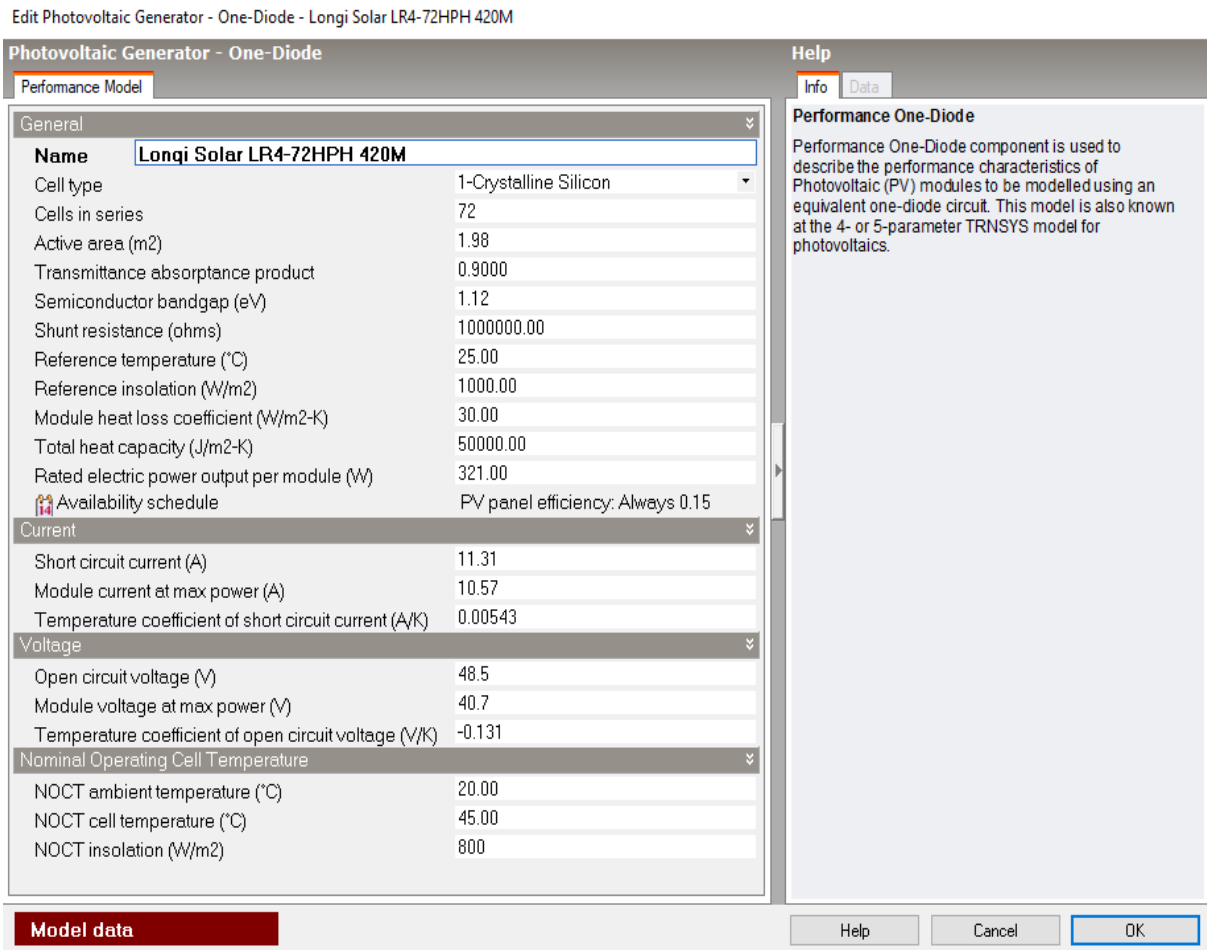

Figure 43 PV module performance model

3.6 Economic Evaluation

The bankability of the solar installation was determined through the Levelized Cost of Energy (LCOE) financial tool was used to measure the lifetime costs by the energy production. A lower LCOE means that the electricity generation is produced at a generally lower price and lower payback period, with likely higher returns for the investor. The LCOE calculates the total solar installation costs, operations, and maintenance net present value over the assumed project lifetime.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (24)$$

Where,

$$I_t = investment\ expenditure\ in\ year\ t$$

$$M_t = Operations\ and\ Maintenance\ expenditure\ in\ year\ t$$

$$E_t = Electricity\ generation\ in\ year\ t$$

$$r = Discount\ rate$$

$$n = Project\ lifetime\ of\ the\ system$$

Estimate costs for the solar installation are presented in the Bill of quantities (BOQ) below. The prices were obtained from a solar PV installation company based in Gaborone.

Table 14 Bill of quantities

Description		**Quantity**	**Unit Price (BWP)**	**Total (BWP)**
PV Module	LR 4-72 HPH 420 M	416	2 000.00	832 000.00
	Support for modules	416	20.00	8 320.00
Inverters	SUN2000-17KTL-M0	9	5 000.00	45 000.00
Other components	Accessories, fasteners	416	20.00	8 320.00
	Wiring	450m	10.00	4 500.00

	Combiner box	9	1 000.00	9 000.00
	Monitoring system	1	6 000.00	5 000.00
	Measurement system	2	2 000.00	4 000.00
	Surge arrester	5	1 000.00	5 000.00
Installation	Global installation per module	416	200.00	83 200.00
	Global installation per inverter	9	500.00	4 500.00
	Grid Connection	1	5 000.00	5 000.00
Total installation cost			1 014 840 .00 BWP	
Operating Costs (Yearly)				
Description			**Yearly Cost (BWP)**	
Maintenance	Salaries		8 000.00	
	Repairs		2 500.00	
	Cleaning		2 500.00	
Insurance	Facilities Insurance		20 000.00	
Operating costs (OPEX)			33 000.00 BWP/year	
*Project Lifetime= 20years				
*Fixed feed-in tariff= 0.350 BWP/kWh				
*Self-consumption tariff= 0.500 BWP/kWh				

Chapter 4: Results and Discussion

The study examined the internal and external temperature profile, cooling demand, and energy consumption for the case study building model. The simulation focused on the annual results of a test reference year and zooming into monthly graphs to understand seasonal variations.

4.1 DesignBuilder Simulation Results

Having built the model from scratch on DesignBuilder, simulations were carried out for the whole building, taking a closer and the herbarium zone.

Figure 44 shows a graphical display of heat balance contribution from the walls, internal partition, floors, and external infiltration into the room, contributing to the heat balance of the herbarium.

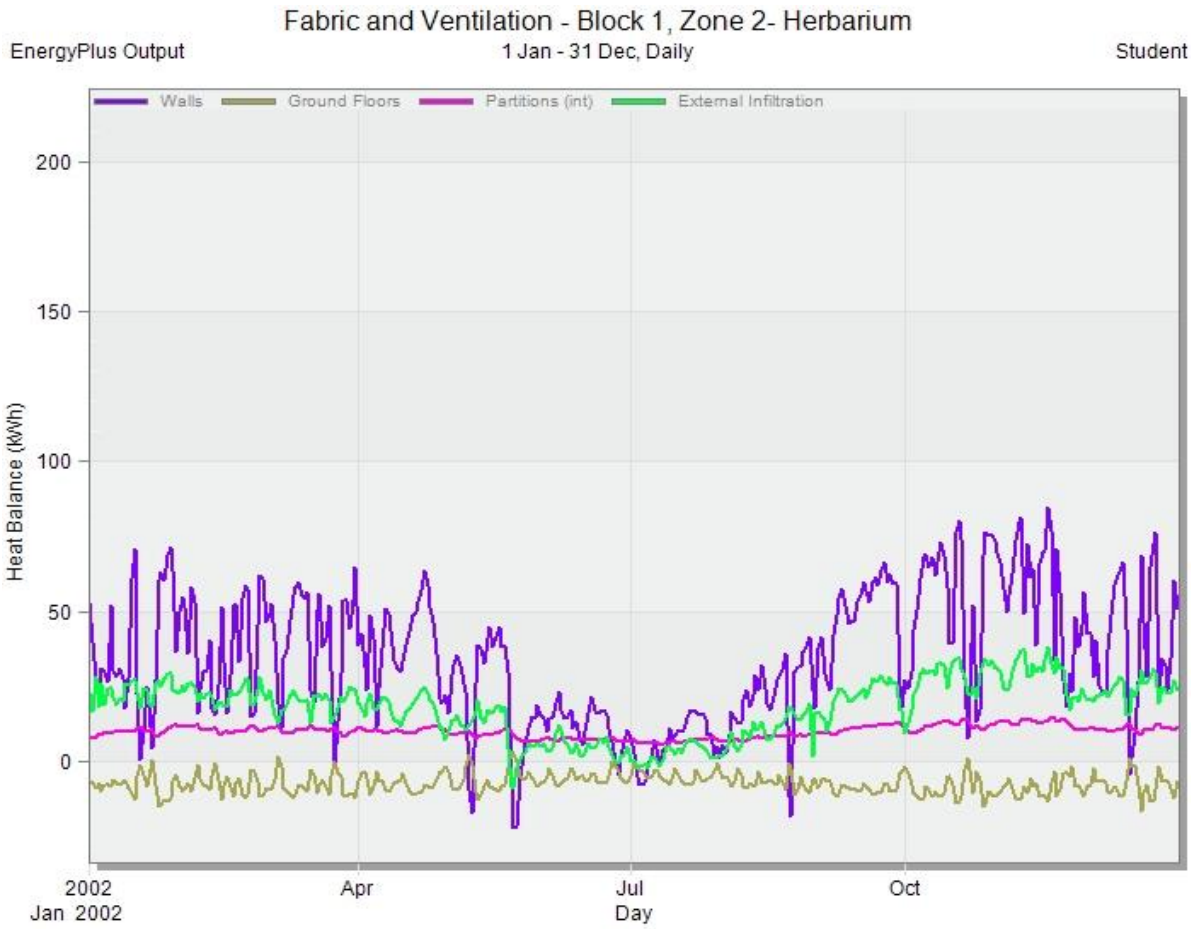

Figure 44 Walls, Fabric and Ventilation

The thermal influence into the herbarium shows a higher contribution from the walls, the internal partition and external infiltration. This demonstrates that although the herbarium is located on the ground floor, the sun's normal rays still significantly affect the room, although not direct. In contrast, the negative value on the ground floor heat balance demonstrates that the ground absorbs some heat, unlike the walls, acting as a heat bank.

Figure 45 shows the annual internal gains in the herbarium. The general lighting and occupancy and computer + equipment are the main internal heat gain contributors in the herbarium, showing a constant annual trend. The zone sensible cooling load shows how much energy must be removed from the herbarium room, including the contribution of the elements in Figure 44, to maintain the required room temperature. The graph shows a reduction in sensible cooling load, during the winter period between May and September, representing the dry bulb temperature profile.

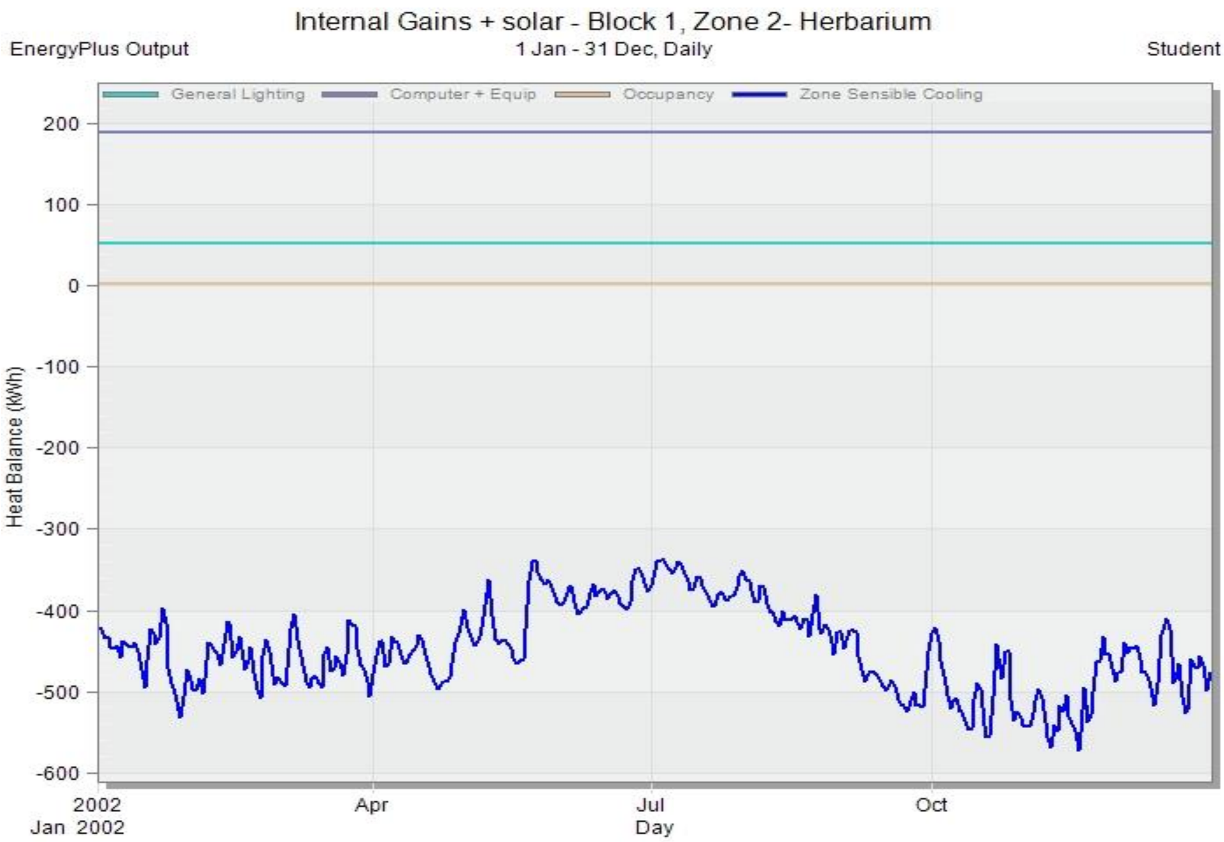

Figure 45 Herbarium Annual Internal Heat Gain

The climate-controlled herbarium is set to operate the HVAC system at a constant temperature of 16°C throughout the whole year, at a constant supply temperature of 14°C.

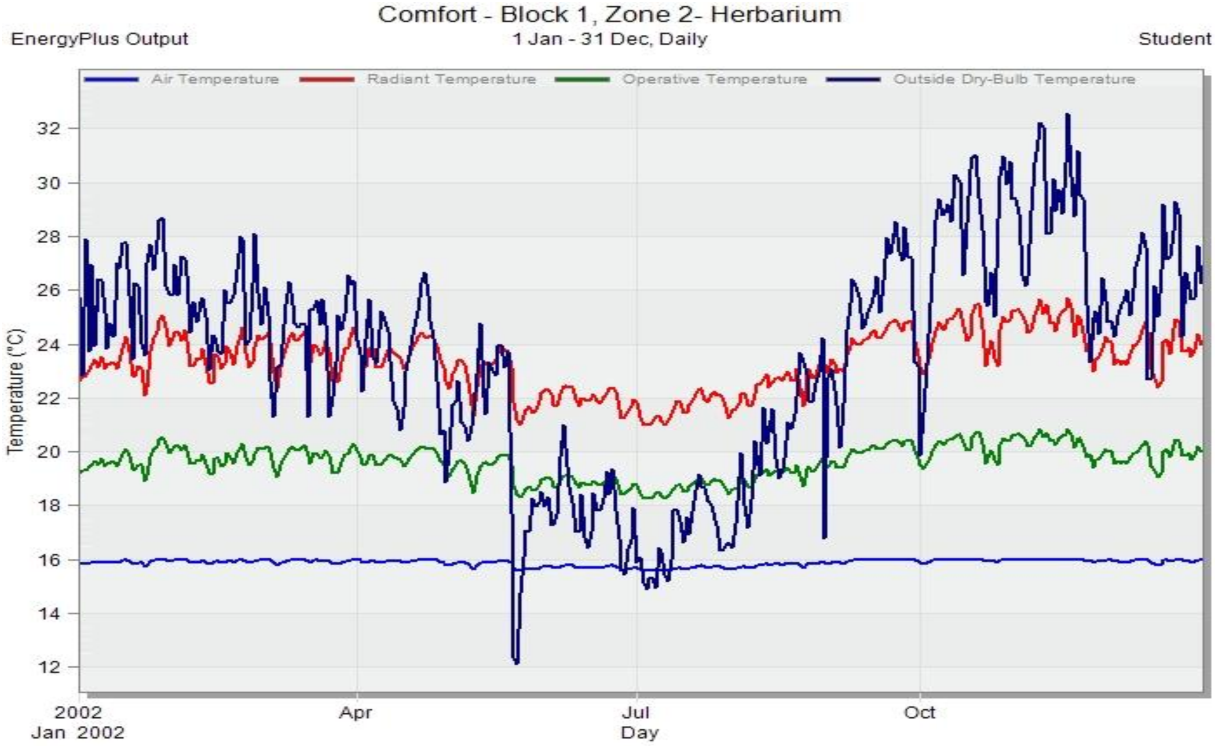

Figure 46 Annual Herbarium Temperature Profile

Figure 46 shows the different temperature variations playing a role in the herbarium.

The outside dry-bulb temperature is the outside temperature which varies according to seasons, dipping below the set air temperature, at 12°C in May. The radiant temperature is the ambient temperature in the room without cooling. At the same time, the operative temperature is the perceived comfort temperature or the average of air and radiant temperature. The air temperature, which is the measure of the room condition, is maintained at 16°, within the herbarium recommended standards range. The air temperature line shows the slight effect of the outside and radiant temperatures and a suitable HVAC to maintain the required temperature.

Figure 47 shows the ability of the HVAC system to match the cooling requirements needed for the herbarium. The graph demonstrated that the system was appropriately sized to meet the desired needs. The heat removed by the chiller, during the winter period was significantly lower than other periods of the year.

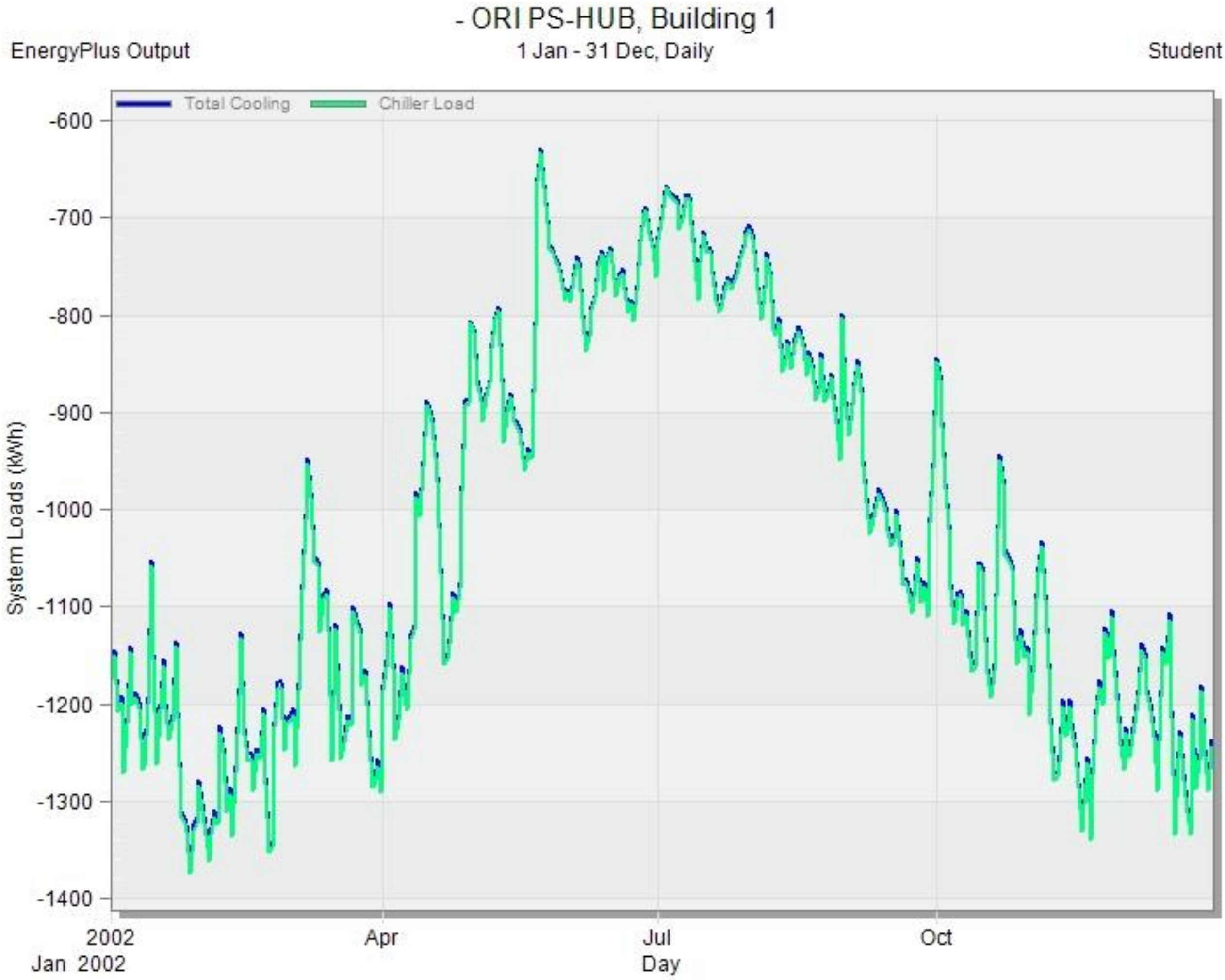

Figure 47 HVAC system load

Figure 48 shows the annual HVAC energy consumption for the herbarium and the VAV system component contribution.

Figure 49 shows the room electricity and lighting show a steady trend throughout the year because the room electricity remains constant without new equipment or a change in usage styles. The room electricity and lighting also show a decline in electricity use over weekends due to the 6-day work week, peaking at 450 and 115 kWh respectively. The system fans and cooling element show an uneven tread of electricity use throughout the year, peaking at 460 kWh for the cooling (chiller) electricity use in November. The fan is slightly lower at 440 kWh. The cooling and fans electrical consumption decreases during the winter season from June to August, showing that with cooler outdoor temperatures, less cooling power is needed.

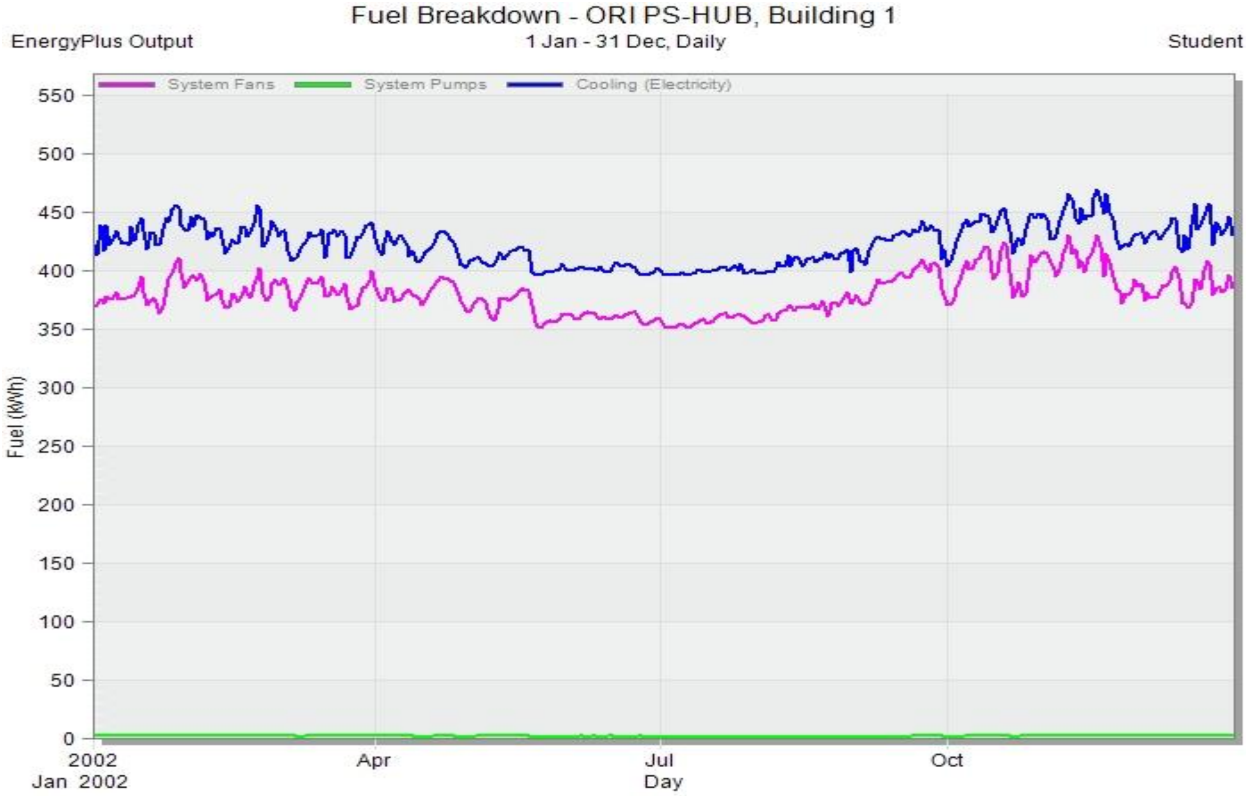

Figure 48 HVAC system components electrical breakdown

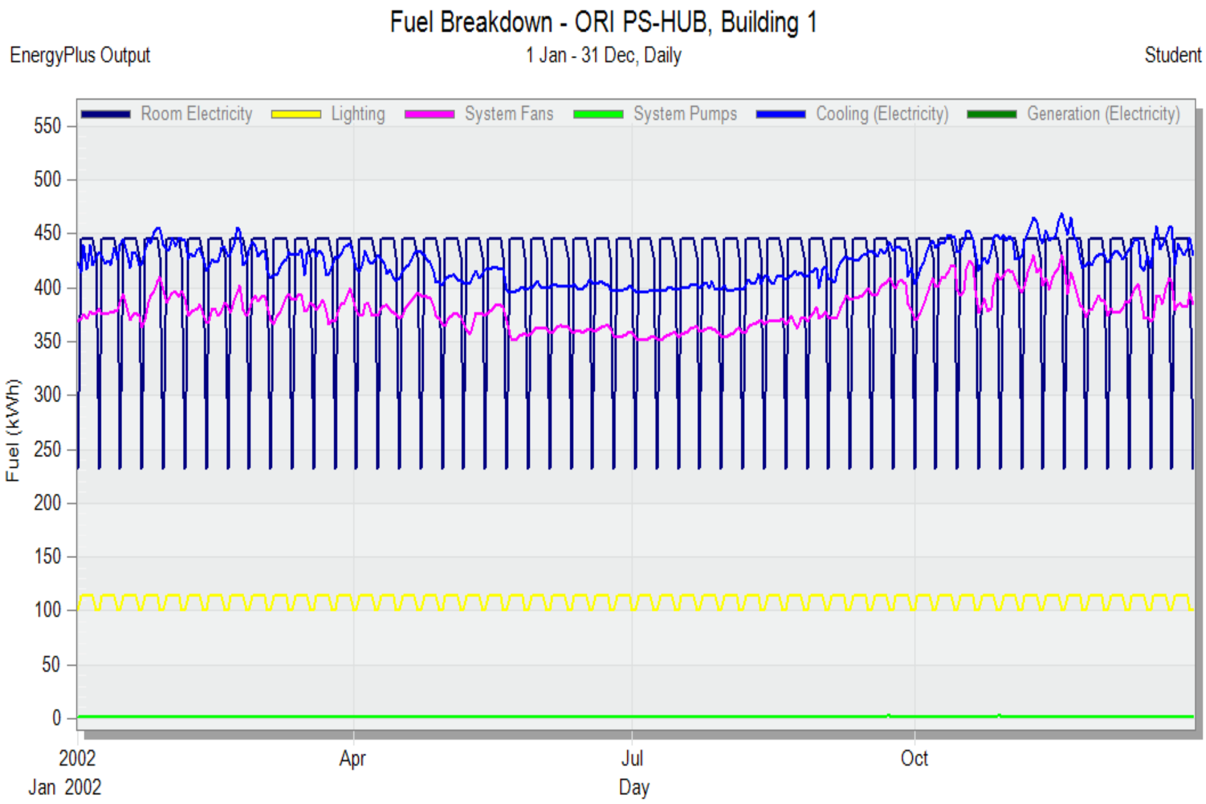

Figure 49 Building Annual Energy Consumption

Figure 50 below shows the total energy consumption for electrical components in a bar graph over the TRY period.

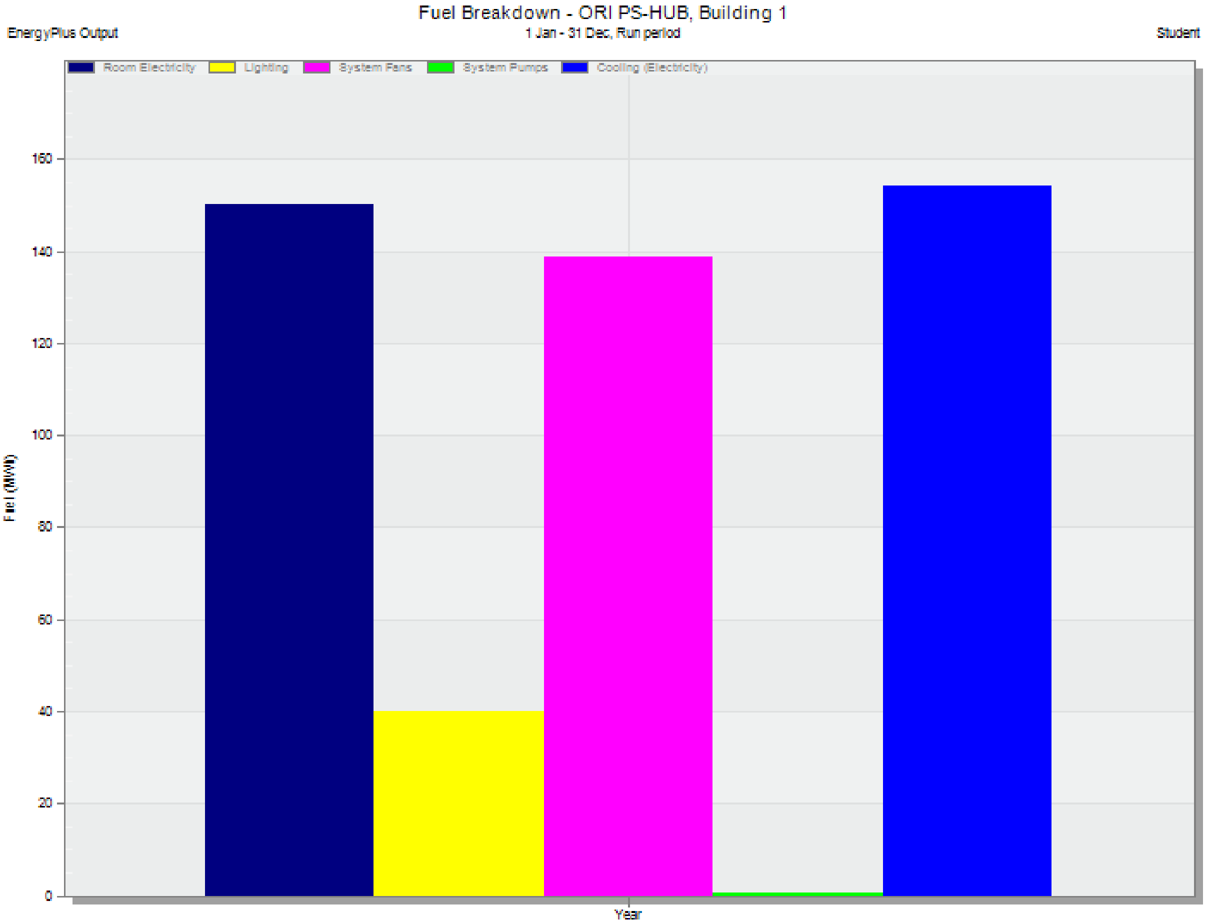

Figure 50 Whole Building Internal Gains Profile

While Figure 51 shows the annual electrical breakdown of building in tabular form.

Fuel Breakdown - ORI PS-HUB, Building 1

EnergyPlus Output — 1 Jan - 31 Dec, Run period — Student

	Year
Room Electricity (MWh)	150.37
Lighting (MWh)	40.03
System Fans (MWh)	138.74
System Pumps (MWh)	0.48
Cooling (Electricity) (MWh)	154.22

Figure 51 Annual total electrical breakdown

Figure 52 demonstrates the electric source contribution onsite and from the utility grid. The simulation showed an annual photovoltaic power contribution of 334 214.6 kWh with 4679kWh lost during DC to AC conversion. The annual PV power produced accounted for 68.11%, roughly 2/3 required for cooling. At the same time, the remaining electricity came from the electric utility grid to cover the other equipment and lighting account to 31.89%.

A limitation of the DesignBuilder software was that the simulation does not show dynamic simulation results of the monthly or daily results for electrical or energy loads.

Electric Loads Satisfied

	Electricity [kWh]	Percent Electricity [%]
Fuel-Fired Power Generation	0.000	0.00
High Temperature Geothermal*	0.000	0.00
Photovoltaic Power	334214.612	69.07
Wind Power	0.000	0.00
Power Conversion	-4679.00	-1.0
Net Decrease in On-Site Storage	0.000	0.00
Total On-Site Electric Sources	329535.607	68.11
Electricity Coming From Utility	222625.941	46.01
Surplus Electricity Going To Utility	68315.824	14.12
Net Electricity From Utility	154310.116	31.89
Total On-Site and Utility Electric Sources	483845.723	100.00
Total Electricity End Uses	483845.723	100.00

Figure 52 Energy Contribution

Figure 53 displays the electricity consumed in the whole building compared to the PV electricity to drive the HVAC unit. The graph affirms that approximately 1400kWh of electricity is needed in the building daily. On the other hand, around 1100kWh is produced by the PV system used for the HVAC unit.

Figure 54 demonstrates the total electrical usage in comparison to the solar PV electricity generated over the TRY.

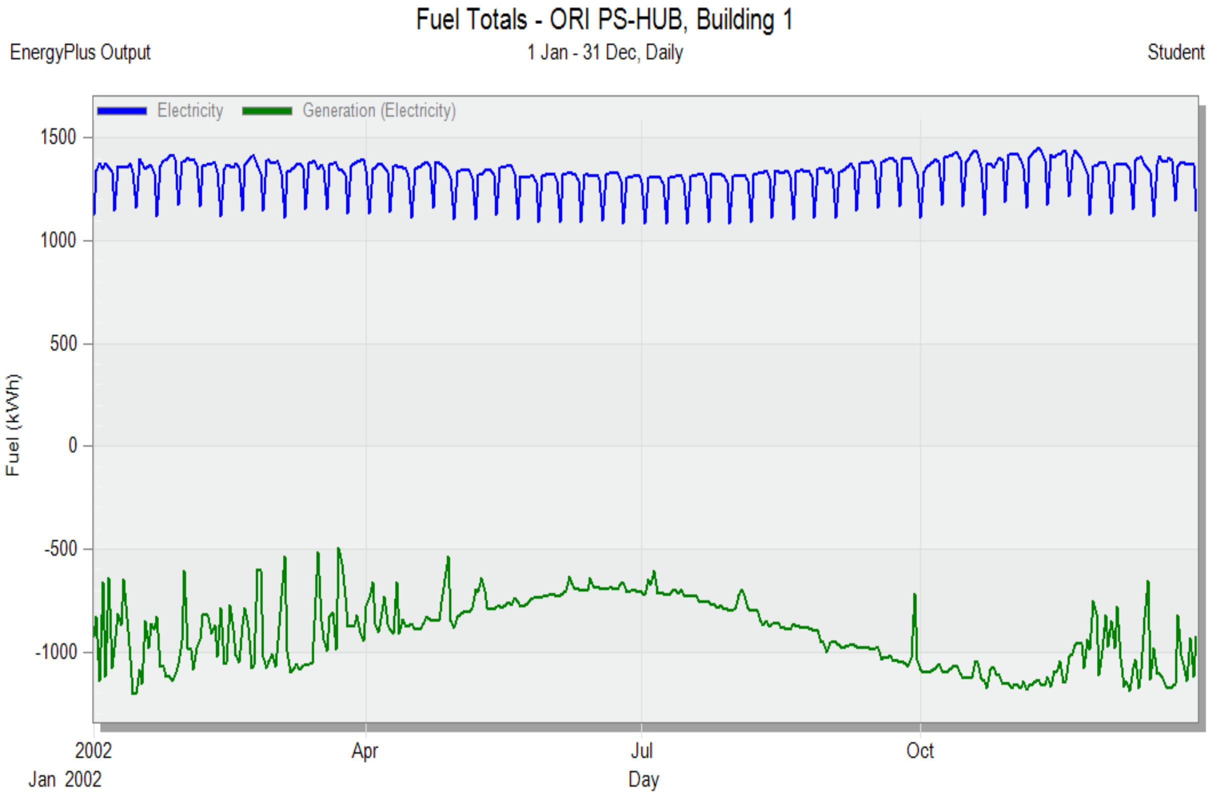

Figure 53 Energy Totals

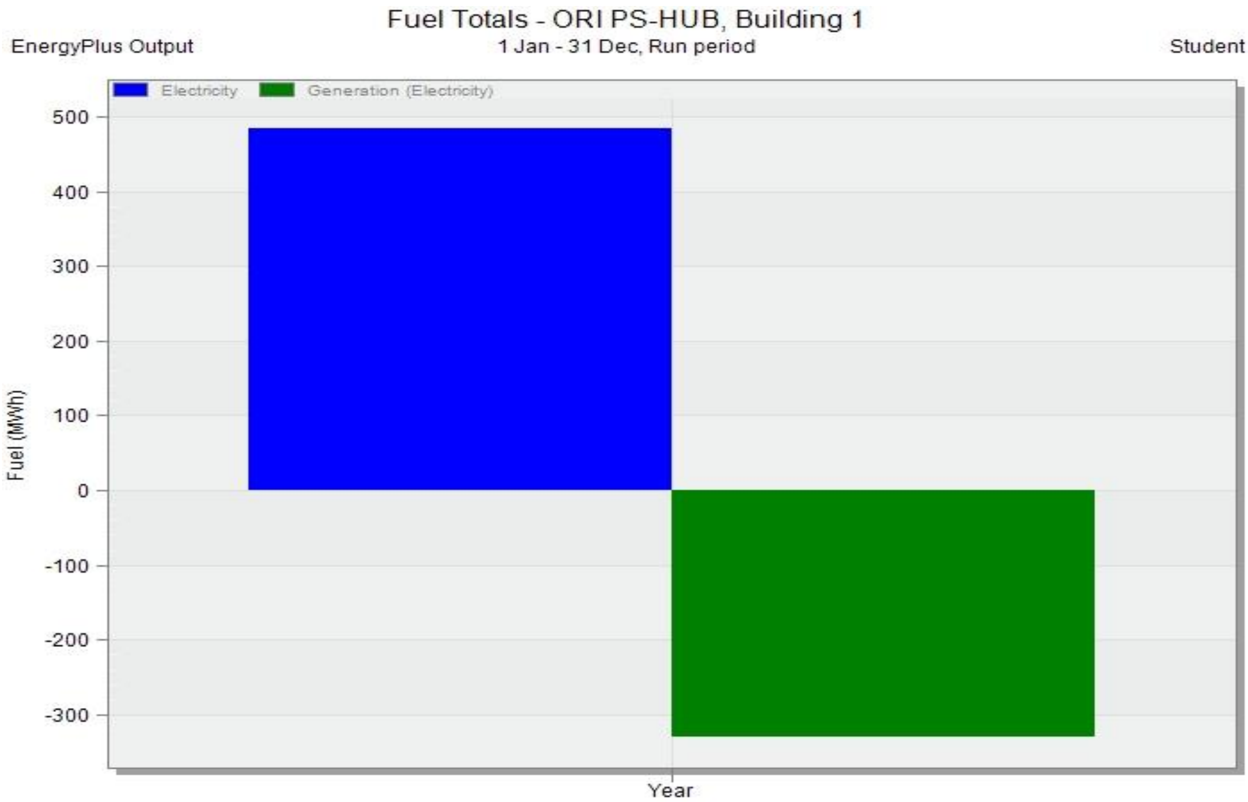

Figure 54 Energy consumption and production distribution

4.2 Economic Analysis

Installation of PV systems is a great alternative to conventional systems, contributing significantly to climate change. Investment into cleaner alternatives requires substantial financial investments. However, PV systems can payback the investment and have further profit with time. Various factors such as the initial investments costs, loan rates, maintenance, repair costs, cleaning, replacement costs, and others need to be considered. Initial investment costs involve the design, installation, devices, material, and connection to the grid.

The cost of produced energy (LCOE) was determined at 0.265 BWP/kWh. At a payback period of 8.8 years, a Net present value (NPV) of BWP 1 291 535.00 and a Return on investment (ROI) of 11.4% annually. 100% self-financing was assumed. Inflation was assumed at 0% and tariffs were assumed to be fixed over the project's lifespan.

Chapter 5: Conclusion

This research project aimed to study the performance and potential of solar cooling systems for use in Botswana. The study of building performance is essential to understanding and improving system sizing, energy consumption and general operations of a building.

5.1 Main Conclusions

The design, modelling and simulation for the solar-powered air-conditioning system were carried out with the DesignBuilder simulation environment to fulfil the objectives of this research. DesignBuilder allowed detailed analysis and characterization of the building. The illustration, the HVAC system and herbarium were modelled with software with more minute specifications in DesignBuilder, such as building material, occupancy, and schedules. The calculated and simulated results showed that:

- A variable-air volume HVAC system sized at 30kW, to maintaining the thermal environment of the herbarium at approximately 16°C throughout the year.
- The simulation results showed that 293 509.60 kWh of electricity is spent annually on the HVAC system.
- The solar PV system was dimensioned to meet this power need at a nominal power of 175.1 kWp of 416 modules, covering an area of 928m^2.
- The area required for solar module installation is slightly higher than the available roof space, requiring some of the modules to be mounted on the ground or solar parking space. This could affect the value of the power produced by these modules and module shading, which was not factored in for this research.
- The simulation also showed that over 68.9% of the electricity used in the building was attributed to HVAC system and the photovoltaic system was capable of powering the HVAC system completely, thus fulfilling the research objectives.
- The economic analysis using PVsyst showed that although the initial investment for the solar PV is exceptionally high at 1 014 840.00 BWP, at an assumed operating cost of 33 000 BWP/year, the investment would be recouped within 8.8 years, with an ROI of approximately 11.4% annually, at a self-consumption rate 0.500 BWP/kWh. The project was also assumed to be self-financed.
- Tariffs, inflation and taxes changes were, however, not factored into the model.
- Therefore, at an estimated project lifetime of 20 years, the Net-Present Value is projected at 1 291 535.00 BWP, with 86 000 tons of CO_2 saved in the first year of the project lifetime and 74 055.57 tons of CO2 saved at the end of the project lifetime.

Undoubtedly, the research showed that solar PV powered HVAC systems have great economic and performance potential in Botswana. However, further extensive research still needs to be carried out on their real-life installed operation and guarantee by academia and industry in the country. Nevertheless, from the simulations, we can conclude that the solar-powered HVAC system could be a feasible future solution, significantly reducing the carbon footprint.

The initial software which was to be used to carry out the research, MATLAB/Simulink CARNOT, provided limitations to the research as the choice in chiller modelling was limited, and the models required significant modifications and characterization to suit the required settings of the model. The CARNOT simulations also presented significant challenges in the running of the simulation. In addition, the model was too heavy for the computers in the university, and technical software issues created bottlenecks in the completion of the research. The work that was carried out using CARNOT has been provided in Appendix 4.

5.2 Future Work

Further extensive research needs to be carried out on energy-efficient buildings in Botswana, and the role building energy modelling can play in understanding building operations, solar cooling potential and energy consumption reduction.

Many limitations exist as there are gaps in published data about the energy landscape in Botswana.

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Appendix

Appendix 1

Table A-3 Climate Zone Definitions (taken from Proposed Addendum b to Standard 169, Climate Data for Building Design Standards).

Thermal Zone	Name	I-P Units	SI Units
0	Extremely Hot – Humid (0A), Dry (0B)	10,800 < CDD50°F	6000 < CDD10°C
1	Very Hot – Humid (1A), Dry (1B)	9000 < CDD50°F ≤ 10,800	5000 < CDD10°C ≤ 6000
2	Hot – Humid (2A), Dry (2B)	6300 < CDD50°F ≤ 9000	3500 < CDD10°C ≤ 5000
3A and 3B	Warm – Humid (3A), Dry (3B)	4500 < CDD50°F ≤ 6300 AND HDD65°F ≤ 3600	2500 < CDD10°C < 3500 AND HDD18°C ≤ 2000
3C	Warm – Marine (3C)	CDD50°F ≤ 4500 AND HDD65°F ≤ 3600	CDD10°C ≤ 2500 AND HDD18°C ≤ 2000
4A and 4B	Mixed – Humid (4A), Dry (4B)	2700 < CDD50°F ≤ 6300 AND 3600 < HDD65°F ≤ 5400	1500 < CDD10°C < 3500 AND 2000 < HDD18°C ≤ 3000
4C	Mixed – Marine	CDD50°F ≤ 2700 AND 3600 < HDD65°F ≤ 5400	CDD10°C ≤ 1500 AND 2000 < HDD18°C ≤ 3000
5A and 5B	Cool– Humid (5A), Dry (5B)	1800 < CDD50°F ≤ 6300 AND 5400 < HDD65°F ≤ 7200	1000 < CDD10°C ≤ 3500 AND 3000 < HDD18°C ≤ 4000
5C	Cool – Marine (5C)	CDD50°F ≤ 1800 AND 5400 < HDD65°F ≤ 7200	CDD10°C ≤ 1000 AND 3000 < HDD18°C ≤ 4000
6A and 6B	Cold – Humid (6A), Dry (6B)	7200 < HDD65°F ≤ 9000	4000 < HDD18°C ≤ 5000
7	Very Cold (7)	9000 < HDD65°F ≤ 12600	5000 < HDD18°C ≤ 7000
8	Subarctic/Arctic (8)	12600 < HDD65°F	7000 < HDD18°C

The criteria for dry and humid are similar but not identical to those enumerated in Table 2B above.

Figure 55 ASHRAE Climate Zone definitions (Stackhouse *et al.*, 2015)

Appendix 2

Originally Proposed Floorplan

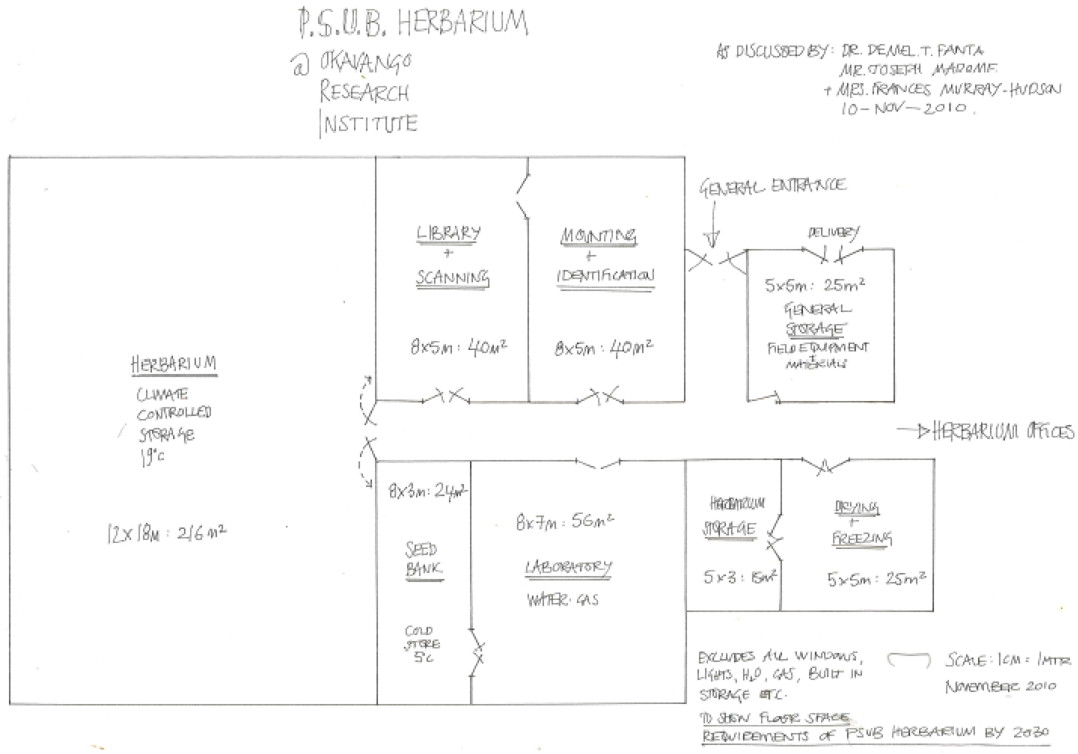

Figure 56 Proposed floorplan herbarium wing

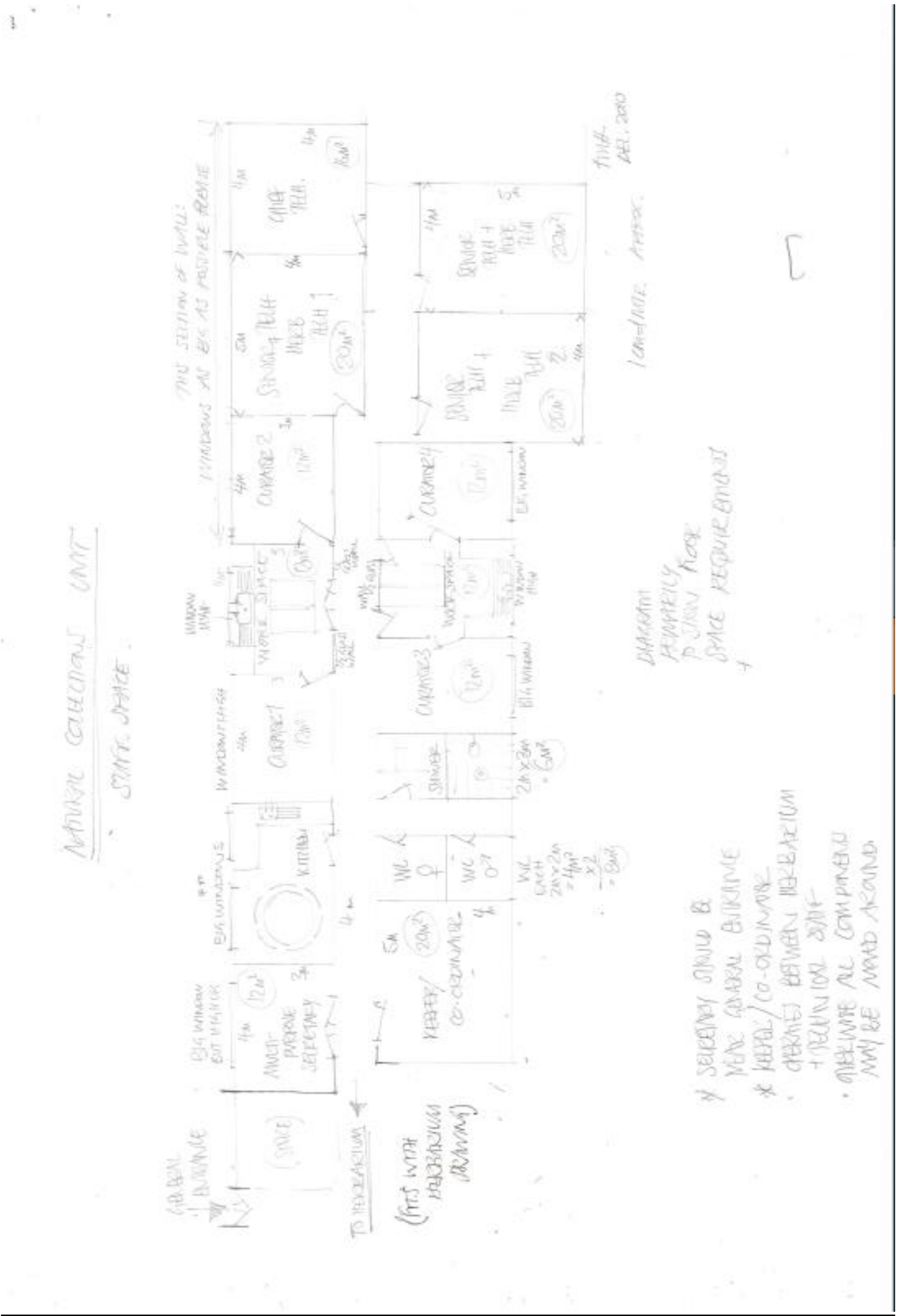

Figure 57 Proposed floorplan wing

Appendix 3

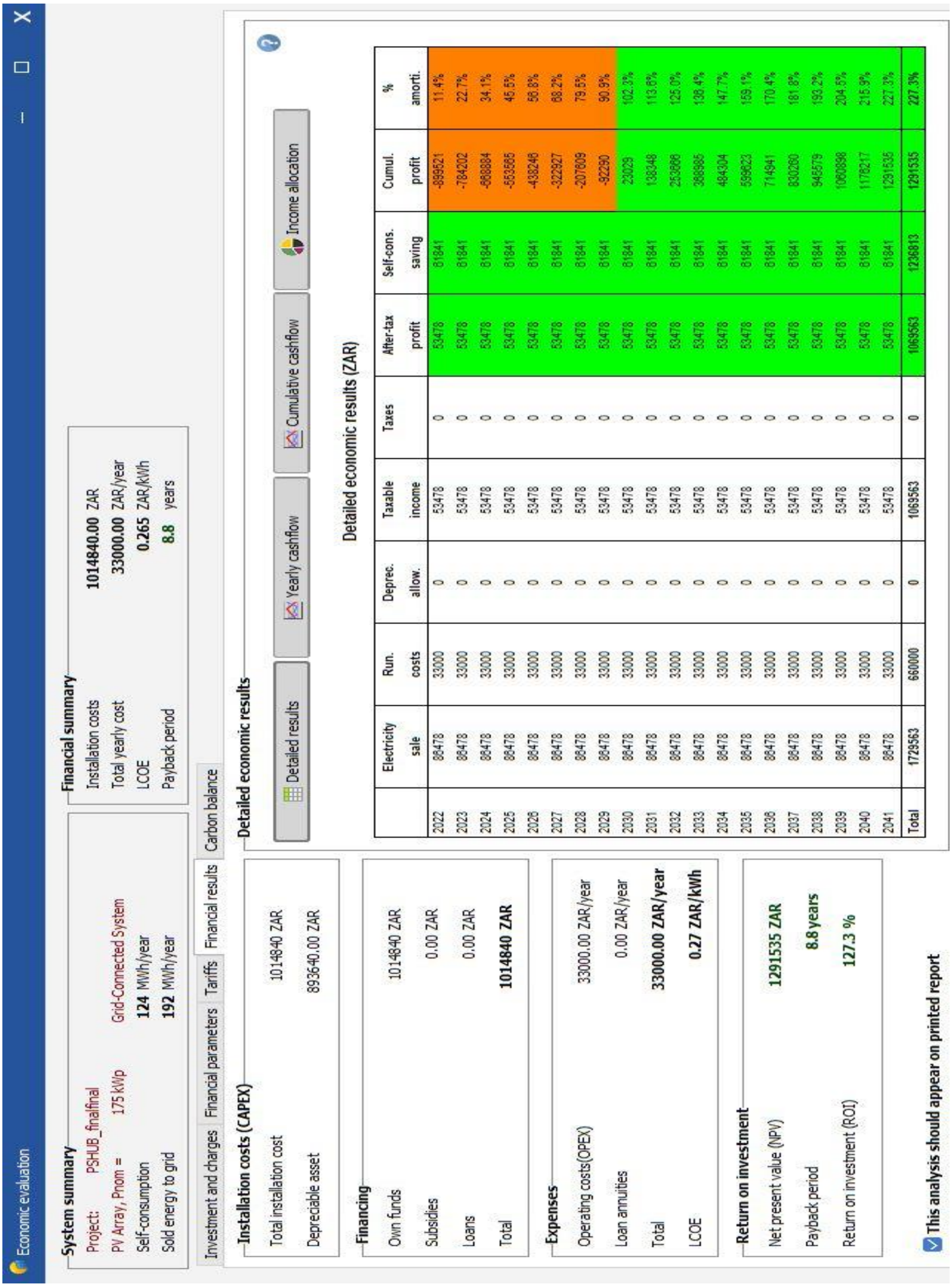

Figure 58 Economic Evaluation

Appendix 4

Herbarium April Results- Autumn

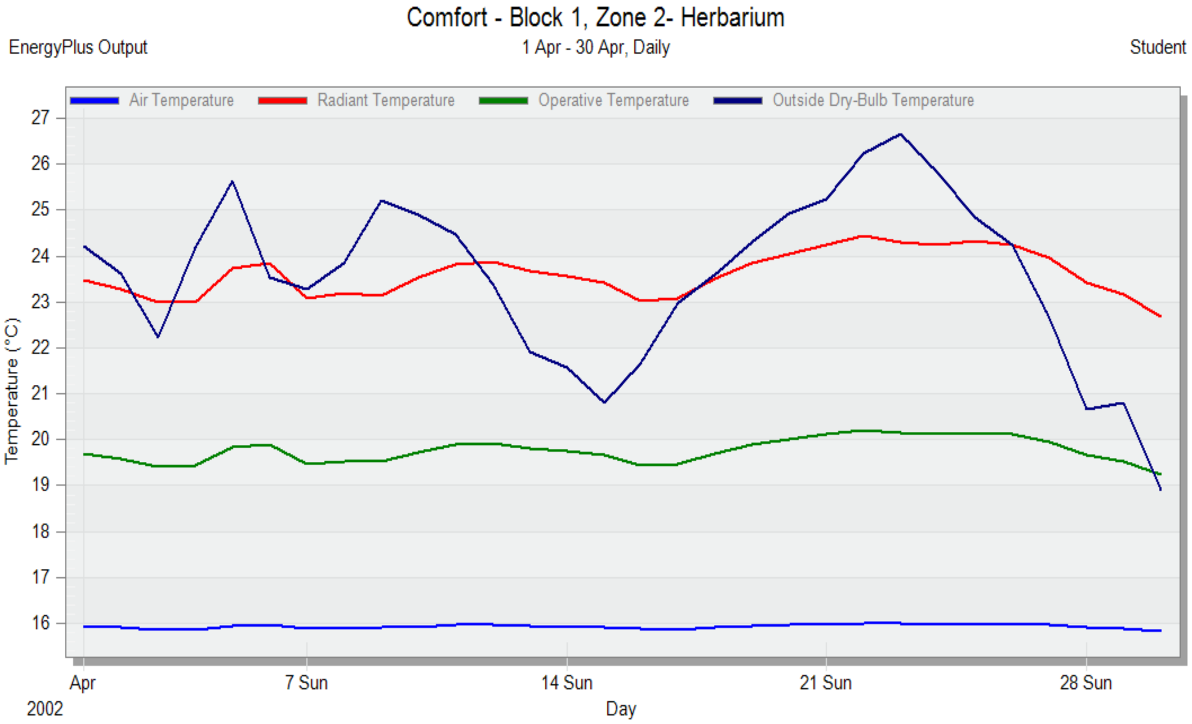

Figure 59 April herbarium temperature profile

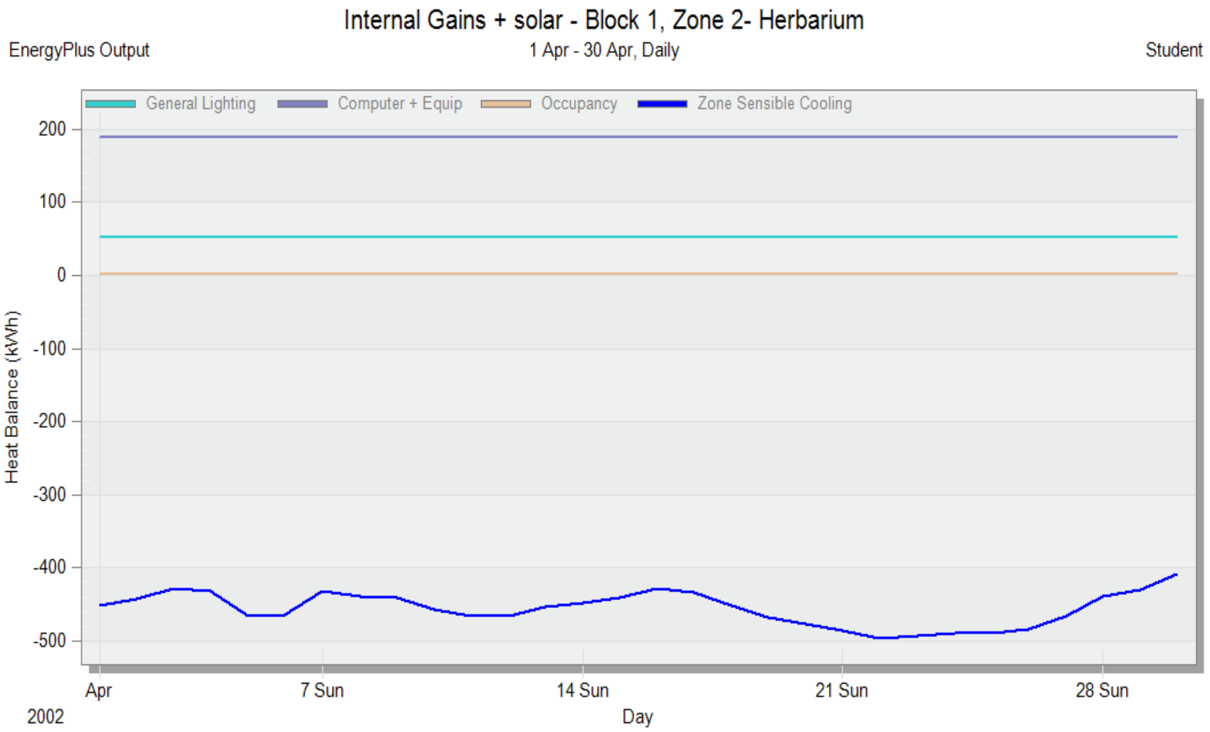

Figure 60 April internal gain profile

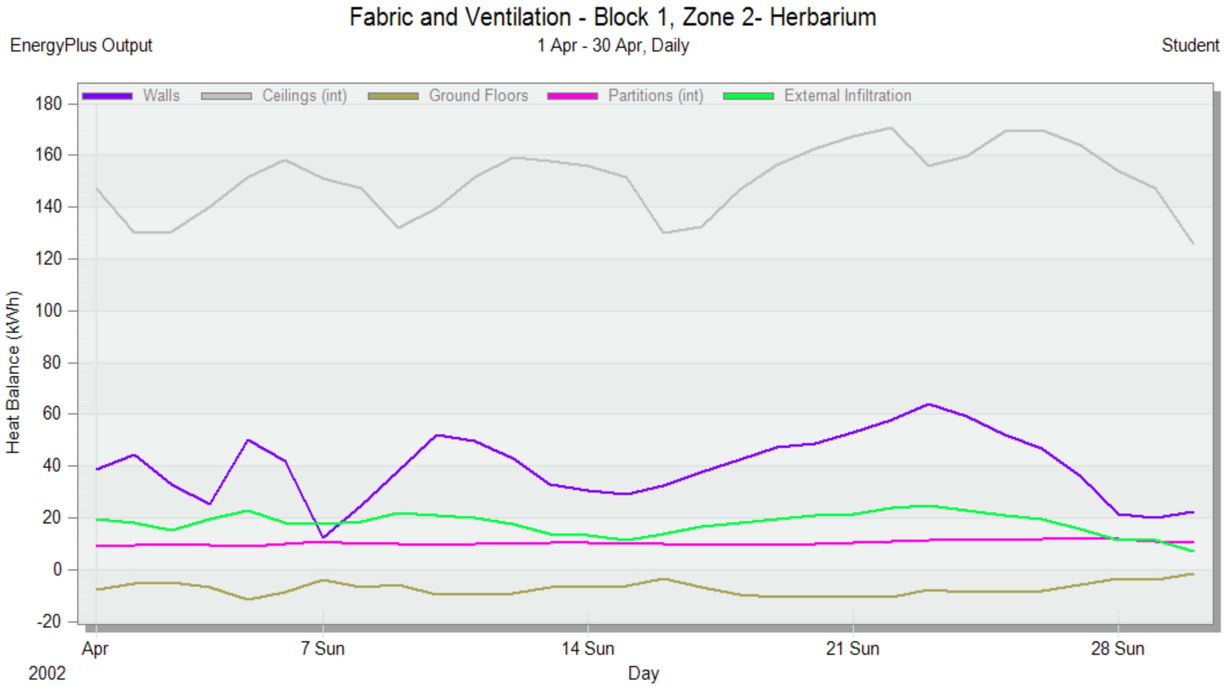

Figure 61 April fabric and vent profile

Herbarium June Results- Winter

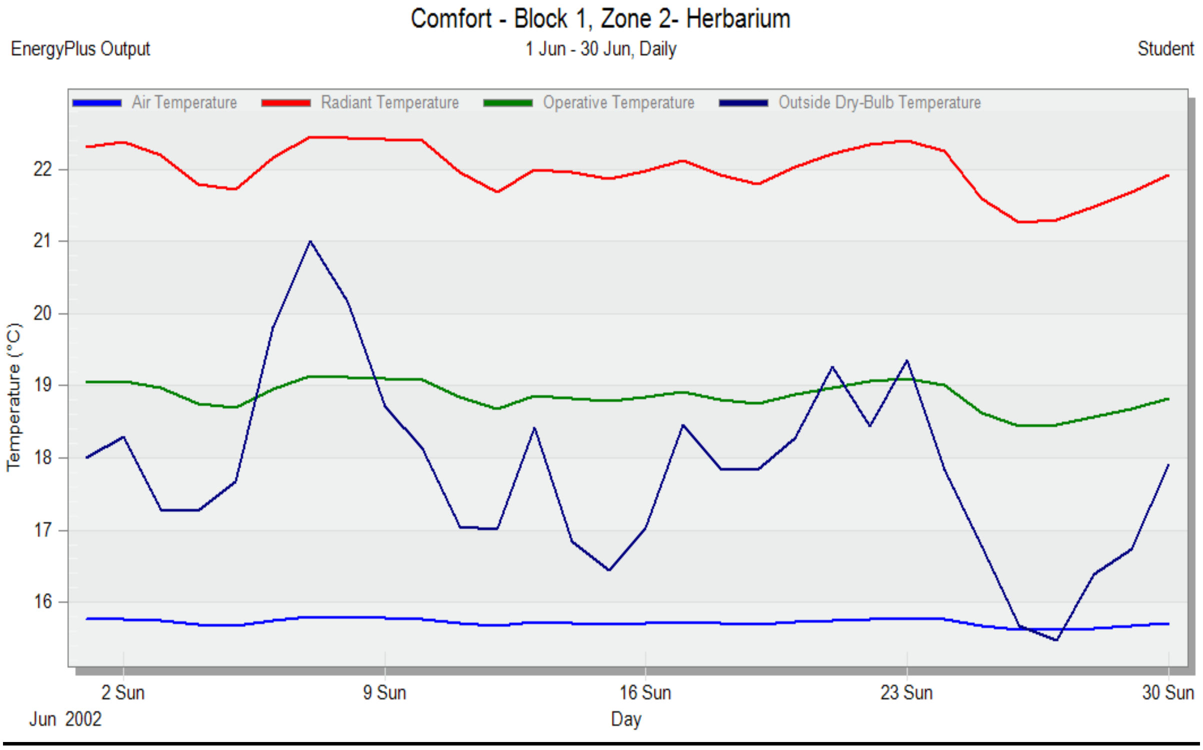

Figure 62 June temperature profile

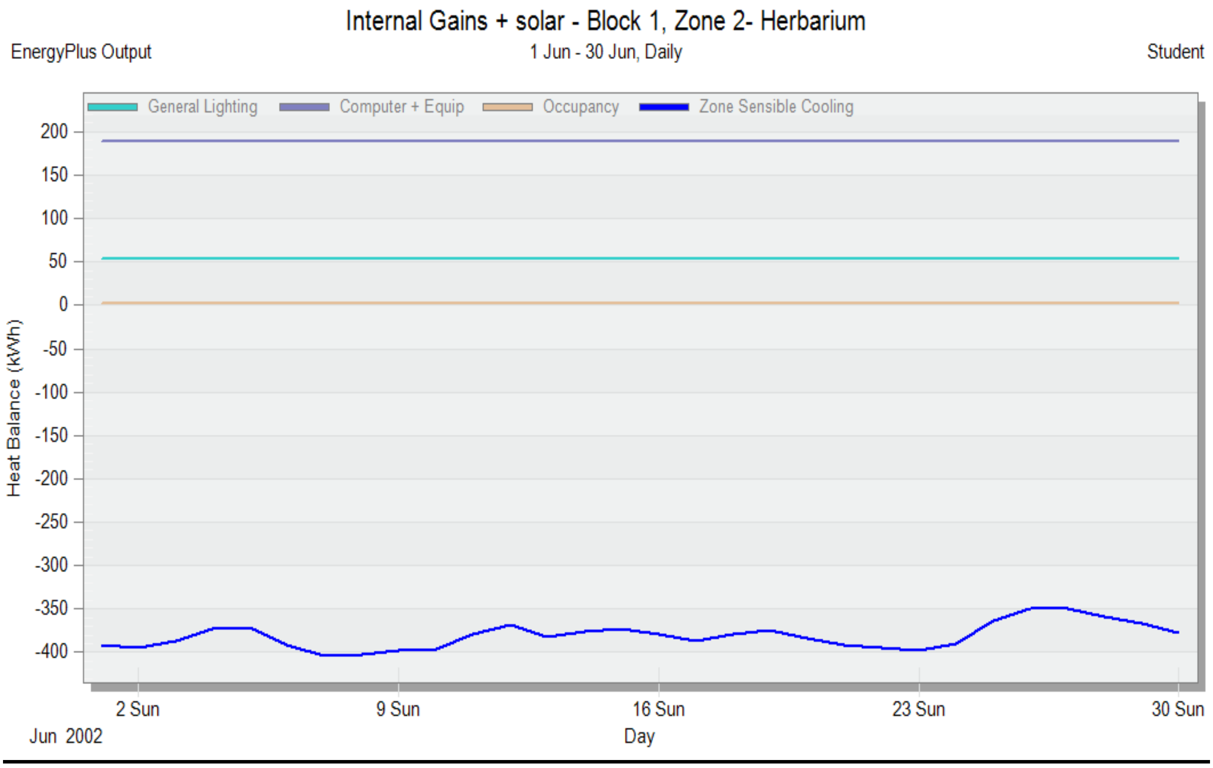

Figure 63 June internal gain profile

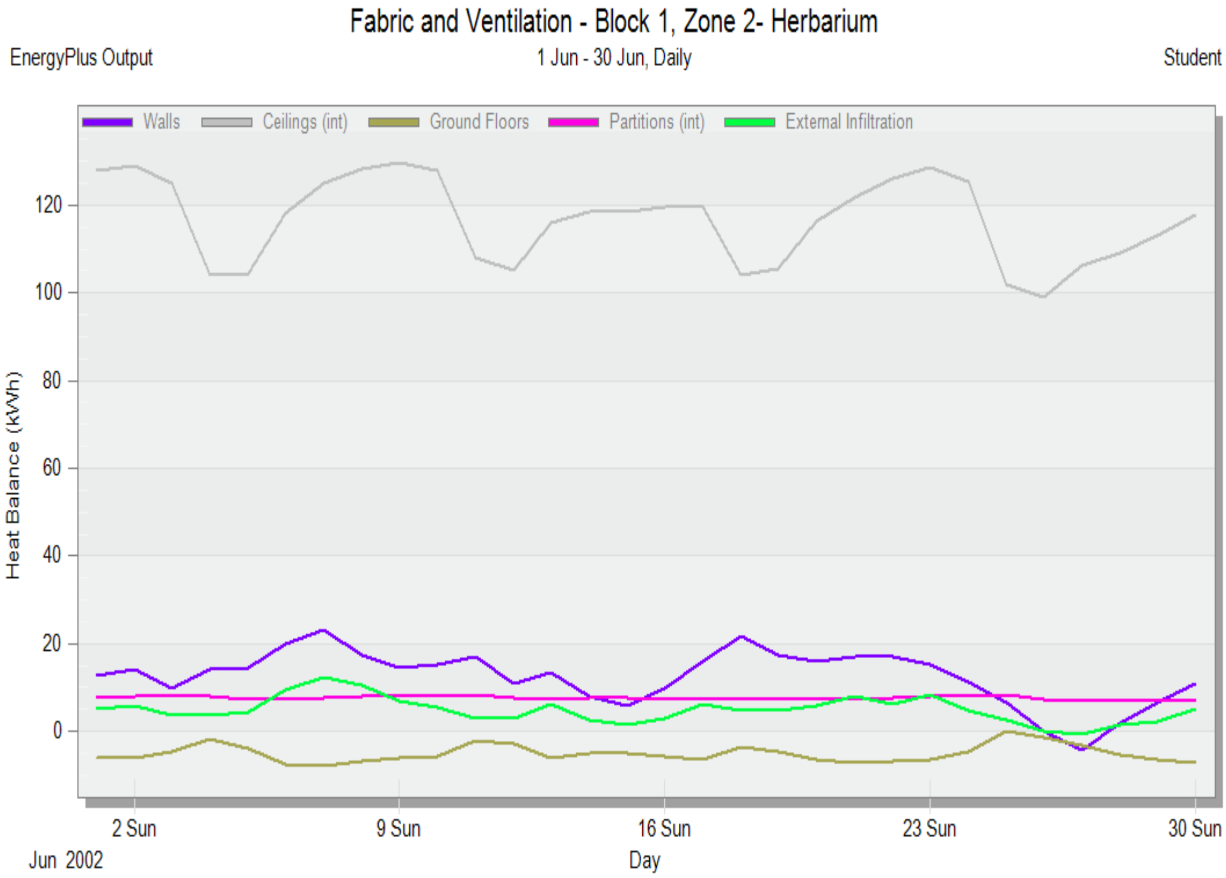

Figure 64 June fabric and vent profile

Herbarium September Results- Spring

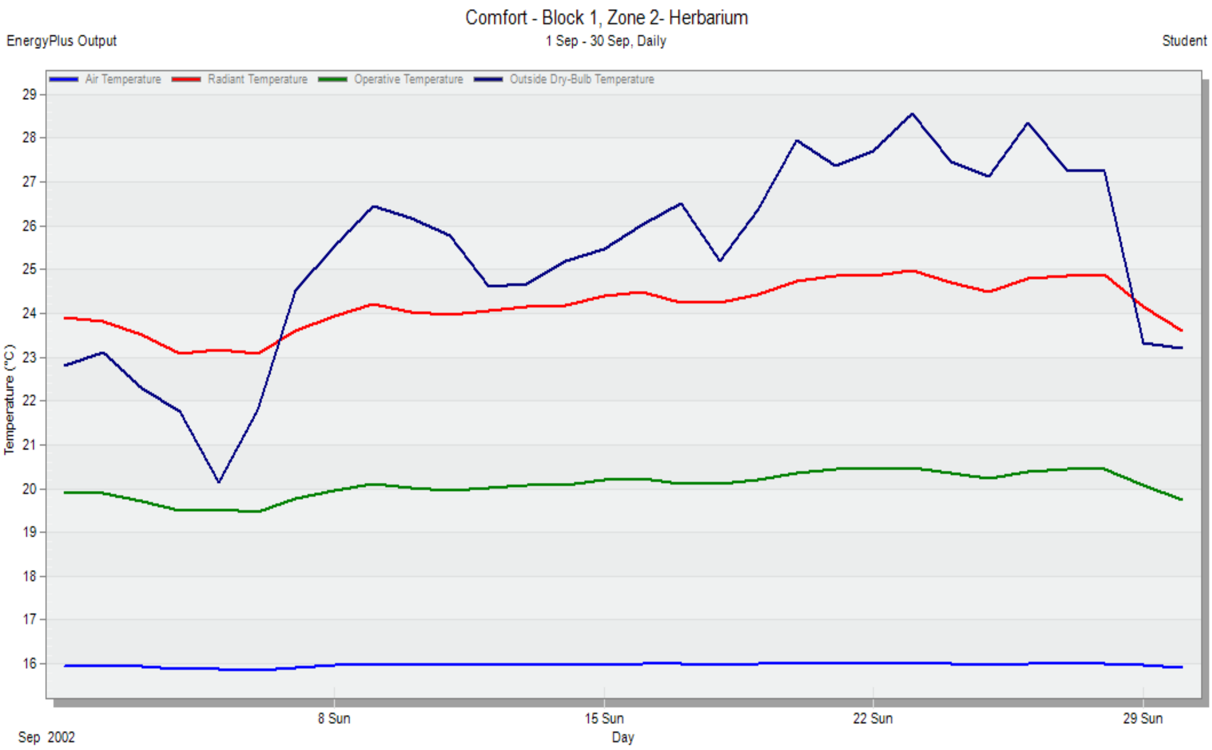

Figure 65 September temperature profile

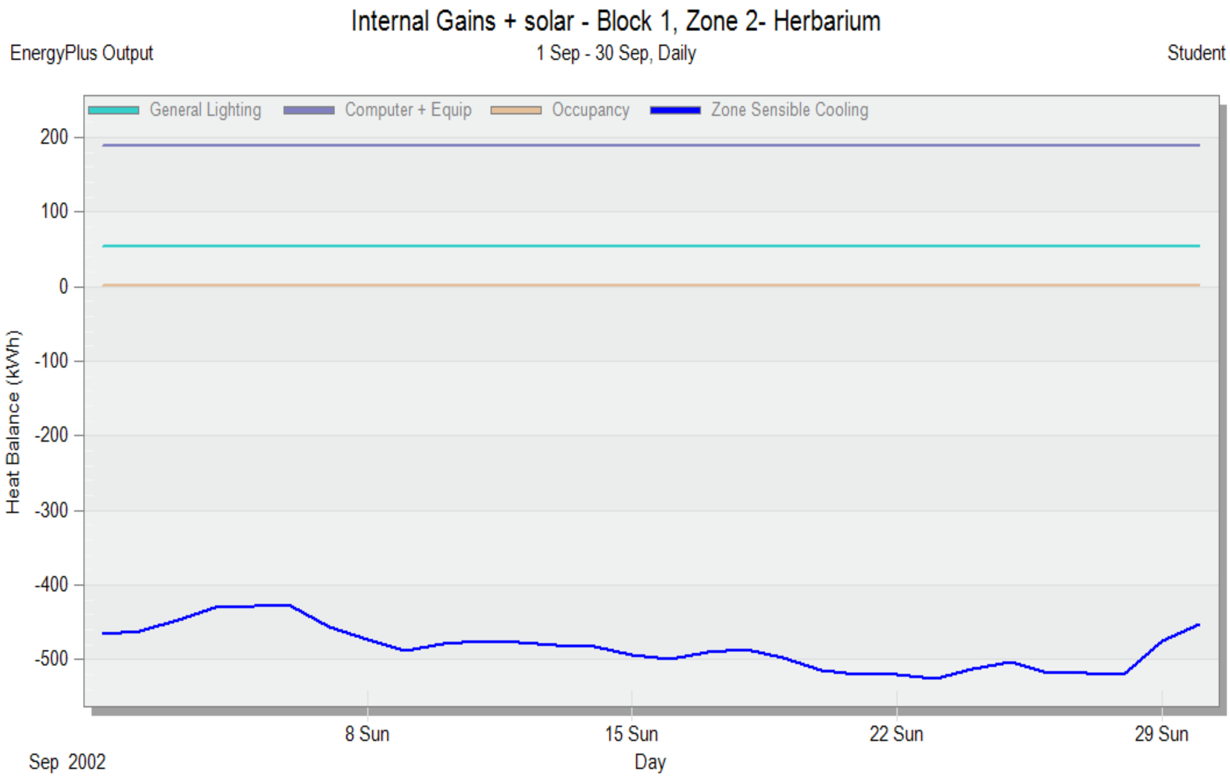

Figure 66 September internal gain profile

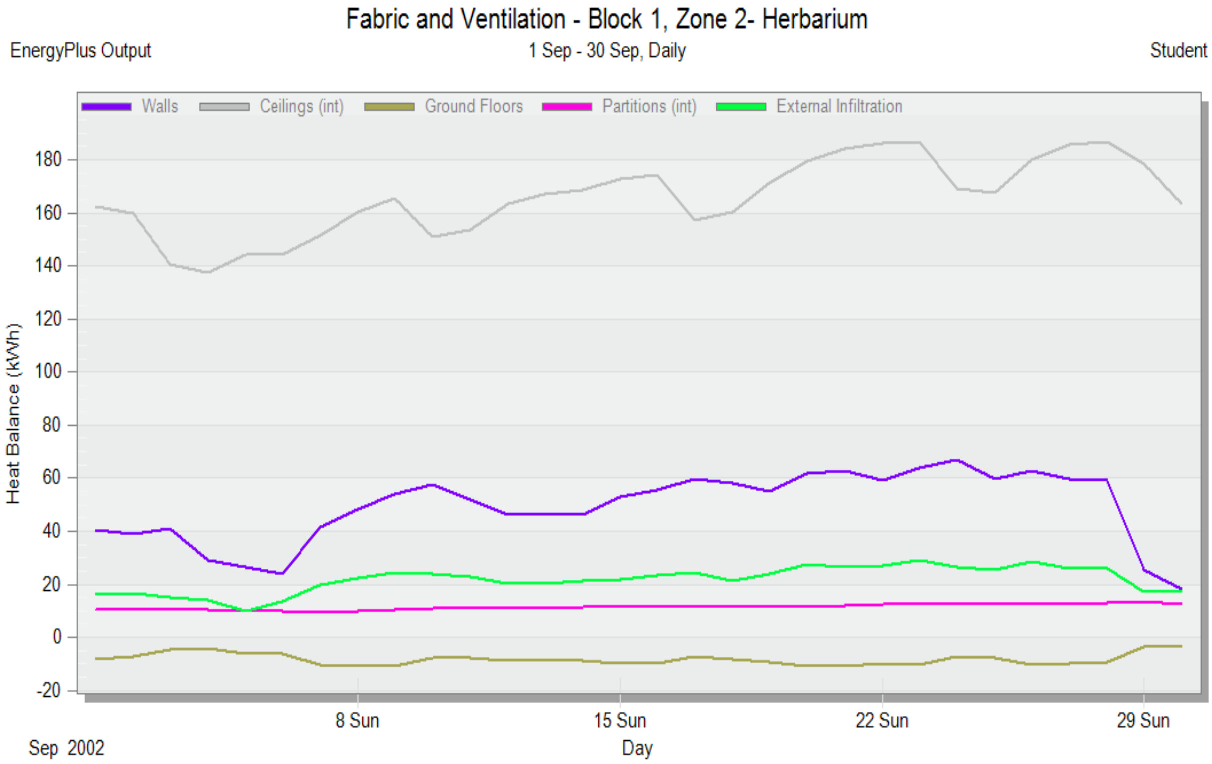

Figure 67 September fabric and vent profile

Herbarium November Results- Summer

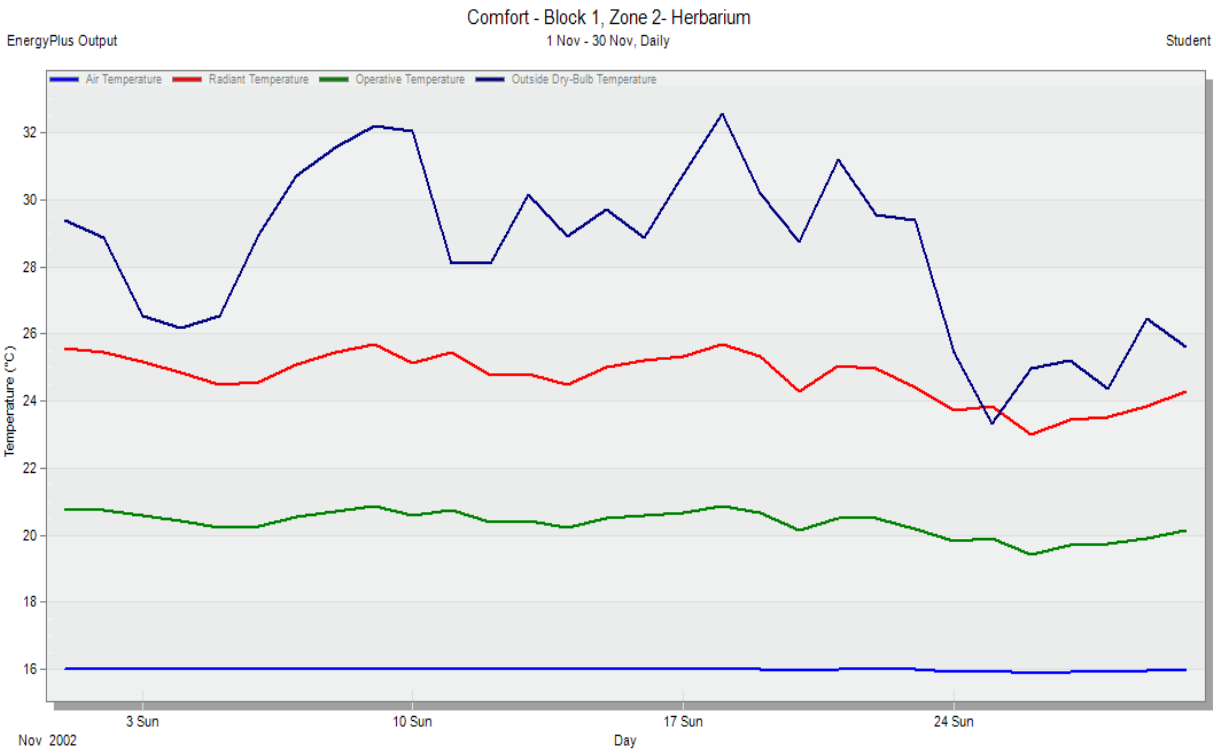

Figure 68 November temperature profile

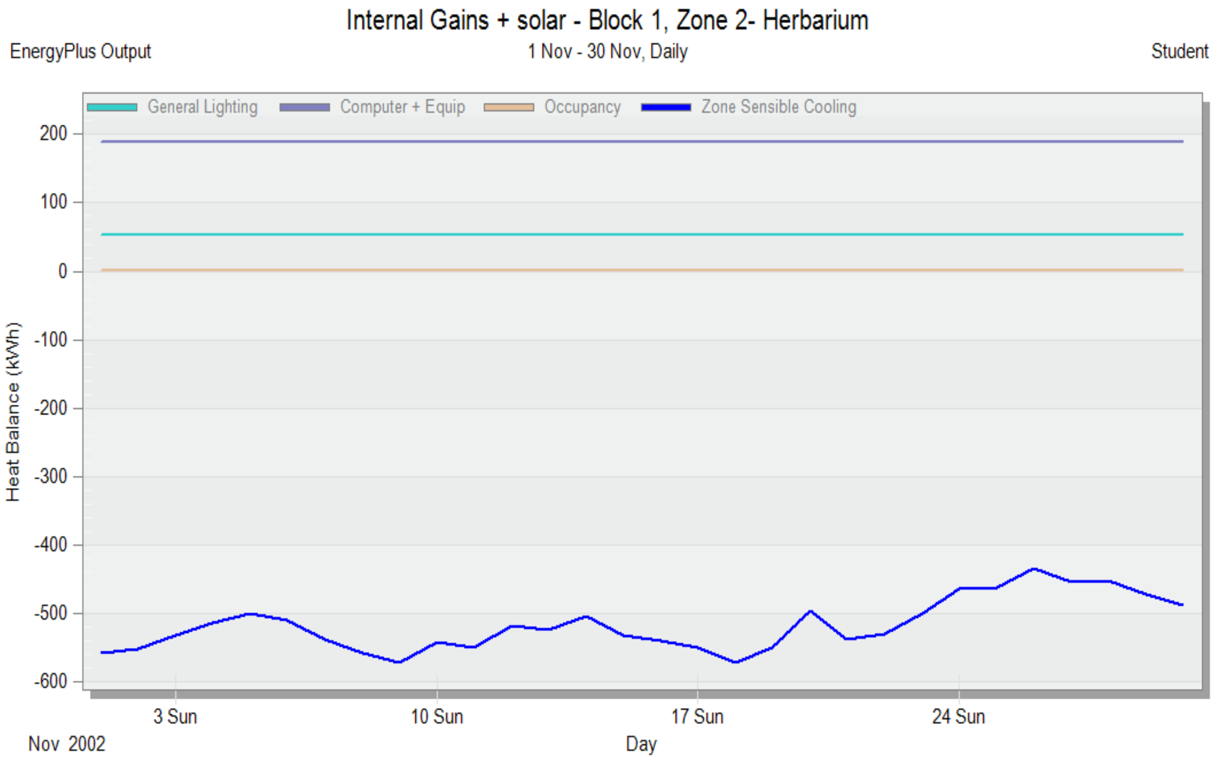

Figure 69 November internal gain profile

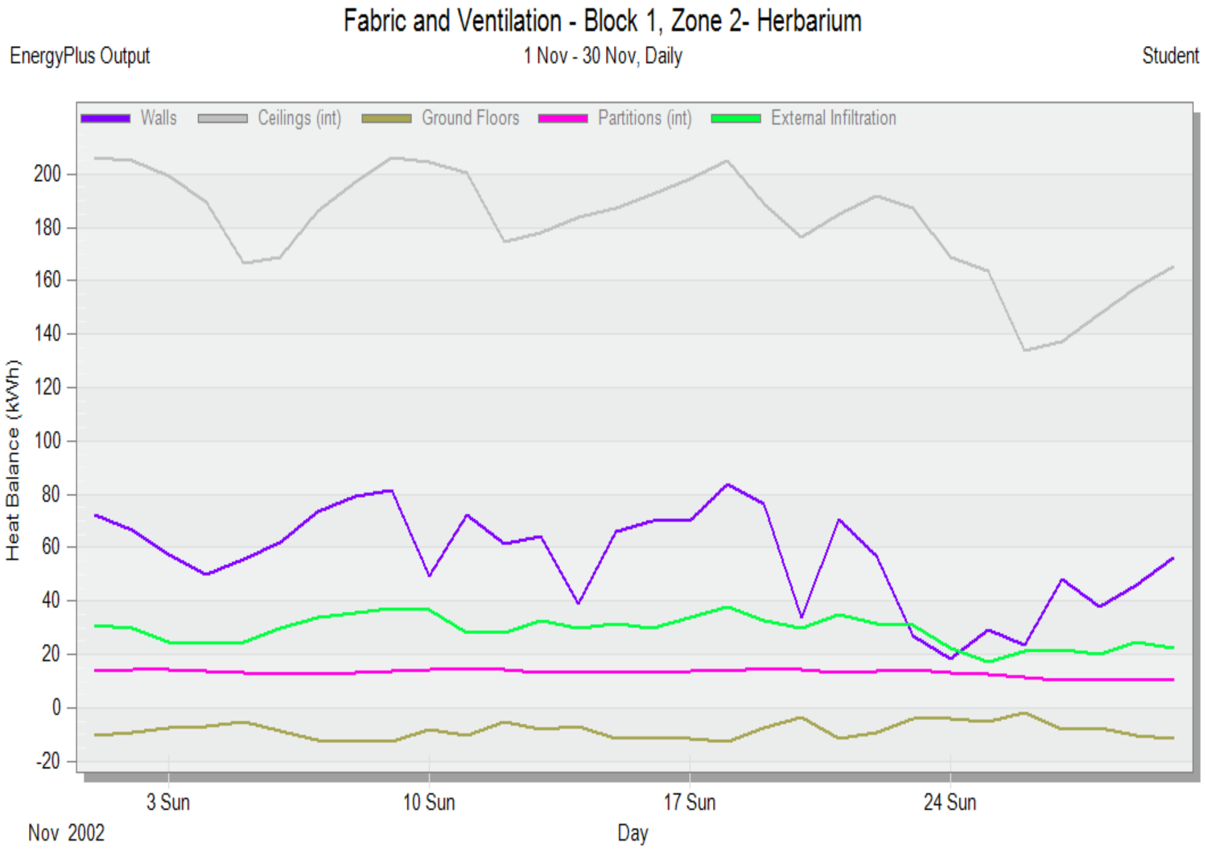

Figure 70 November fabric and vent profile

Appendix 5

MATLAB/ Simulink Carnot Toolbox Model

The initial simulation tool that was supposed to be used for this project is the CARNOT (Conventional And Renewable eNergy Optimization Toolbox), an extension for MATLAB/ Simulink technical computing program, developed by the Solar-Institute Jülich of the FH Aachen (Sciebo, 2020). The CARNOT blockset is similar to the standard Simulink library, and it contains most of the components for modelling an HVAC system (Salvadori et al., 2020).

The following shows the work carried out in this simulation environment.

Building Model

The building model was built on the simple house block of the CARNOT_7.1 toolbox with an integrated heating system. The building model inputs the weather data vector/ bus (WDB), thermo-hydraulic vector or input for the flow of a refrigerant fluid (THB), and internals such as the temperature of the ground and the neighbouring house, which can be modelled using the same block or as a constant temperature zone (RDB). In addition, the building model can include windows. However, the herbarium does not include windows for this model, and the adjacent rooms are modelled with a constant temperature zone. The mathematical description for the building model (house_simple) can be represented by the equation below using some of the equations depicted in table 7.

$$\dot{m}C_p \times \frac{dT_{house}}{dt} = UA_{wall,roof}(T_{amb} - T_{house}) \times UA_{ground}(T_{ground} - T_{house}) \times UA_{neighbour}(T_{neighbour} - T_{house}) + (1 - Sunshade \times [G_{window1} \times A_{window1} \times I_{glb,window1} + G_{window2} \times A_{window2} \times I_{glb,window2} + G_{window3} \times A_{window3} \times I_{glb,window3}] + \dot{Q}_{vent} + \dot{Q}_{int} + \dot{Q}_{heating} \quad (25)$$

Since the herbarium was cooling based, the radiator is replaced with a heat exchanger to transfer cooling energy from the chiller to the herbarium room. The outputs of the building model are the room temperature, heating/cooling power given from the heating system to the herbarium (positive for heating, negative for cooling, in W), and the returning thermo-hydraulic vector. Thus, the building model provides a load, thermo-hydraulic vector from the chiller into the room and observes the effects of the chiller on the room temperature.

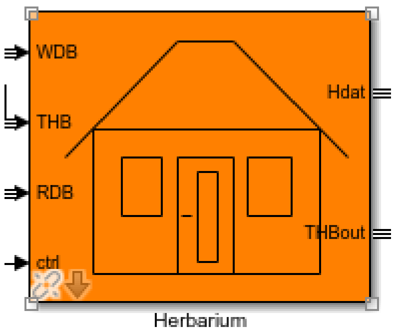

Figure 71 House_Simple Level 1

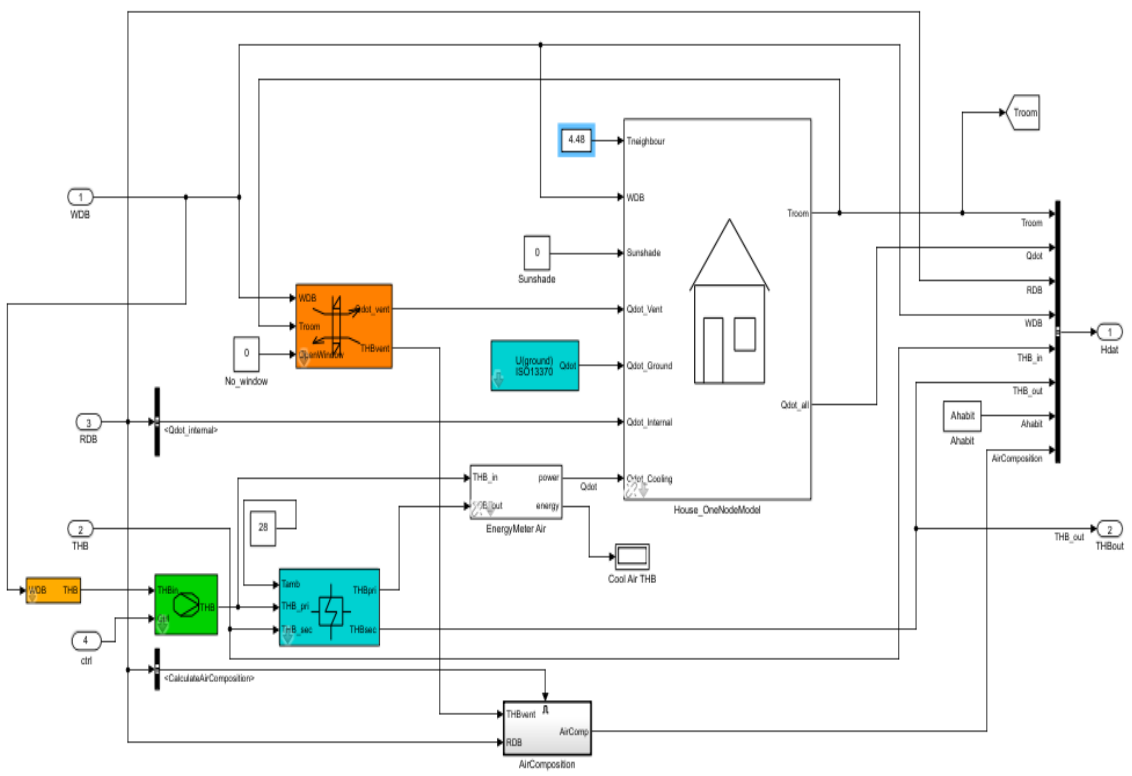

Figure 72 Herbarium Building Level 2

The ground model used in the building model is based on the DIN ISO 13370 standard on Thermal performance of buildings - Heat transfer via the ground - Calculation methods (ISO, 2017). The standard is integrated into CARNOT 7.1 and contributes to the heat transfer into the herbarium building. Therefore, no modifications were made to the floor/ground aspect of the model.

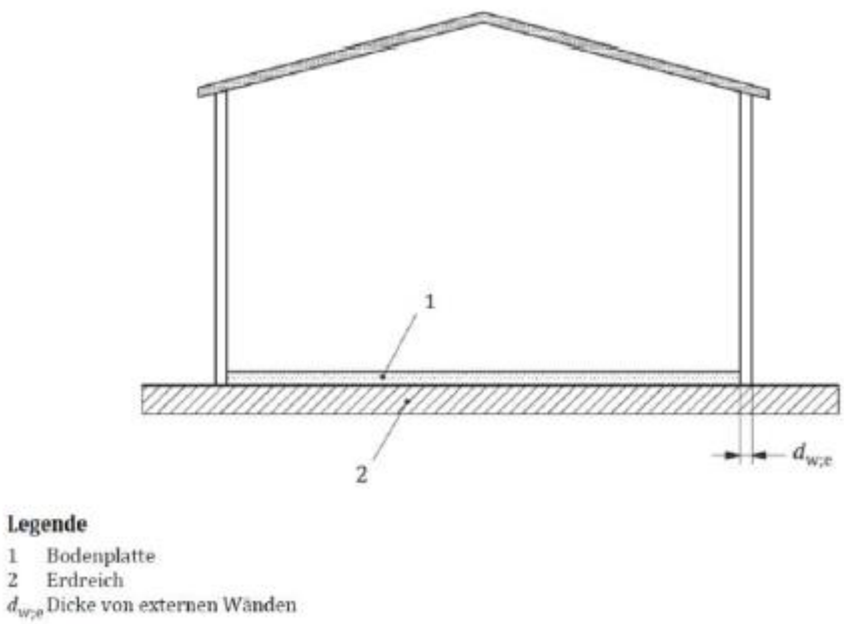

Figure 73 Ground model in CARNOT 7.1 based on DIN ISO 13370

Original Chiller Levels

The CARNOT library is equipped with different, i.e. chillers, Adsorption, Absorption, Vapour Compression, and a Cooling tower. For this project, a vapour compression chiller block was used.

The original Compression_Air_Water_Chiller block has an input for the thermal bus water inlet, the ambient air temperature, and the chiller's control. The chiller block has no electrical power input, while the outputs of the system are the cooling capacity (Q_cold), coefficient of performance (COP), electrical power (P_el) used by the chiller and the THB_water_out. The output "P_el" is the theoretical power required to operate the chiller and maintain the set room temperature. The "Q_cold" output is the cooling capacity of the chiller. It is used for data logging, together with the COP, which is the ratio of useful cooling provided to work (energy) required. The "THB_water_out" and "THB_water_in" supply water to the heat pump, which helps remove heat from the circulating air from the building.

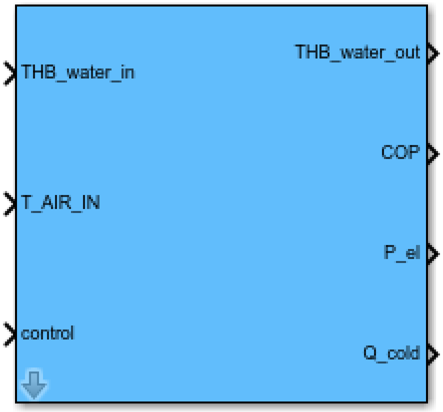

Figure 74 Original CARNOT Compression_Air_Water_Chiller block level 1

Level 1: Chiller Control

The input control setting in the model operates with a connected controller_bang_bang which acts as a hysteresis controller for thermal systems. The output is set to zero is T_{hot} or T_{cold} is bigger than T_{max}. For this project, the control temperature of the herbarium is set at a constant value of 18 °C and switches off when the room temperature is 17°C. The set temperature is taken from the recommended herbarium standards, ranging from 21-13°C. The controller compares the actual temperature of the room, $T_{room}/T_{hot,}$ with the set temperature, T_{set}/T_{cold}. The controller block produces an output signal of 1 when the room temperature is higher than the set constant value, signalling the chiller to switch on. When the room temperature is lower than the set constant value, the chiller switches off, signalling output of 0.

Figure 75 CARNOT controller_bang_bang

Understanding the applied operation of a chiller compared to theoretical or ideal operation is fundamental before the model can be modified to suit any specific function. The controller block operates both the chiller pumping system, the THB water flow, and the air-cooling fan to the heat exchanger. The fan operates simultaneously with the heat exchanger, blowing ambient air through the heat exchanger while the chiller operates, allowing the room temperature to decrease to the set temperature. The air fan takes air from the outside ambient air, gaining the cooling effect from the cool water in the heat exchanger. As a result, the air gains a cooling effect which is inputted into the room. The ventilation into the room is controlled and monitored at 0.7 air changes per hour (ACH), as mentioned previously.

Level 2: Original Chiller Subsystem

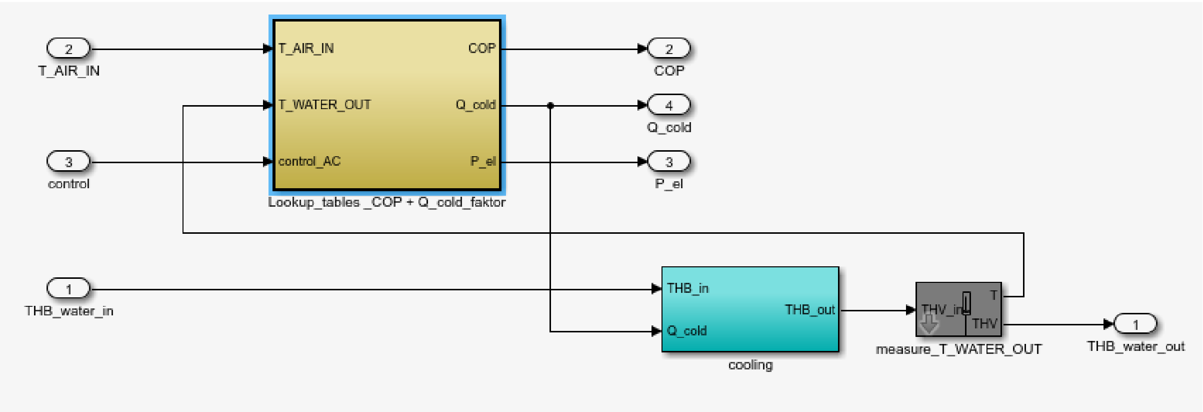

Figure 76 Original CARNOT Chiller block level 2

Figure 59 is the first subsystem and second level in the component build-up of the chiller block. The THB water is recirculated from the cyan cooling block, which calculates the new cold water temperature using the cooling capacity provided by the Lookup_tables_EER + Q_cold_faktor block. The THB_water_in does not interact with any other block apart from the cooling block.

The Lookup_tables_EER+ Q_cold_faktor block is where the power demand is calculated using the cooling capacity. The COP is calculated from the useful cooling/ water and air temperatures and the work provided on the manufacturer specifications. The values stored in the lookup tables are linearly interpolated and used to calculate new values. The manufacturer can provide these values or provided in technical data sheets and manually inputted into the lookup tables. The newly calculated cooling capacity is used to determine the new water temperature THB_out, which is recirculated to provide the cooling effect in the room in an iterative cycle.

Level 3: Original Chiller Lookup Table Subsystem

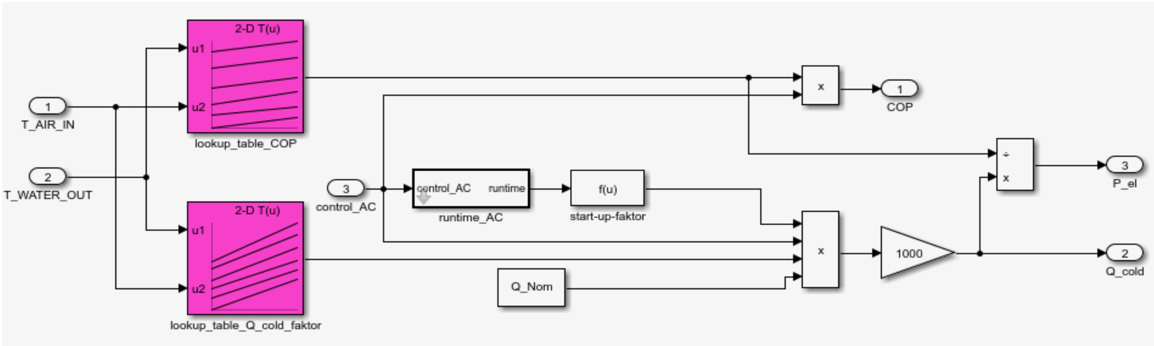

Figure 77 Original CARNOT Lookup table block level 3

The lookup tables directly calculate the COP from the manufacturers' datasheet, comparing the ambient air temperature u2 (source temperature) to the chilled water temperature, T_water_out, and interpolating the result. The bottom table, lookup_table_Q_cold_faktor, calculates the cooling capacity to output the theoretical electrical need, P_el and cooling capacity, Q_cold. The Q_cold_faktor block essentially multiplies the nominal input power, entered by the person modelling the system in the level 1 block settings by the cooling capacity, Q_cold_faktor, to get an output. The input option allows the chiller size to get a scaled output to the input.

The start-up faktor, activated by the control or controller_bang_bang input, is a key factor in calculating the system's cooling capacity as it determines whether the chiller is on/off and can have an output.

Level 3: Original cooling block subsystem

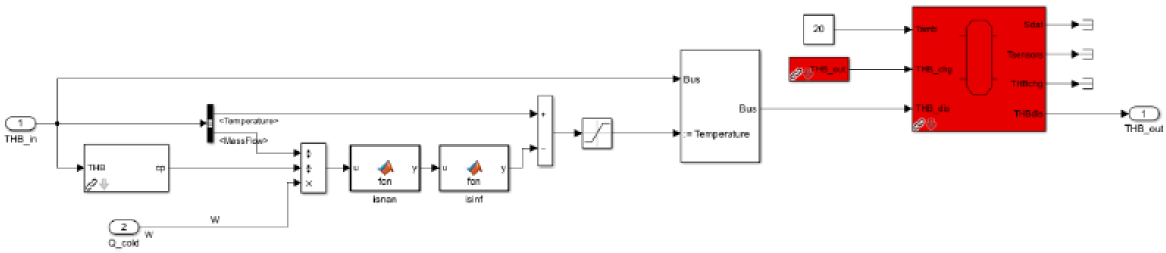

Figure 78 Original CARNOT cooling block level 3

The cooler block uses the chiller's cooling capacity to calculate a new temperature output in the chiller and compare it to the actual incoming water temperature. The block contains a storage device and a separate calculation for water's heat capacity, Cp= 4.185kJ/kgK. The cooling block also allows for the minimum and maximum water temperature to be set. The change in temperature or THB_{out} can be calculated by rearranging the equation as demonstrated below.

$$\triangle T = \frac{\dot{Q}_{cold}}{\dot{m} * C_p} \qquad (26)$$

Chiller Modified Chiller Levels

One of the main aims of this project was to modify the chiller to match a more realistic operation and allow an electrical power input. The original chiller only showed a theoretical power output needed to keep the chiller operational and the room temperature steady as dictated by the controller block. The modified chiller block aims to provide an electrical power input function.

The modified chiller was designed to be powered by solar PV energy, backed up by grid electricity to supplement during the evenings and in the event of a power disruption from the solar PV system with considering a battery. The operation of the chiller is directly affected by the technical specifications of the heat pump used, the incoming water temperature used by the chiller, the setpoint controller system, the ambient air conditions of the room, and the electrical power inputs. The chiller then outputs the required air temperature into the room, power availability and the transition from grid power to solar PV, and quantifies the system efficiency through the COP. The figure displays the information flow process of the chiller.

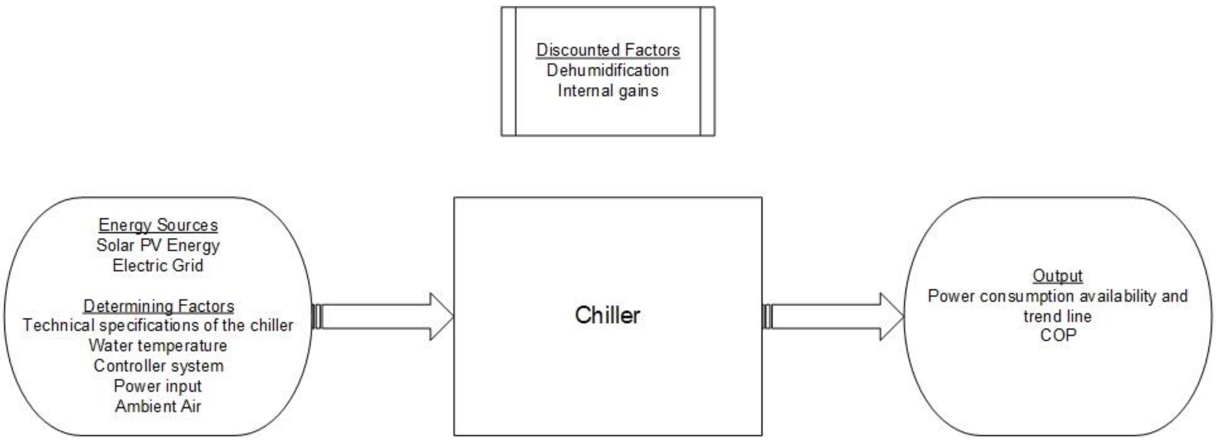

Figure 79 Overview of Chiller information flow

The original chiller was not designed to reflect an output of the cooled air, which is channelled in the room and energy input. The energy input into the chiller is modelled so that the cooling effect is linked to the energy input. In the event of an energy deficit, the system switches off, and the room temperature will rise as an effect of the deficiency. Level 1 of the chiller is modified as below.

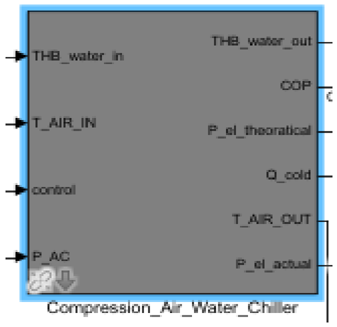

Figure 80 Modified Chiller block level 1

Level 2: Modified chiller block subsystem

In level 2 of the modified chiller system, a new air temperature calculation block was added following the cooling capacity equation mentioned earlier. The calculated T_Air_temp is the cooled air that enters the herbarium room, maintaining the required temperature.

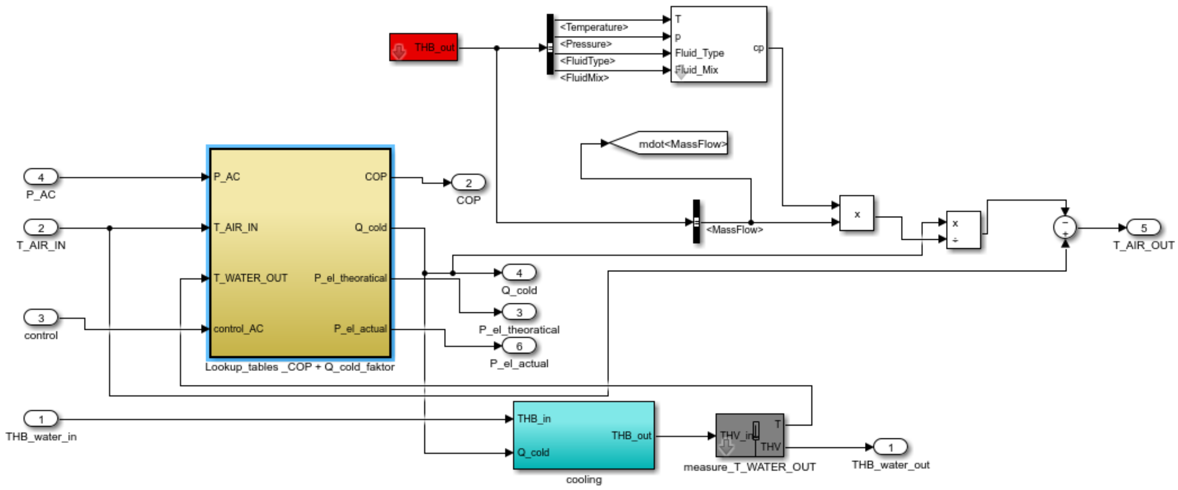

Figure 81 Modified chiller block level 2

Level 3: Modified chiller block subsystem

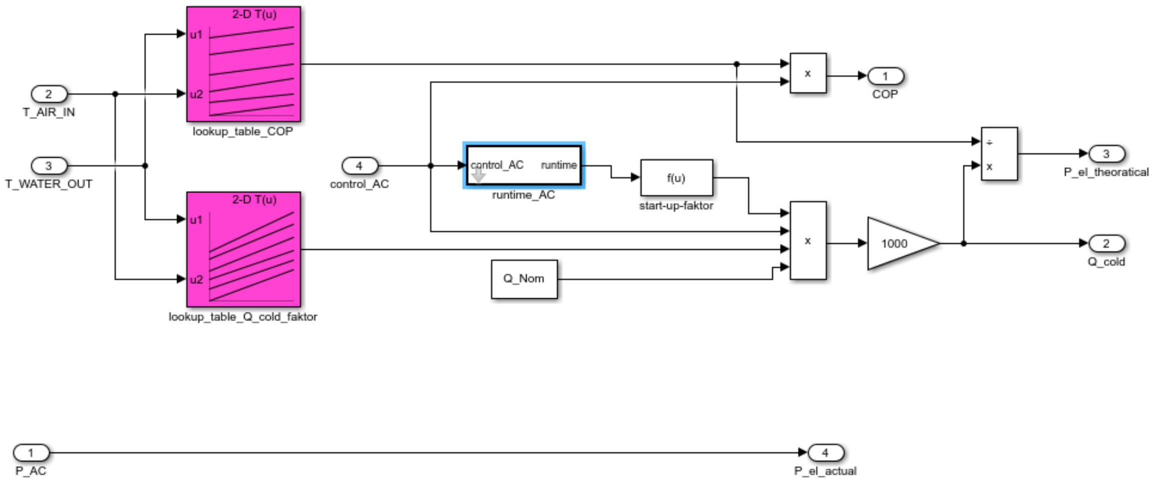

Figure 82 Modified chiller block level 3

No significant changes were carried to level 3 of the system other than incorporating energy input and the actual electrical output on which the system operation is dependant.

Chiller Specifications

The CARNOT chiller block is a relatively new addition to the toolbox, which has been only heating based. The original chiller block does not factor in a realistic operation of the system. The CARNOT chiller block is not extensively documented in the software and lacks a detailed mathematical model. The documentation does, however, that the chiller used is modelled based on the characteristic curves for cooling capacity and coefficient of performance of the reversible air-to-water heat pump with waste heat recovery LI 16TER+ by Dimplex (Sciebo, 2020).

A significant aspect of this research is to modify the chiller block to operate using solar PV and the grid and to supply a constant room temperature without damaging the inbuilt mathematics and thermodynamic loops in the simulation.

The figure below shows the technical data sheet of the Dimplex chiller in which the CARNOT chiller is modelled to mimic.

Order reference		LI 16TER+
Set-up / Colour		Indoors / White
Maximum flow temperature		58 °C
Temperature operating limits for air		-25 °C to 35 °C
Temperature operating limits for cooling		15 °C / 40 °C
Heat output / COP at A-7/W35*	kW/-	10,60 / 3,00
Heat output / COP at A+2/W35*	kW/-	12,80 / 3,40
Heat output / COP at A+2/W50*	kW/-	12,00 / 2,50
Heat output / COP at A+7/W35*	kW/-	15,10 / 3,80
Heat output / COP at A+10/W35*	kW/-	16,70 / 4,10
Cooling capacity / COP at A+27/W18*	kW/-	16,40 / 2,80
Cooling capacity / COP at A+35/W8*	kW/-	11,10 / 2,10
Electrical nominal power consumption at A+2/W35	kW	3,80
Sound power level	db(A)	57
Refrigerant R404A	kg	5,70
Flow rate (heat source) at int. pressure differential	m³/h / Pa	4000 / 25.0
Heating water flow rate with an int. pressure differential of	m³/h / Pa	1.4 / 4500
Dimensions (W x D x H)**	mm	750 x 875 x 1570
Weight (incl. packing)	kg	260
Control voltage	V	230
Supply voltage		3/PE~400V, 50 Hz
Starting current with soft starter	A	25
Fuse	A	20
Defrosting / type of defrosting		Reverse cycle
Device connections for heating		1 1/4"

* The specified values have the following meaning, e.g. A+2/W35: heat source temperature +2 °C, heat outlet temperature 35 °C.
** Please note that additional space is required for pipe connections, operation and maintenance.

Figure 83 Chiller Technical Datasheet

Original Solar PV Generator

The PV generator block in the CARNOT toolbox calculates the output based on module characteristic parameters at Standard Test Conditions (STC) in W. STC are the lab conditions solar panels are tested under and do not reflect real-world conditions. The STC simulates peak sunshine, zero cloud cover, low air temperature, which prevents the solar panels from overheating and a panel position directly facing the sun. The PV module will typically be rated at 25°C under 1kW/m^2 (Infinite Energy, 2016). The peak power of the solar panel (P_{max}) is calculated with the mathematical equation below.

$$P = \frac{solar\_radiation}{1000} * incidence\_angle\_modifier * P_{max} * (1 - \left(T_{amb} + \frac{40*solar_{power}}{1000}\right) - 25°C\ ) \quad (27)$$

Where 40 is the temperature difference to ambient at full solar radiation (1000 W/m^2) and the incidence_angle_modifier is 1 for vertical direct solar radiation. It follows the reflection las of Fresnel (Sciebo, 2020). The original solar PV generator blocks are displayed below.

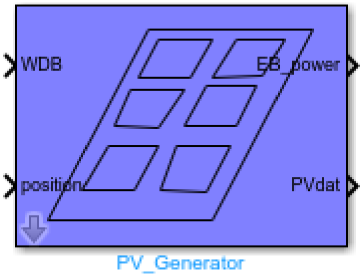

Figure 84 Original Solar PV Generator level 1

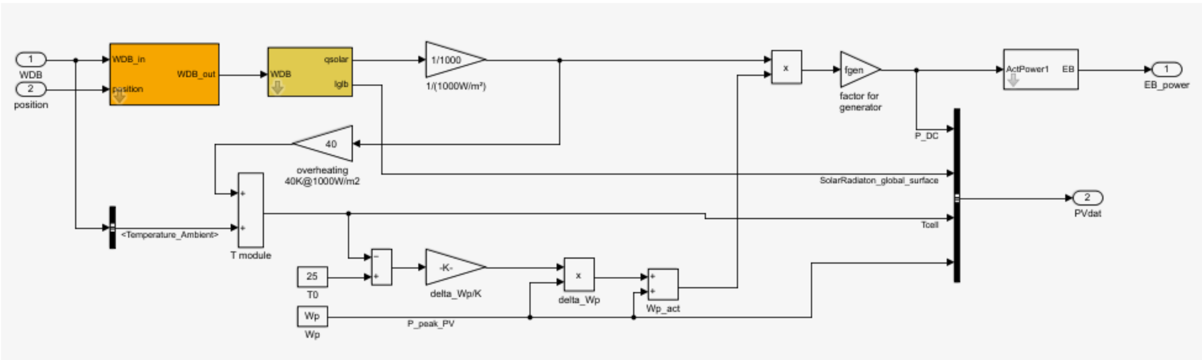

Figure 85 Original Solar PV Generator level 2 subsystem

The level 2 subsystem is a graphical model of the mathematical equation above. The block parameter input settings are entered in the interface below.

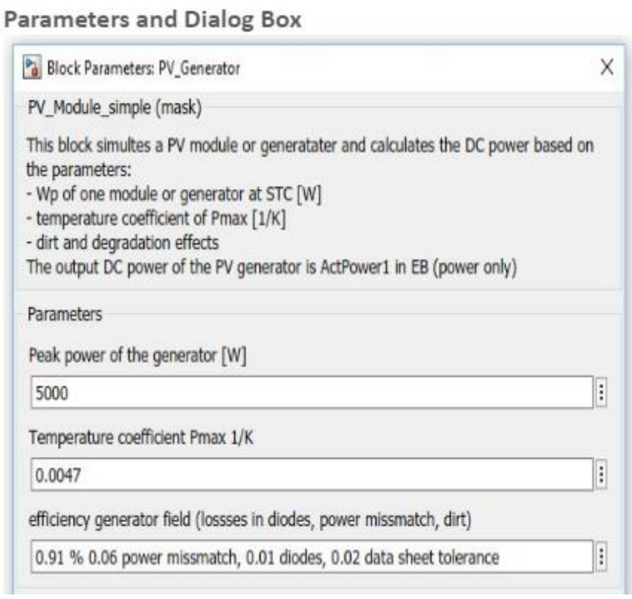

Figure 86 Original Solar PV Generator Parameter Box

Modified Solar PV Generator

To attain a more realistic model of the solar generator, it is helpful knowing and utilise Nominal Operating Cell Temperature (NOCT) conditions, which are not included in the original solar generator. NOCT settings reflect a realistic maximum power output than STC settings as testing conditions are much closer to real-world conditions that the solar panel would face daily. To model NOCT conditions, improvements were made to the original model, with the Watt Peak (Wp) of the module at the NOCT from the manufacturer technical data sheet integrated into the model design. In addition, the number of solar modules used and the array area was also integrated into the design to provide a more accurate output. The NOCT output was anticipated to be less than the STC output as it is modelled under lower, ideal conditions. However, the NOCT output is more realistic and geared to the operating conditions of the solar cells. It is defined as the temperature reached by open-circuited cells in a module assuming 800W/m^2 irradiance, 20°C ambient temperature, wind speed at 1m/s with the PV module at a tilt angle of 45°, with its backside open to the breeze and a panel surface temperature of +/-45°C (Sinovoltics, 2018). The equation representing NOCT conditions can be seen below.

$$T_{cell} = T_{Air} + \frac{NOCT - 20°C}{800 \frac{W}{m^2}} * S \qquad (28)$$

Where S is the insolation. After the NOCT cell temperature calculation, a similar method is followed to calculate Pmax as the original solar PV generator block. The difference between the cell temperature and the NOCT condition temperature is multiplied by the Pmax temperature coefficient in percentage power decrease per temperature degree Celsius, as per the solar PV module technical datasheet.

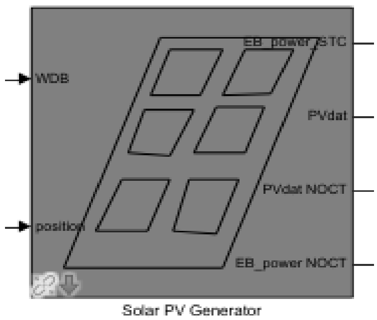

Figure 87 Modified Solar PV Generator Level 1

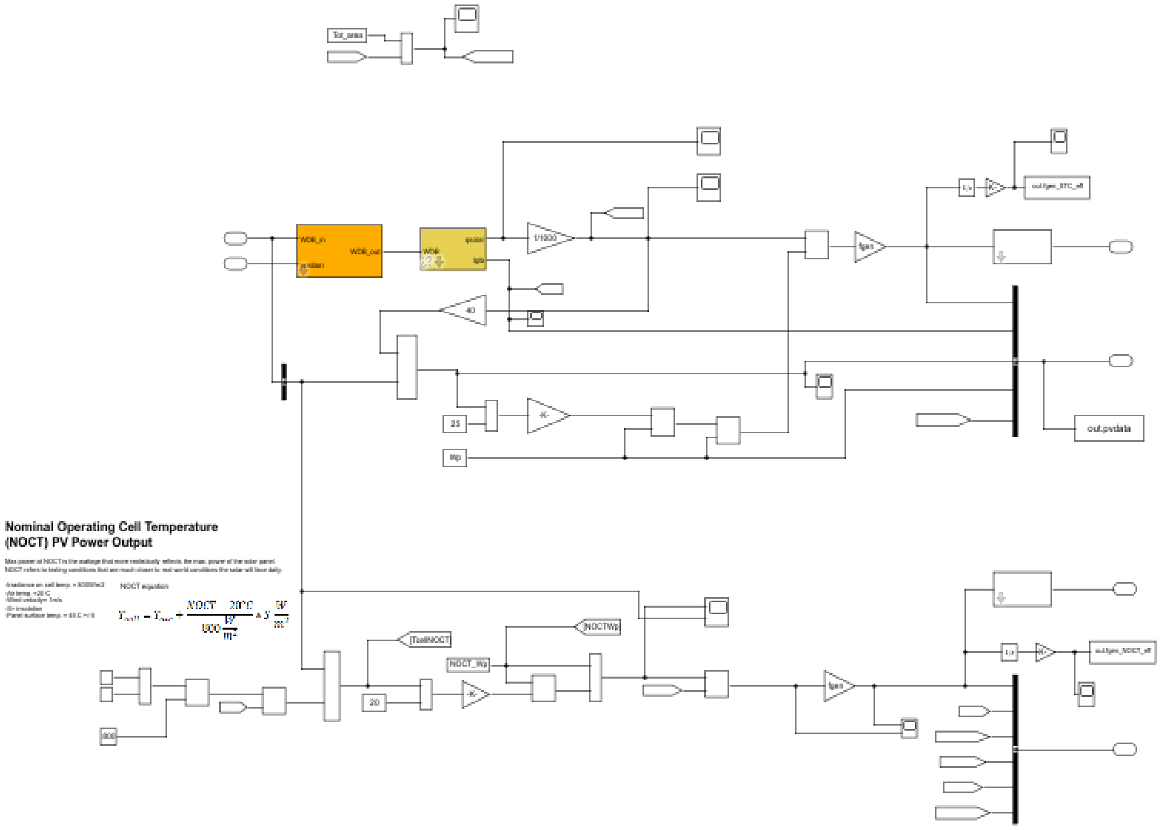

Figure 88 Modified Solar PV Generator Subsystem Level 2

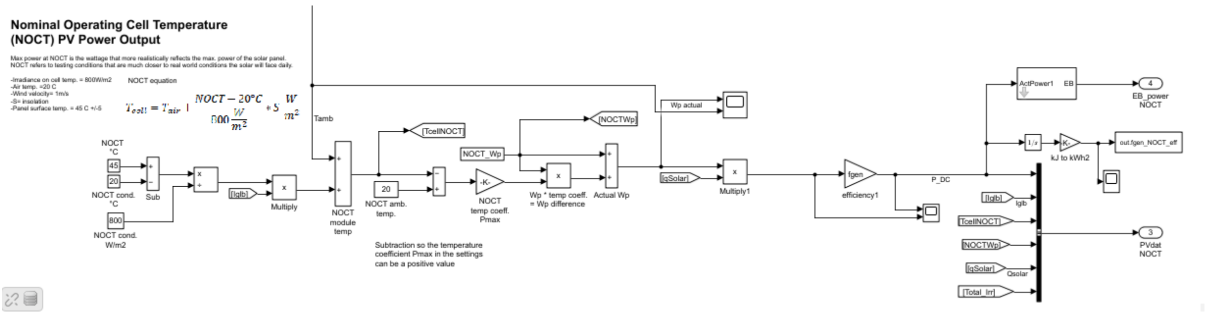

Figure 89 Closer Look at Modified Solar PV Generator level 2

The parameter dialogue block can be seen below.

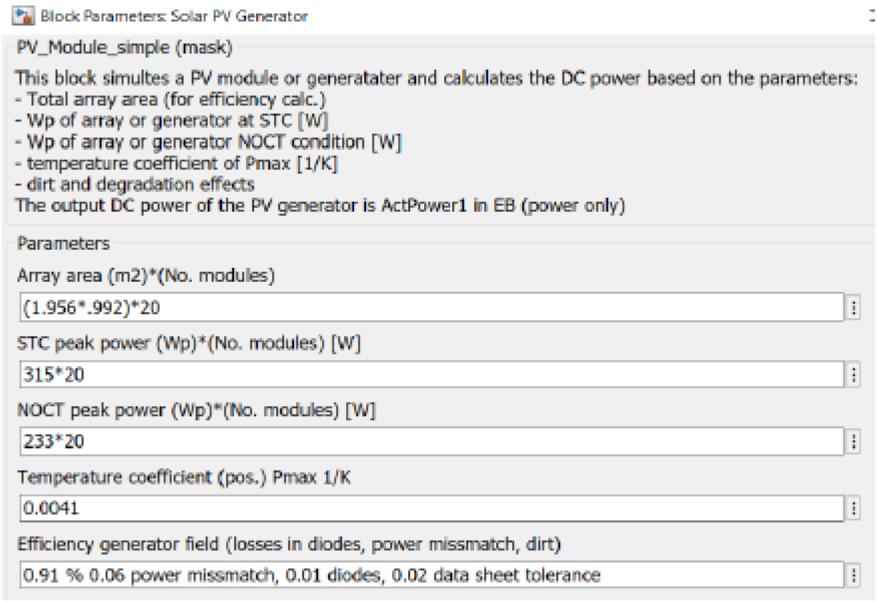

Figure 90 Modified Solar PV Parameter Block

MATLAB CARNOT complete model

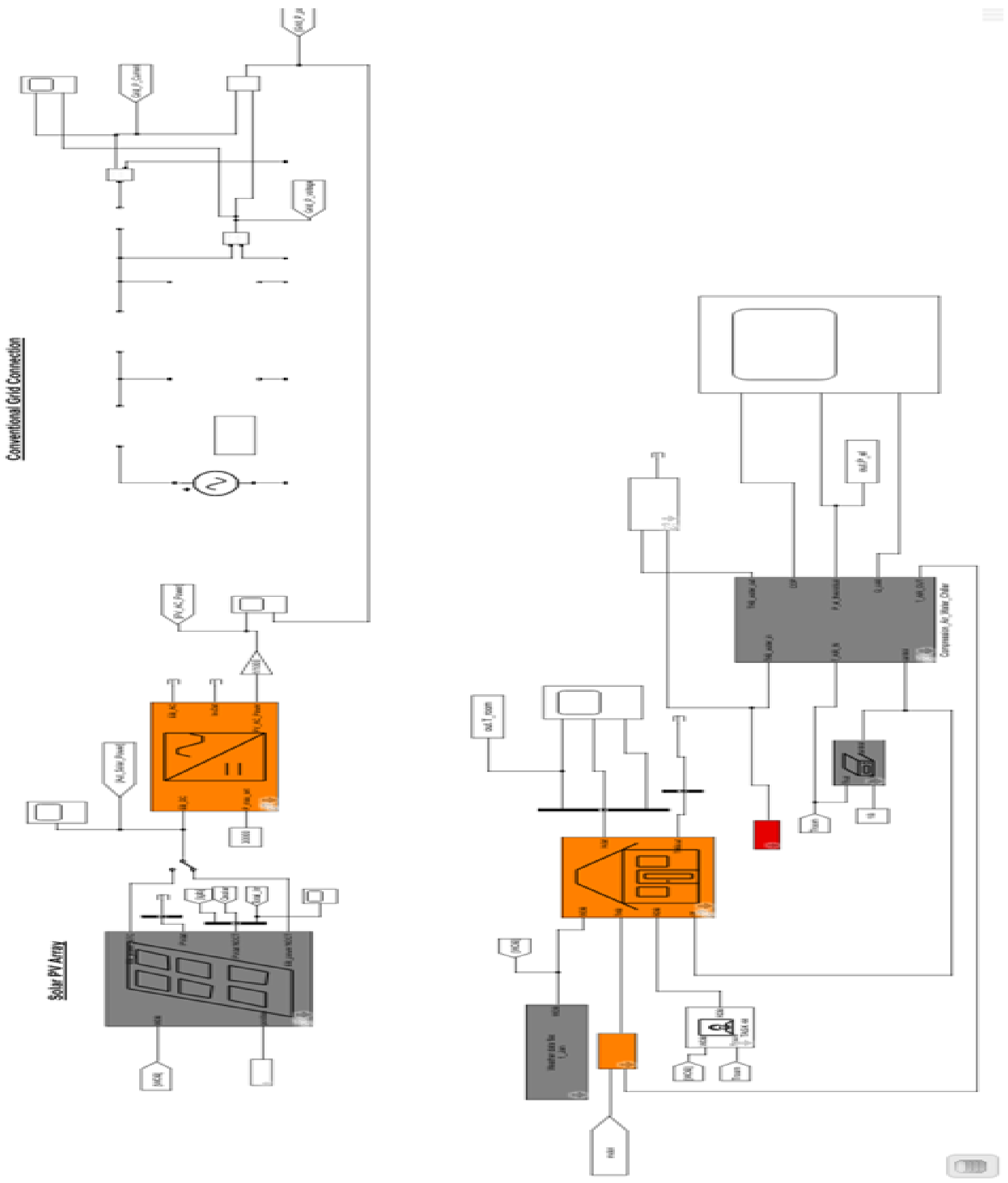

Figure 91 CARNOT model