National University of Lesotho

Potential Analysis for Solar Photovoltaic-Thermal (PVT) Systems in Educational Institutions - NUL Case Study

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Abstract

Educational institutions in Lesotho, such as the National University of Lesotho (NUL), face challenges related to energy reliability and the increasing cost of grid electricity. These issues highlight the need for more resilient, sustainable and cost-effective energy alternatives. Solar photovoltaic (PV) systems are used for electricity generation and solar thermal systems for heating purposes. However, the combination of these two technologies into a single photovoltaic-thermal (PVT) system remains largely unexplored within the education sector. Therefore, this study investigates the potential for PVT systems to meet the energy needs of the student residences at the NUL using the POLYSUN simulation software. The PVT system was designed to provide 5,000 litres of hot water daily at a target temperature of 50 °C for one case study residence, and its performance was compared against a corresponding solar water heating (SWH) system. The PVT system design utilised a collector area of 75 m^2, whereas the SWH system employed 50 m^2. A comparative assessment is carried out to analyse the systems in terms of technical performance, cost-effectiveness and environmental impact.

Simulation results indicate that the PVT system achieves a solar fraction of 88% and generates 46,398 kWh of thermal energy annually. Further, the PVT system produces an additional 23,773 kWh of electricity each year, with 20,818 kWh to be used directly on-site. This results in energy savings of 72,615 kWh. It also attains a performance factor of 4.5 and an overall efficiency of 40%, comprising 26.7% thermal and 14% electrical efficiency. Environmentally, the PVT system significantly reduces carbon emissions, saving 38,951 kg of CO_2 annually (26,199 kg from thermal production and 12,752 kg from electricity generation). From an economic perspective, the PVT system requires an initial investment of M1,425,000.00, which can be financed through 60% equity and 40% debt. However, this higher upfront cost is offset by improved financial performance over time. The PVT system achieves a levelized cost of energy of M1.62/kWh, a net present value of M1,546,935.60 and an internal rate of return of 17.7%. It also delivers an impressive return on the investment of 8.7% per year, a payback period of 9 years and annual energy cost savings estimated at M170,129.68. Therefore, the PVT system has the potential to meet the hot water demand and a portion of the electricity demand in educational institutions. To support broader adoption within Lesotho's education sector, targeted policies, such as subsidies, incentives and accessible financing mechanisms, will be essential to offset the high initial costs.

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1. Introduction

This chapter introduces the study by placing it within the wider context of renewable energy integration and sustainable energy solutions for educational institutions. It begins by outlining the background and motivation for investigating solar photovoltaic-thermal (PVT) systems, especially in response to the increasing energy demand and costs at the National University of Lesotho (NUL). The chapter clarifies the research problem and details the specific objectives and research questions that steer the investigation. Additionally, it emphasises the importance of the study by highlighting its potential contributions to reducing energy costs, lowering carbon emissions and supporting sustainable campus operations. The chapter concludes by describing the overall structure of the report, providing a clear roadmap for the following chapters.

1.1 Background

Globally, buildings are responsible for approximately 40% of the total energy use and roughly one-third of carbon emissions [1, 2]. Fossil fuels, which dominate energy production and contribute significantly to carbon emissions, are depleting, leading to inflation in energy prices [3]. These challenges have intensified the global pursuit of sustainable energy solutions, prompting the rapid adoption of renewable technologies across various sectors, including education [4]. Educational institutions with large campuses are ideal candidates for implementing renewable energy systems because of their high energy consumption patterns and their role in promoting sustainability and environmental awareness [5]. Solar energy combined with innovative technologies highlighted in Figure 1 is a promising alternative amongst renewable technologies, given its abundance and potential to reduce energy costs and drive buildings towards carbon neutrality [6], [7], [8].

Figure 1: Innovative solar technologies [9]

The National University of Lesotho (NUL) presents a unique opportunity to analyse the potential of solar photovoltaic-thermal (PVT) systems in this context. PVT systems combine photovoltaic (PV) and solar thermal technologies into a single unit. This is done to generate electricity and thermal energy simultaneously, as illustrated in **Error! Reference source not found.** [9]. This dual energy generation capability can improve the overall system efficiency, making it a more attractive option compared to separate installations of solar thermal systems [10]. Implementing PVT systems in educational institutions like NUL can lead to substantial energy cost savings, improve energy efficiency, and serve as a model for other institutions in Lesotho and beyond.

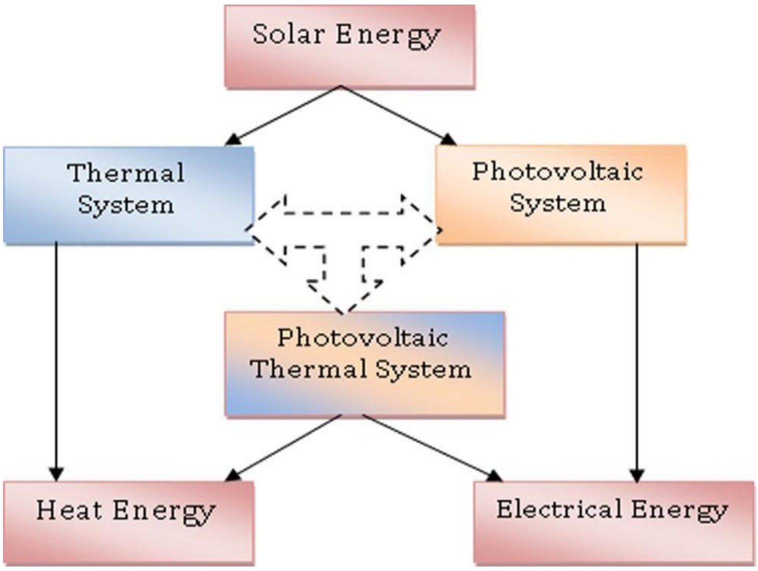


Figure 2: Interrelation between different solar energy technologies [11]

However, the feasibility and potential advantages of PVT systems in comparison with traditional isolated PV and solar thermal systems in buildings (as illustrated in Figure 3), require a comprehensive investigation. This research utilises POLYSUN modelling software to analyse and compare the performance, cost-effectiveness and environmental impact of solar thermal and PVT systems at the NUL. POLYSUN is a software platform for energy system design that enables detailed simulation and optimisation, facilitating in-depth analysis of energy systems across various scenarios [12].

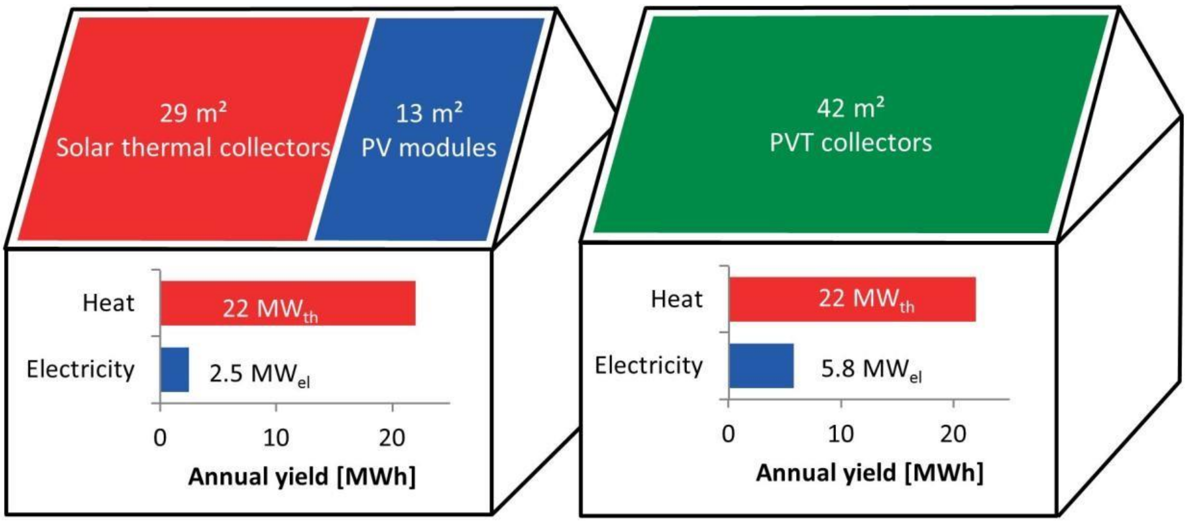


Figure 3: Isolated PV and thermal systems versus integrated PVT system [13]

1.2 Problem Statement

Educational institutions in Lesotho, including the NUL, encounter significant challenges in managing energy supply and usage. Rising costs of grid electricity, coupled with frequent supply disruptions, have driven the search for alternative, more reliable and sustainable energy sources [14]. Although solar PV systems have been considered for electricity generation and solar thermal systems for heating, the potential of combining these two technologies into a PVT system remains largely unexplored. Existing research in sub-Saharan Africa has mainly focused on the techno-economic analysis of PVT systems in manufacturing and residential settings, with limited attention given to their application in other sectors such as education [10], [15]. Additionally, Maoulida et al. explored the performance and benefits of PVT systems under tropical African climatic conditions and emphasised the need for further research that includes both techno-economic evaluations and environmental factors, such as greenhouse gas emissions [16].

The core issue lies in the lack of comprehensive analysis and comparison between conventional solar water heating and integrated PVT systems in educational institutions. Without such analysis, decision-makers at the NUL and similar institutions cannot make informed choices about the most suitable renewable energy systems for their specific needs. This study, therefore, aims to fill this gap by evaluating the potential of PVT systems in terms of energy production, economic viability, and environmental impact, using the NUL as a case study.

1.3 Research Objectives

The primary objective of the study is to analyse and compare the potential of a PVT system with a SWH system at the NUL using POLYSUN modelling software. This is to be achieved based on the following secondary objectives:

1. To assess the current energy consumption patterns and requirements of the NUL's student residences.
2. To model and optimise a conventional SWH system and an integrated PVT system using POLYSUN and evaluate their technical performance.
3. To conduct a cost-benefit analysis of each system, considering initial investment, operational costs and potential energy savings.
4. To analyse the environmental impact of each system in terms of greenhouse gas emissions reduction.

1.4 Research Questions

1. What is the potential energy generation capacity of a conventional SWH system and a PVT system at the NUL's student residences?
2. How can the POLYSUN modelling software be utilised to simulate, optimise and compare the performance of these systems?
3. What are the economic benefits and costs associated with the deployment of SWH and PVT systems in educational institutions?
4. How do SWH and PVT systems compare in terms of environmental impact and overall energy efficiency?

While all four questions address vital aspects of the study, Questions 2 and 3 are particularly important for decision-making and implementation. The potential energy generation capacity (Question 2) determines the technical feasibility of each system, whilst the assessment of economic benefits and costs (Question 3) provides the financial justification necessary for investment. Together, these two questions form the basis for selecting the most suitable system for deployment at the NUL's student residences and for supporting evidence-based policy and investment decisions.

1.5 Significance of the Study

Student accommodation facilities on university campuses represent some of the highest energyconsuming buildings within the education sector. Their significant energy demand arises from the requirements for space and water heating, lighting, operation of electrical appliances, and various other services essential to sustaining the students' daily activities [17]. Exploring the potential of solar technologies within the educational sector is essential for several reasons. First, it fills a significant gap in existing research by providing a detailed comparison of solar thermal and PVT systems in an educational institution. Focusing on the NUL offers a practical case study that can serve as a valuable reference for similar institutions in the country and the region. Second, the research introduces the use of POLYSUN modelling software, an advanced tool for energy system analysis and optimisation, to assess the feasibility and performance of various solar energy systems. This approach enables a thorough technical, economic, and environmental evaluation, delivering reliable data to aid decision-making.

Third, the study's findings will have practical benefits for the NUL, supporting the institution in lowering energy costs, enhancing energy reliability, and contributing to sustainability objectives. Demonstrating the advantages of PVT systems can also promote wider adoption of this technology across Lesotho and other developing nations. Last, the study aligns with Lesotho's broader renewable energy and climate action strategies by advocating for sustainable energy solutions in vital sectors such as education [18]. Successfully implementing renewable energy systems at the NUL can serve as a model for other public institutions, illustrating the practicality and benefits of integrating renewable energy into existing infrastructure. In conclusion, this research will offer valuable insights into the potential of PVT systems for educational institutions in Lesotho. By comparing the SWH and PVT systems, the study provides a comprehensive framework for assessing and choosing the most suitable renewable energy options, supporting the sustainable development of the country's education sector and beyond.

1.6 Report Structure

This report is organised into five chapters. Chapter One presents the introduction, which outlines the background of the study, the problem statement, research objectives and questions, as well as the significance of the research. Chapter Two provides a literature review, focusing on various solar energy technologies, with particular emphasis on the theoretical framework of PVT systems. It also includes relevant case studies and discusses the simulation tools commonly used for modelling solar energy systems, along with key performance, economic and environmental indicators. Chapter Three details the research methodology, describing the approach adopted for the design and performance modelling of both the SWH and PVT systems, as applied to a selected student residence at the NUL. Chapter Four presents the results and discussion, offering a comparative analysis of the technical performance, environmental impact and economic viability of the modelled systems. Finally, Chapter Five concludes the report by summarising the main findings, drawing conclusions, and offering recommendations for future research.

2. Literature Review

2.1 Overview

This literature review examines theoretical ideas related to energy demand in educational institutions, focusing specifically on energy usage patterns in student residences and their sustainability implications. It offers an overview of solar energy technologies, starting with a brief introduction to solar thermal and photovoltaic (PV) systems, followed by a detailed discussion of PVT systems. The review explores various PVT system configurations, including the types of collectors, working fluids, and common applications.

Additionally, the review explores theoretical frameworks for modelling and performance analysis of solar energy systems, emphasising commonly used simulation tools and methodologies. It also examines relevant performance metrics, economic indicators and assessment of environmental impacts. Relevant case studies are presented to contextualise the application of PVT systems in different settings. Finally, the chapter identifies gaps in the existing literature, establishing the foundation and significance of the current study.

2.2 Energy Demand and Sustainability in Educational Institutions

Student residences on university campuses are amongst the most energy-intensive facilities in the education sector. These buildings consume large amounts of energy for space and water heating, lighting, appliance usage, and other essential services that support daily student life [17]. The high energy demand is primarily because of continuous occupancy, the need for thermal comfort in varying weather conditions, and the general electricity usage for academic and recreational activities. This level of consumption significantly contributes to the overall energy footprint of universities and has serious financial implications for institutional operations. Therefore, addressing energy demand in university residences is critical for managing operational costs and improving energy efficiency across educational institutions.

The drivers of high energy consumption in student residences are multifaceted, involving both behavioural and structural factors. Occupant schedules, student behaviour, building design and the cultural and social norms surrounding energy use collectively contribute to variations in consumption patterns [19]. One key issue is that the students rarely bear the full costs of the electricity or hot water that they consume, unlike in their own homes [20]. As a result, there is often little motivation to conserve energy, leading to wasteful consumption practices. This lack of financial accountability increases the institution's reliance on grid electricity and raises utility expenses. Consequently, promoting energy consciousness in campus environments remains a critical challenge for achieving sustainability goals.

Empirical studies have underscored the growing scale of energy use within higher education institutions. A study by Ding et al. in China found that universities contribute approximately 8% to the national energy consumption, with the student dormitories alone accounting for about 18% of that total [21]. Further, the study indicated that the per capita energy use of university students exceeds the national average, emphasising the intensive nature of energy demand in campus residences. These findings highlighted the urgency of implementing targeted interventions in institutional settings to manage consumption and reduce the environmental and economic impact of excessive energy use.

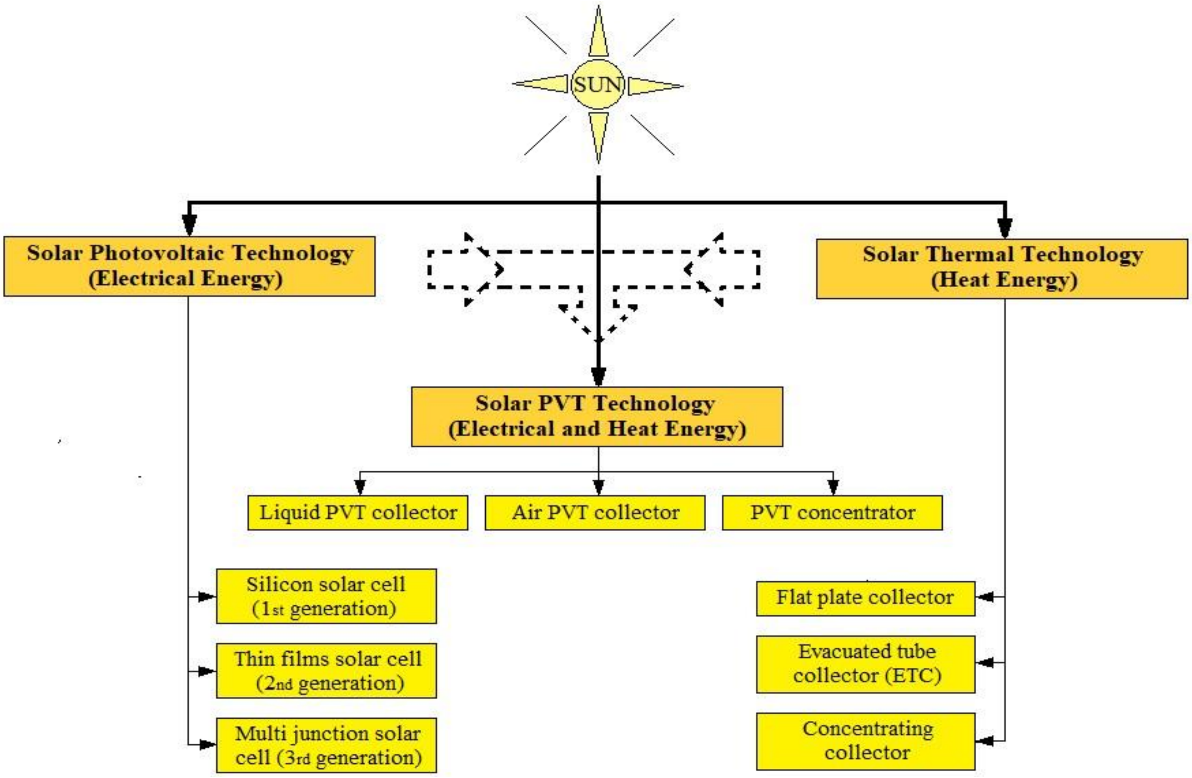


Figure 4: Types of solar technologies for electrical and heat energy [22]

Meeting the growing energy demand in the university residences necessitates the deployment of reliable, resilient and sustainable energy systems. Amongst the most promising solutions are solar technologies, which provide renewable energy in the form of electricity, heat or both, depending on the system type. As illustrated in Figure 4, various configurations are available, including standalone PV systems for electricity generation, solar thermal systems for water and space heating, and hybrid PVT systems that simultaneously produce heat and electricity [23].

Selecting the most appropriate and cost-effective solar technology for a given application requires a comprehensive analysis of both technical performance and economic viability. Such an evaluation must consider system efficiency, output potential, installation and maintenance costs, and long-term financial and environmental benefits.

2.3 Overview of Solar Energy Technologies

Solar energy technologies harness the sun’s energy to generate electricity, produce heat, or do both at the same time. These technologies have advanced greatly over the past decades, driven by the increasing demand for sustainable energy solutions and the need to cut reliance on fossil fuels [3]. Generally, solar energy technologies can be divided into three main types: photovoltaic systems, solar thermal systems, and hybrid photovoltaic-thermal systems.

2.3.1 Solar Photovoltaics (PV) Systems

Photovoltaic (PV) systems represent a widely adopted renewable energy technology that directly converts sunlight into electricity [24]. However, much of the absorbed solar energy is dissipated as heat, increasing cell temperatures as illustrated in Figure 5 [25]. This thermal effect negatively impacts the system’s efficiency, reducing performance by approximately 0.40.5% for each 1°C temperature rise [26]. Additionally, prolonged exposure to elevated temperatures can accelerate the degradation of PV modules [27].

According to Kumar et al., innovative materials (silicon, thin films and multi-junction solar cells) shown in Figure 4 and cooling strategies for solar cells have been actively investigated to enhance their efficiency and durability [28]. While advancements in multi-junction and perovskite cells have shown promising results, achieving efficiencies of up to 20% and costeffectiveness, crystalline silicon cells remain dominant due to their lower cost and the abundance of silicon on Earth.

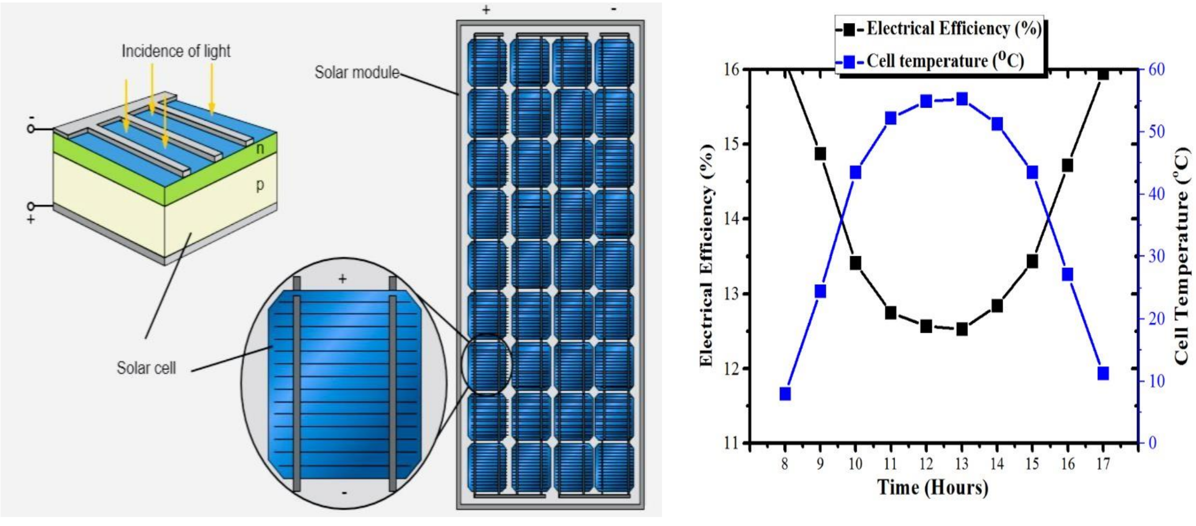


Figure 5: Structure of solar PV module (left) and the effect of temperature rise on the electrical performance of PV cells (right) [25], [29]

2.3.2 Solar Thermal Systems

Solar thermal systems harness the sun’s energy to generate thermal energy for various applications, such as the heating of fluids, space heating and industrial processes [30]. Unlike photovoltaic systems, which directly convert sunlight into electricity, solar thermal systems capture solar heat to heat fluids [28]. Solar water heaters, which are a common solar thermal technology, utilise solar collectors to absorb sunlight and heat water or a water-antifreeze mixture [31].

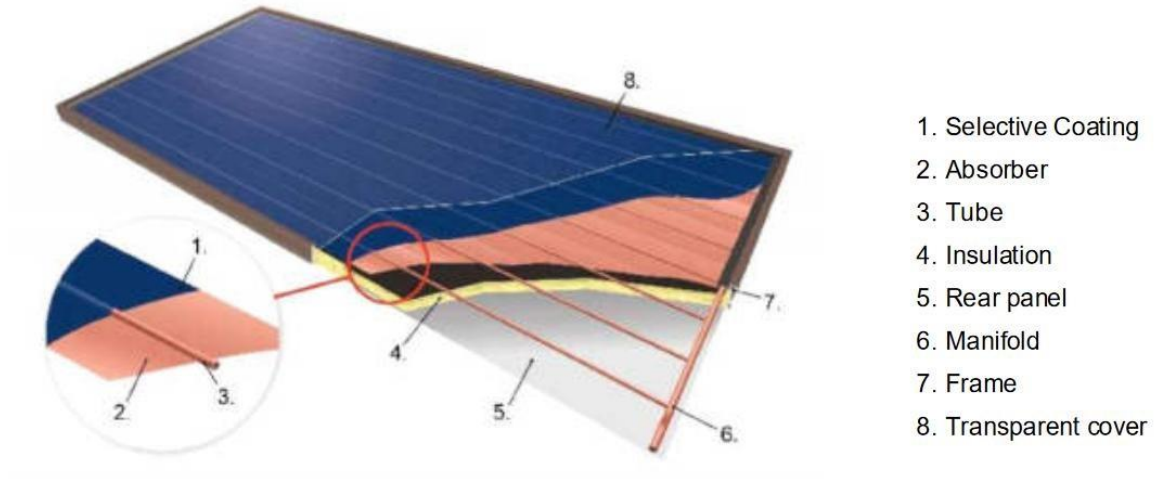


Figure 6: Flat-plate collector design [32]

Flat-plate collectors, shown in Figure 6, are a widely used type of solar thermal collector due to their affordability, ability to capture both direct and diffuse sunlight and high efficiency, reaching up to 70%. However, their performance can be significantly affected by adverse weather conditions, which limit their efficiency in less favourable environments [33]. Despite these limitations, their lower manufacturing costs make them a popular choice for many applications. In contrast, evacuated tube collectors, illustrated in Figure 7, are designed for superior performance, especially at higher temperatures. Their innovative design incorporates a heat pipe within a vacuum-sealed tube, which minimises heat loss and enhances efficiency [34]. Like flat-plate collectors, they can harness both direct and diffuse sunlight. However, evacuated tube collectors are particularly effective at lower sun angles, providing better overall daily performance. Although they typically involve higher initial costs, their improved efficiency often offsets this expense over time, making them a cost-effective solution in the long run [35].

An important consideration for evacuated tube collectors is the need for getters, which help maintain the vacuum within the tubes. Over time, atmospheric hydrogen can penetrate the vacuum, reducing its effectiveness. Getters absorb these gases, ensuring that the vacuum remains intact and the system's performance remains consistent throughout its lifespan.

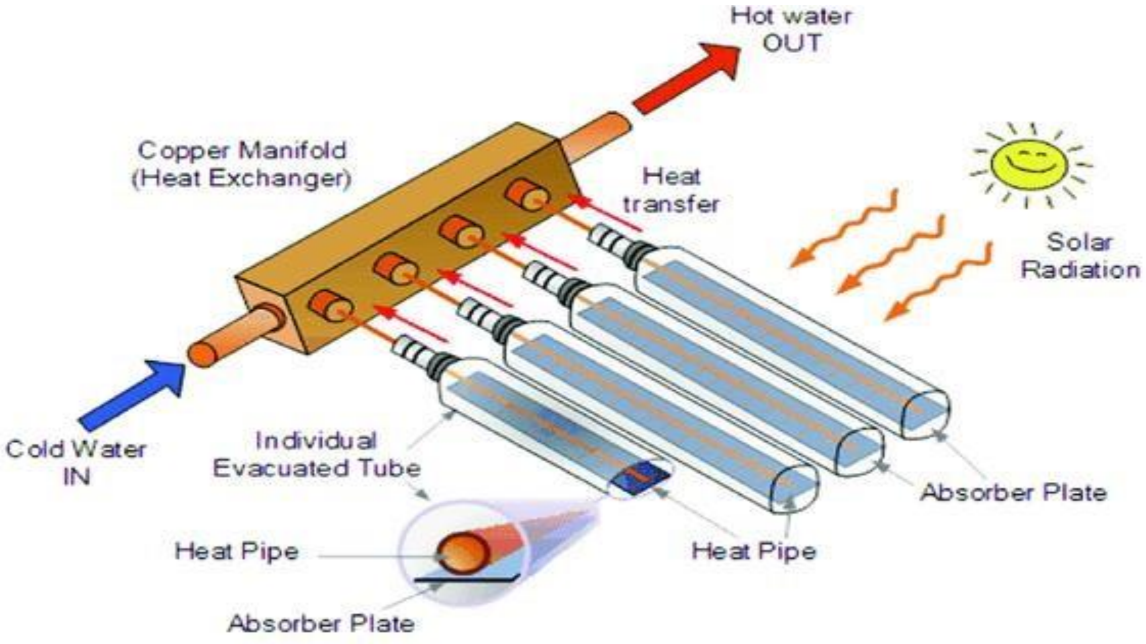


Figure 7: Evacuated tube solar collector schematic [36]

2.4 Solar Photovoltaic-Thermal (PVT) Systems

Solar PVT systems offer a synergistic approach to solar energy utilisation by integrating photovoltaic and solar thermal components into a single unit [37]. This innovative design allows for the simultaneous generation of electricity and heat, addressing complementary energy demands [38]. While PV cells convert only a small fraction of incident solar radiation into electricity, the remaining 80-90% is dissipated as waste heat. The PVT collector in Figure 8 mitigates this issue by recovering a portion of this waste heat using a working fluid and utilising it for thermal applications [39]. This simultaneous cooling of the PV module helps to maintain optimal electrical efficiency, thus improving the overall efficiency of the collector to as high as 89%.

Figure 8: Typical PVT collector [40]

PVT systems can be categorised based on their working fluid and collector type for different specific applications. They can employ either natural or forced circulation to move the fluid. In natural circulation, the heated fluid rises to the storage tank due to its lower density, while cooler fluid flows back into the collector [41]. This process occurs with no external pump. While simple and cost-effective, natural circulation is less efficient than forced circulation, which uses a pump to actively circulate the fluid. While forced circulation ensures optimal fluid flow and heat transfer, it also incurs higher operational costs [42]. As a result, natural circulation is commonly used in basic solar water heaters, while forced circulation is employed in more complex and efficient PVT systems.

2.4.1 PVT Working Fluid

The working fluid plays a vital role in extracting heat from the PV module and transporting it to a storage tank or point of use in a PVT system [43]. The primary function of the working fluid is to absorb the thermal energy generated by solar irradiation on the collector surface while simultaneously cooling the photovoltaic cells. This cooling effect improves the electrical efficiency of the PV module, which usually decreases as the cell temperature increases [44]. Therefore, the selection of the working fluid significantly impacts the overall system performance, efficiency and operational reliability. PVT systems utilise either liquid-based or air-based working fluids.

2.4.1.1 PVT Air Systems

Air has been used as a working fluid in PVT systems, initially in the systems with natural circulation and later in the systems with forced convection [45]. PVT air collectors share a similar structure with solar air collectors, except that the thermal absorber sheet is replaced by a PV layer, as shown in Figure 9. In these systems, air passes behind the PV layer, absorbing heat that can be utilised for various applications such as drying or space heating [46]. Air-based PVT systems offer several advantages, including the absence of leakage and freezing issues, as well as lower costs [47]. However, air has limitations as a heat transfer fluid because of its low density, thermal conductivity and specific heat [42]. Consequently, air-based PVT systems exhibit lower efficiency compared to water-based systems.

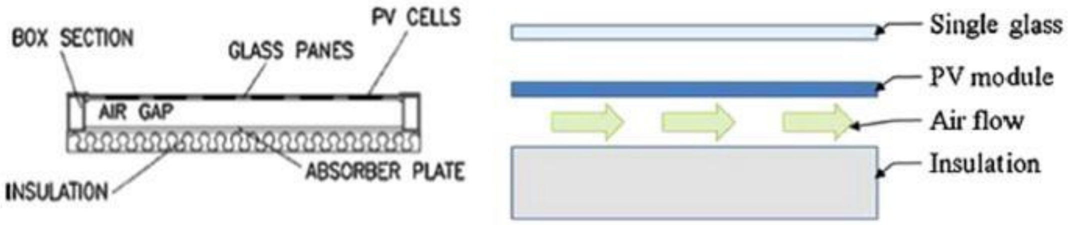


Figure 9: PVT air collector with glazing [11]

2.4.1.2 PVT Water Systems

Water-based PVT systems utilise water as a working fluid to cool the PV modules, as indicated in Figure 10, enhancing their electrical efficiency [11]. A pump circulates water through a network of tubes beneath the PV modules and efficiently transfers heat from the modules to the water [48]. Water, with its superior thermal properties, offers higher efficiency than air [49]. According to Herez et al., this increased efficiency comes at a cost, including the need for leakage detection, maintenance, and insulated thermal devices [42]. Further, a study by Pang et al. demonstrated that water-based PVT systems can achieve higher overall efficiency (87%) compared to air-based systems (74%) due to the water's higher specific heat capacity [6].

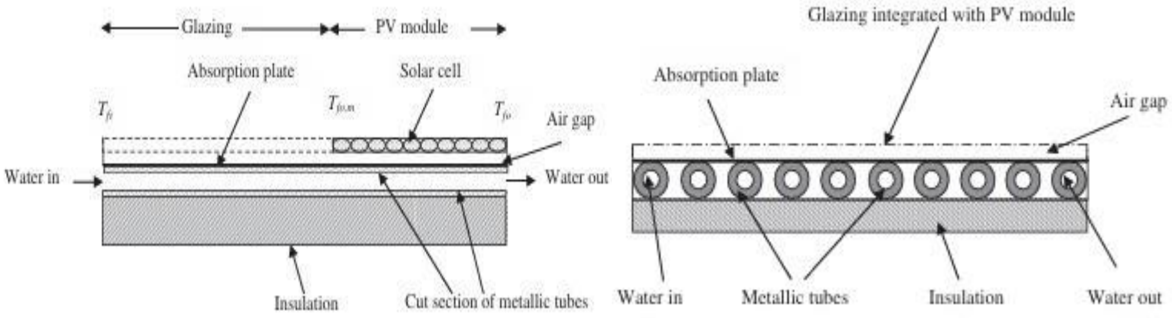


Figure 10: PVT water collector side view (left) and front view (right) [50]

While water-based systems offer significant advantages, their performance is influenced by factors such as flow distribution within the absorber tube. Research by Rodgers and Eveloy suggests that intermittent water flow can offer better cooling and efficiency than continuous flow, thus optimising system performance while potentially reducing energy consumption [51]. Water-based PVT systems find applications in various sectors, including space heating, desalination and water heating.

2.4.1.3 Combined Water and Air PVT Systems

To further improve the efficiency of PVT systems, researchers have developed combined air and water PVT systems, illustrated in Figure 11. These systems utilise both air and water as circulating fluids, allowing for enhanced heat transfer and improved performance [48]. By combining the advantages of both air-based and water-based systems, these systems can achieve higher thermal and electrical efficiency [39]. However, despite their potential benefits, combined PVT systems face challenges in terms of design complexity, higher costs and increased maintenance requirements. These factors have limited their widespread adoption, although ongoing research and technological advancements may help to address these issues in the future.

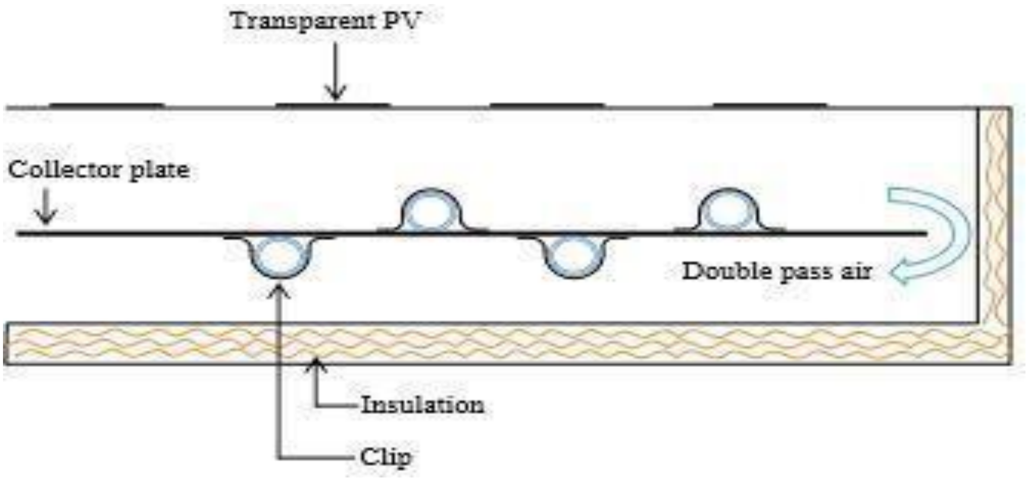


Figure 11: Combination of water and air in PVT collector [50]

2.4.2 PVT Collector Types

PVT collectors are designed in various configurations to optimise both electrical and thermal energy generation. This subsection provides an overview of the different PVT collector types based on their structural configuration, including flat-plate, concentrating and buildingintegrated designs. Each configuration differs in its construction, operating temperature range, and efficiency trade-offs, making them suitable for specific applications and climatic conditions [10].

2.4.2.1 Flat Plate PVT Collectors

Similar to traditional flat-plate collectors, flat-plate PVT collectors heat water while simultaneously generating electricity for various domestic and industrial applications [52]. The collectors utilise a transparent cover to capture sunlight and transfer heat to a circulating fluid [32]. Reducing convective heat loss and long-wave radiation from the absorber plate is the purpose of the transparent cover [53]. Metallic sheets and tube absorbers are commonly used for flat plate PVT collectors. However, copolymer absorbers have gained attention due to their advantages, such as reduced weight, simpler manufacturing, and lower cost [38]. While copolymer absorbers offer these benefits, they have limitations regarding thermal conductivity, thermal expansion and service temperature. Therefore, they must possess good physical strength, UV-light resistance and chemical stability.

Flat-plate PVT collectors can be classified into two types based on the presence of a glass cover: covered and uncovered. The primary distinction lies in the absence of a transparent protective cover and air gap above the PV module and absorber in uncovered collectors [54]. This structural difference significantly influences the thermal behaviour of the system. Covered PVT collectors benefit from enhanced thermal insulation and improved optical properties, contributing to superior overall performance. In a study by Dupeyrat et al., the thermal and electrical efficiencies of a PVT solar hot water system were compared [55]. The covered collector achieved a thermal efficiency of 72% at zero reduced temperature, along with an electrical efficiency of 11%. In contrast, the uncovered collector demonstrated a slightly lower thermal efficiency of 67% but with substantially higher thermal losses. These findings highlight the performance advantage of incorporating a glass cover in PVT collector design.

2.4.2.2 Concentrating PVT Collectors

Concentrating photovoltaic-thermal (CPVT) systems offer a promising approach to harnessing solar energy by combining electricity generation with heat recovery [56]. Unlike the flat-plate PVT systems, CPVT systems utilise concentrators, such as mirrors or lenses, to focus sunlight onto a smaller, high-efficiency PV cell. This concentration significantly increases the cell's operating temperature, which can lead to higher electrical efficiency if temperatures are properly managed through effective cooling [57]. A key advantage of CPVT systems is the potential to recover waste heat from the PV cells, further increasing the overall system efficiency. This recovered heat can be used for various applications, including domestic hot water, space heating, and industrial processes.

Reflectors are commonly used as concentrators because of their lower cost compared to lenses, as shown in Figure 12. Lenses offer advantages, such as lower weight and material costs; however, they are less effective at focusing diffuse sunlight, limiting their performance in areas with cloudy weather [58]. Therefore, reflector-based CPVT systems are often preferred for medium to high-temperature applications, like cooling, desalination and industrial processes. While flat-plate PVT systems may offer higher efficiency at lower operating temperatures, the concentrator systems become more advantageous as the temperature increases [59]. The reason is that the larger surface area of flat-plate collectors can lead to significant heat losses at higher temperatures.

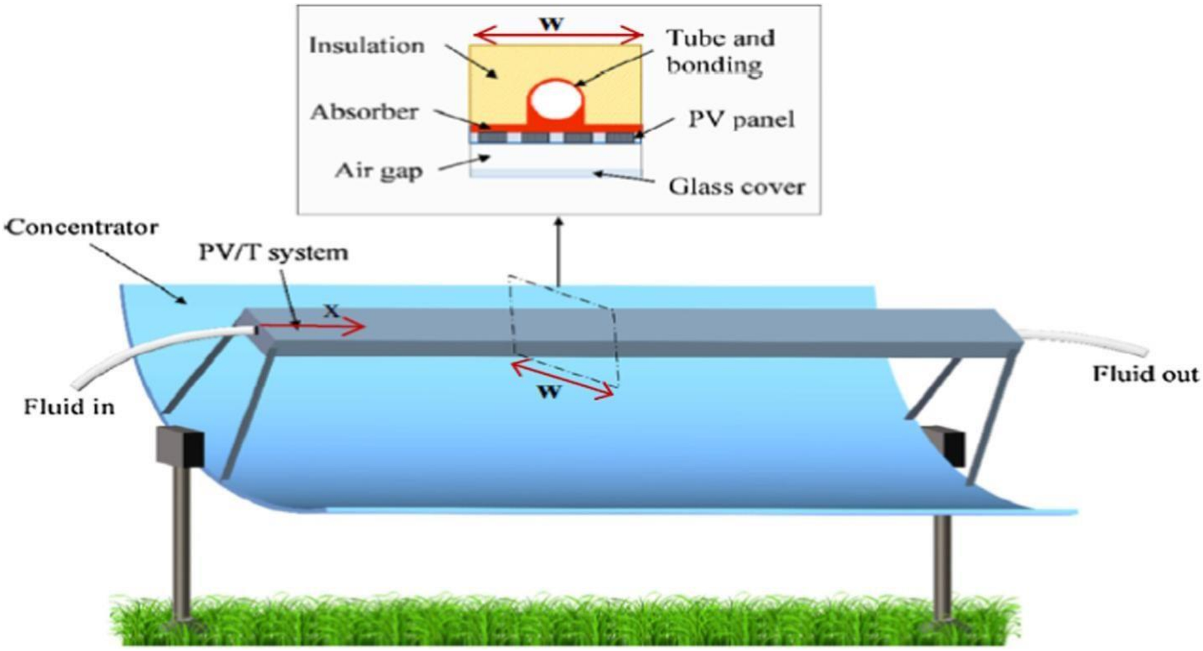


Figure 12: Concentrating PVT system schematic [42]

2.4.2.3 Building Integrated PVT Collectors

Building-integrated photovoltaic-thermal (BIPVT) systems combine roof, photovoltaic, thermal and insulation components into a single, integrated product [60]. This integration reduces costs by sharing resources and functions. BIPVT systems, illustrated in Figure 13, can also contribute to reduced cooling needs in buildings. These systems can be semi-transparent or opaque. Semi-transparent systems can be integrated into walls, roofs and windows, providing both energy generation and daylighting [61]. Opaque systems, which prioritise electricity generation, are typically integrated into walls and roofs. While opaque systems offer higher electrical output, semi-transparent systems provide additional benefits, such as improved indoor lighting and reduced heat gain [38]. BIPVT systems hold significant potential as a major source of renewable energy in urban environments, offering a sustainable and efficient solution for building energy needs.

Figure 13: Façade integrated PVT system (left) and roof-integrated PVT system (right) [32]

2.5 Modelling and Performance Analysis of Solar Systems

System modelling is a fundamental component in the design, optimisation, and evaluation of solar systems. It provides a virtual environment to simulate real-world operating conditions; it enables engineers, researchers and decision-makers to explore various system configurations, material options and control strategies without the time and cost constraints of physical prototyping [62]. In the context of solar energy systems, performance modelling is used to predict key output parameters, such as energy yield, efficiency and temperature profiles, based on location-specific climate data and load profiles. This predictive capability is essential for assessing how a system will behave under actual environmental conditions.

Accurate modelling is especially critical given the sensitivity of solar systems to factors, such as solar irradiance, ambient temperature, collector orientation and end-user consumption patterns. By simulating these variables, modelling supports the selection of appropriate system components and facilitates the optimisation of design parameters [63]. Variables such as collector surface area, storage tank size, tilt angle and flow rates can be adjusted within the model to maximise thermal and electrical output. This process not only informs technical decision-making but also ensures the long-term reliability and cost-effectiveness of the system.

Beyond design optimisation, performance analysis is integral to evaluating the environmental and economic benefits of solar systems. It allows for the estimation of energy savings, reductions in greenhouse gas emissions, and financial metrics such as payback period and levelized cost of energy (LCOE) [62]. These indicators are particularly valuable when justifying project investment, applying for funding, or meeting regulatory and institutional sustainability targets. Through comprehensive modelling, stakeholders can quantify the return on investment and demonstrate the alignment of the system with broader energy and climate objectives.

Advanced simulation tools also enable scenario analysis, allowing users to explore “what-if” conditions such, as equipment degradation, load fluctuations or climatic variability [64]. This enhances system resilience by supporting preventive maintenance planning and long-term performance monitoring. However, while detailed models offer high accuracy, they are often computationally intensive and time-consuming, especially when multiple configurations are evaluated. In such cases, simplified mathematical models may be employed during early-stage assessments. Although these models rely on assumptions and offer less precision, they are effective for rapid feasibility studies and comparative analyses across multiple design options.

2.6 Simulation Models for PVT System

Several studies on PVT systems employ simulation tools such as TRNSYS and MATLAB/SIMULINK, each offering distinct advantages. TRNSYS is widely recognised for its robustness in thermal system simulation, and it also effectively accommodates photovoltaic modelling [22]. Its modular structure and flexibility make it particularly suitable for detailed and dynamic simulations of solar thermal and PVT systems. TRNSYS enables in-depth analyses of component interactions, which are essential for capturing hourly or sub-hourly fluctuations in energy performance [65], [66]. However, the software’s complexity can present a steep learning curve, especially for integrated system modelling and typically requires advanced expertise.

MATLAB/SIMULINK is another popular platform, especially valued for its customisable modelling environment [67]. It has been used successfully to simulate PVT systems, with several studies reporting firm agreement between simulation outcomes and experimental data. Its versatility in control system design and real-time simulation also makes it suitable for hybrid and smart grid-integrated systems [68].

POLYSUN, in contrast, offers a more user-friendly interface while supporting a wide range of renewable technologies, including solar PV, solar thermal, PVT, geothermal, heat pumps and combined heat and power systems [69]. It enables the design, optimisation, and economic evaluation of hybrid energy systems. POLYSUN's extensive component library includes detailed technical specifications, which enhance the accuracy of simulations. Its built-in tools allow for performance assessments under various operational scenarios, making it particularly suitable for feasibility studies and techno-economic analyses.

Given the NUL's commitment to reducing energy costs and carbon emissions, POLYSUN presents a practical and efficient choice. Its capability to model both grid-connected and offgrid scenarios, alongside sub-hourly, scenario-based analyses under variable solar irradiance and load conditions, enables a comprehensive comparison between PVT systems and conventional solar thermal solutions [70]. This supports decision-making in terms of long-term cost savings, system reliability and alignment with sustainability targets.

2.7 Key Performance Indicators

Key performance indicators are used to evaluate the technical performance of solar energy systems. This section outlines the key metrics used in the assessment, including energy output, electrical and thermal efficiencies and solar fraction. These indicators provide a structured framework for analysing and comparing different system configurations.

2.7.1 Energy Output

Energy output refers to the total useful energy generated by a solar system, which may be electricity, thermal energy or both with a PVT system. The PVT systems are designed to maximise solar energy harvested per unit collector area by simultaneously producing electricity and low-grade heat [71]. An additional benefit of this integration is the cooling of PV modules by the thermal absorber, which reduces their operating temperature and improves electrical efficiency.

In steady-state operation, the thermal output of a solar collector can be described by an energy balance that accounts for absorbed solar energy, thermal losses and optical losses [64]. Assuming constant solar irradiance, inlet fluid temperature, wind speed and ambient temperature, the useful thermal energy output $\boldsymbol{Q_u}$ is expressed in $Qu = A_c[S - U_L(T_{pm} - T_a)]$ Equation 1 as:

$$Q_u = A_c[S - U_L(T_{pm} - T_a)] \quad \textit{Equation 1}$$

Here,

For PVT systems, a modified heat loss coefficient $\bar{U}_L$ accounts for the reduced thermal loss due to the part of the absorbed solar energy being converted into electricity, given by$\bar{U}L=U_L-(\tau\alpha)\eta_{ref}\beta_{ref}G_T$ Equation 2 [33].

$$\bar{U}_L = U_L - (\tau\alpha)\eta_{ref}\beta_{ref}G_T$$ *Equation 2*

Where

Since the mean absorber plate temperature is difficult to measure directly, the Hottel–Whillier–Bliss model is often used [72]. It expresses useful heat gain in terms of the fluid inlet temperature and includes a heat removal factor, ***F***F_R, which accounts for how effectively the heat is transferred from the collector surface to the fluid. The model is given by $Qu=A_c[G_TF_R(\tau\alpha)_{av}-\bar{U}_L(T_i-T_a)]$.

$$Q_u = A_c[G_TF_R(\tau\alpha)_{av}-\bar{U}_L(T_i-T_a)]$$ *Equation 3*

Here, $(\tau\alpha)_{av}$ represents the average transmittance-absorptance product across different components of solar radiation; and T_i is the inlet fluid temperature.

Electrical energy in a PVT system is generated through solar cells embedded within the collector. These cells operate on the photovoltaic effect, where sunlight excites electrons in a semiconductor material, creating an electric current. The output from the PV module is influenced by solar intensity, cell temperature, and system orientation [73]. The electrical behaviour of a PV cell can be approximated using a diode-based equivalent circuit, leading to $I= N_pI_{pn}-N_pI_d\left[exp\left(\frac{qV}{kTAN_s}-1\right)\right]$ Equation 4 [74].

$$I = N_pI_{pn}-N_pI_d\left[exp\left(\frac{qV}{kTAN_s}-1\right)\right]$$ *Equation 4*

where, I is the output current (***Amperes***); V is the output voltage (***Volts***); N_p and N_s are the number of modules in parallel and cells in series respectively; I_{ph} is the photocurrent (***Amperes***); I_d is the diode reverse saturation current; q is the electron charge; k is Boltzmann's constant; A is the diode ideality factor; and T is the cell temperature (***K***).

The corresponding electrical power output is given by $P=I\times V$ Equation 5 and $P= N_pI_{pn}V-N_pI_dV\left[exp\left(\frac{qV}{kTAN_s}\right)-1\right]$ Equation

6 [74].

$$P = I \times V$$ *Equation 5*

$$P = N_p I_{pn} V - N_p I_d V \left[exp\left(\frac{qV}{kTAN_s}\right) - 1\right]$$ *Equation 6*

Therefore, the total energy generated by a PVT collector combines both thermal and electrical contributions given by$PVToutput = P + Q_u$ Equation 7.

$$PVT_{output} = P + Q_u$$ *Equation 7*

A more detailed representation of this combined output includes both the electrical performance model and the thermal energy gain as expressed in $PVToutput = N_p I_{pn} V - N_p I_d V \left[exp\left(\frac{qV}{kTAN_s}\right) - 1\right] + A_c[G_T F_R(\tau\alpha)_{av} - \bar{U}_L(T_i - T_a)]$

Equation 8 [33], [74].

$$PVT_{output} = N_p I_{pn} V - N_p I_d V \left[exp\left(\frac{qV}{kTAN_s}\right) - 1\right] + A_c[G_T F_R(\tau\alpha)_{av} - \bar{U}_L(T_i - T_a)]$$

Equation 8

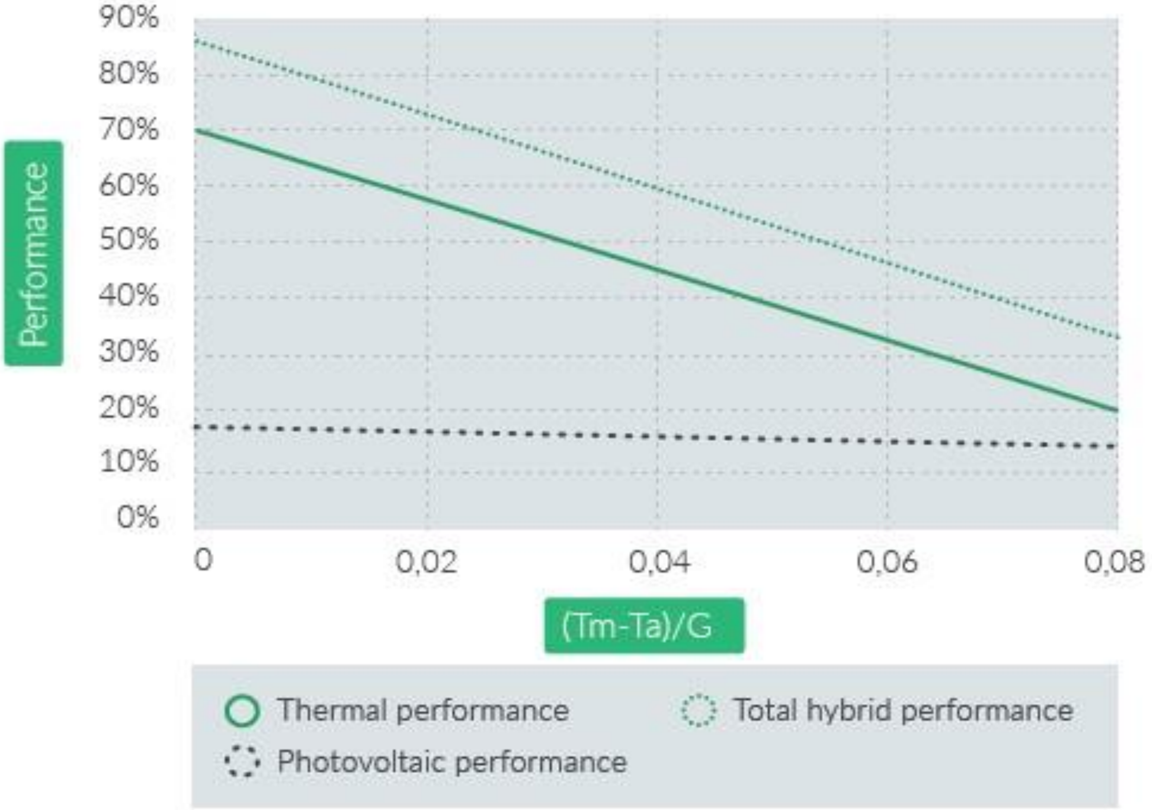
It

2.7.2 Efficiency

The overall efficiency of a PVT system is the sum of its thermal and electrical efficiencies [76]. From a first-law thermodynamics perspective, this is the ratio of total useful energy output (both heat and electricity) to the total solar energy incident on the collector surface given by $\eta PVT = \eta_{el} + \eta_{th} = \frac{P+Q_u}{A_c G_T}$ Equation 9 [48].

$$\eta_{PVT} = \eta_{el} + \eta_{th} = \frac{P+Q_u}{A_c G_T}$$ *Equation 9*

This



Figure

2.7.3 Solar Fraction

The

The solar fraction is influenced by several variables, including the magnitude of the energy load, the surface area of solar collectors, the capacity of the thermal storage system and the availability of solar radiation [81]. Designing a system to meet 100% of the energy demand throughout the year is typically neither efficient nor cost-effective. Instead, most solar energy systems are optimally sized to supply a significant share of the demand, with auxiliary energy sources providing support during the periods of low solar availability or peak consumption.

T h

$F = \frac{L-L_{AUX}}{L}$ *Equation 10* i s

where **L** is the total annual energy demand, and **L_{AUX}** is the energy supplied by non-solar

auxiliary systems.
i

^{s}The solar fraction varies with seasons, typically lower in winter and higher in summer, and provides an estimate of how much energy is saved compared to a fully conventional system. e x

p

r

According to Kalogirou, well-optimised systems can achieve annual solar fractions as high as 79%, demonstrating strong potential for solar energy to offset grid-based consumption [82].

2.8 Economic Evaluation and Environmental Analysis

The economic analysis of solar energy systems is carried out to determine the least cost of meeting the energy needs, considering both solar and non-solar alternatives. In the design and evaluation of energy systems, assessing economic viability is essential. This requires a comprehensive analysis of both costs and anticipated benefits over the system's lifetime [83]. To support investment decision-making, analysts and energy professionals utilise a range of economic performance indicators that provide insights into the financial feasibility and longterm sustainability of proposed systems.

2.8.1 Investment Costs

Investment costs refer to the total capital expenditure required to implement an energy system, including the cost of equipment, installation, labour and supporting infrastructure [64]. These costs can differ depending on factors, such as system scale, geographic location and the type of technology employed. The total investment cost can be quantified using $Investment\ cost(I_c) = A_c \times Average\ Costs$ Equation 11.

$$Investment\ cost(I_c) = A_c \times Average\ Costs \qquad Equation\ 11$$

where ***Ac*** represents the collector area of the system in m^2, and average costs per m^2.

2.8.2 Payback Period

The payback period represents the time required for an energy system to recover its initial investment through accumulated net cash flows or energy cost savings [84]. A shorter payback period is considered more attractive, as it reflects a quicker return on investment and reduced financial risk. The payback period can be calculated using**Error! Reference source not found.**.

$$Payback\ Period = \frac{I_c}{C_{sav}} \qquad Equation\ 12$$

Here, I_c is the initial investment cost and C_{sav} is the energy cost savings per annum.

2.8.3 Return on Investment (ROI)

Return on investment (ROI) quantifies the financial return of an energy system by measuring the net gain or loss relative to the initial capital investment. It is calculated by dividing the net profit typically derived from energy cost savings or revenue by the total installation cost and is expressed as a percentage [85]. A positive ROI indicates that the system is generating a financial return above its initial cost, thereby signifying a profitable investment. The ROI can be calculated using **Error! Reference source not found.**.

$$ROI = \left(\frac{Net\ Profit}{Investment\ Costs}\right) \times 100 \qquad \textit{Equation 13}$$

2.8.4 Internal Rate of Return (IRR)

Internal Rate of Return (IRR) is a critical financial indicator used to assess the profitability and attractiveness of an energy system investment [86]. It is defined as the discount rate at which the Net Present Value (NPV) of all the projected cash flows, both incoming and outgoing, equal zero. An IRR higher than the interest rate suggests a more financially viable investment, as it implies a greater return relative to the capital invested. The IRR can be determined by solving **Error! Reference source not found.**.

$$NPV = 0 = \sum_{t=0}^{n} \frac{C_t}{(1+IRR)^t} \qquad \textit{Equation 14}$$

where

C_t is the Cash flow in year t and n is the total number of years.

The IRR is used by investors to compare their potential investment in a solar energy project to the same investment in another project to determine if the solar energy investment is better. For large projects, the investors usually finance in part by their equity investment and the rest by debt. In such cases, the periodic debt payments, including the principal and interest, are considered as a part of the expenses during that year. Therefore, the IRR for the equity investment is leveraged by the debt. Since the interest on the debt is lower than the rate of return, leveraging improves the IRR of the equity investment.

2.8.5 Levelized Cost of Energy (LCOE)

Levelized cost of energy (LCOE) is a fundamental metric used to assess the economic viability of energy technologies over their entire operational lifespan [15]. It represents the average cost of generating one unit of energy, typically expressed in cost per kWh and incorporates all the relevant expenses, including capital investment, operation and maintenance, fuel (if applicable) and decommissioning costs [87]. A lower LCOE reflects higher economic efficiency and competitiveness of the energy system. The LCOE can be calculated using **Error! Reference source not found.**.

$$LCOE = \frac{\sum_{t=0}^{n} \frac{Ct}{(1+R)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)t}} \qquad \text{Equation 15}$$

Here, C_t is the total costs in year t (including installation, maintenance, amongst others). E_t is the total energy produced in year t; n is the lifespan of the system, while r is the discount rate.

2.8.6 Cost of Energy Savings

The deployment of solar energy systems provides a practical and sustainable approach to reducing electricity consumption and lowering utility expenses [88]. By harnessing clean, renewable energy from sunlight, these systems decrease reliance on grid-supplied electricity and contribute to substantial long-term financial savings. The economic benefits are most pronounced when a significant proportion of the generated energy is consumed on-site, thus minimising dependence on external energy sources. To accurately assess potential cost savings, typically expressed as cost per kilowatt-hour (cost/kWh), it is essential to consider both the average energy consumption of the building and the prevailing electricity tariff. Energy cost savings are determined by the extent to which solar energy displaces grid electricity usage, directly translating into monetary savings over time [89]. This type of analysis is vital for evaluating the financial viability of solar energy investments, particularly in institutional environments, such as student residences, where energy demand is relatively stable and electricity costs continue to rise. In such contexts, solar technologies offer a compelling solution for enhancing energy sustainability while reducing operational costs.

2.8.7 Greenhouse Gas Emissions

Substituting electric water heaters with solar water heaters (SWH) in educational facilities can result in substantial reductions in greenhouse gas (GHG) emissions. Renewable energy systems not only contribute to financial savings by reducing electricity consumption but also play a critical role in lowering carbon dioxide (CO_2) and other GHG emissions associated with fossil fuel-based energy generation [90]. In this context, solar thermal systems offer a sustainable and efficient alternative to conventional hot water production methods. By decreasing reliance on fossil fuels, they support environmental conservation and climate change mitigation efforts.

Greenhouse gas reductions are typically quantified as the annual CO_2-equivalent emissions avoided through the use of solar energy instead of fossil fuels [91]. The extent of these reductions is directly related to the system's efficiency in meeting thermal energy demands; the more energy the system generates, the greater the emission offsets. The systems with higher collector output, such as PVT systems, are expected to achieve even greater CO_2 reductions than conventional solar thermal systems due to their enhanced energy yield.

2.9 Sample Case Studies

The PVT systems have gained considerable attention in recent years because of their dualgeneration capability, producing both electricity and heat within a single, integrated system [92]. This technology offers notable advantages over traditional standalone PV or solar thermal installations, particularly in terms of energy efficiency, space optimisation and system integration. For instance, Hamdoon et al. conducted a study on a five-person household and found that the PVT system delivered superior electrical and thermal performance compared to separate PV and thermal systems [93]. This efficiency gain is primarily attributed to the lower operating temperatures of the PV modules in PVT configurations, which enhances their electrical output. Figure 15 illustrates the methodology used in this comparative evaluation. Supporting evidence from Kalidasan et al. [94] and Bianchini et al. [95] also confirms the applicability of PVT systems in both residential and commercial settings, despite the relatively higher initial capital costs [94], [95]. These studies highlight long-term benefits, such as reduced operational costs, improved system synergy and space savings, reinforcing the case for broader PVT adoption.

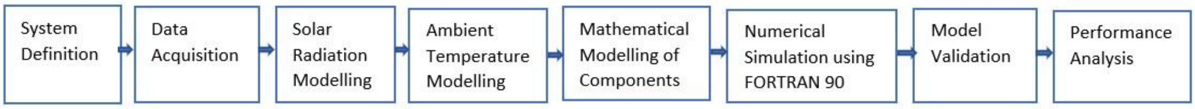


Figure 15: Hamdoon et al.'s framework for comparing a PVT system to solar thermal and PV systems for a household [93]

In the industrial sector, PVT systems have also demonstrated strong potential. A study by Ngunzi et al., highlighted in Figure 16, examined the use of PVT systems in Kenya's smallscale manufacturing industry for low- to medium-temperature thermal applications [10]. The results showed that the PVT systems significantly reduced thermal energy costs while enhancing energy self-sufficiency. This underscores their practicality in the settings where both electricity and moderate heat demand coexist. These findings illustrate the versatility of the PVT systems across various sectors and geographical regions, especially where energy reliability and cost control are critical.

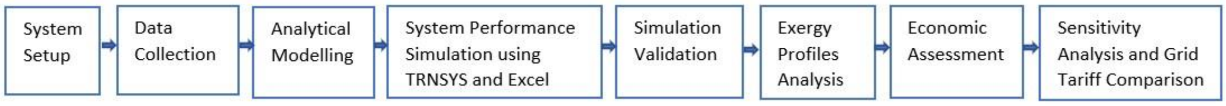


Figure 16: Ngunzi et al.'s methodology for assessing PVT system applicability in Kenyan industries [10]

In Sub-Saharan Africa, where energy systems are often constrained by limited grid capacity, high tariffs, and frequent outages, the PVT systems present an interesting alternative [96]. Abdul-Ganiyu et al. conducted a comparative study of PV and PVT systems in Ghana. It was revealed that, although PVT systems incur higher upfront costs, they outperform conventional PV systems in terms of total energy output, particularly when integrated with battery storage [15]. Under average solar conditions of 4.5 peak sun hours, the levelized cost of electricity (LCOE) was estimated at \$0.33/kWh for PVT systems compared to \$0.45/kWh for PV systems. However, the study also found that in scenarios without thermal energy demand or battery support, conventional PV systems remain more economically viable because of lower capital and maintenance requirements. These findings reinforce the importance of evaluating PVT feasibility based on specific site conditions, energy needs and economic constraints, particularly in regions like Sub-Saharan Africa, where access to both thermal and electrical energy is often limited.

2.10 Research Gap

PVT systems have gained increasing attention for their ability to generate thermal and electrical energy simultaneously from a single collector. Originally developed to address the decline in PV module efficiency at elevated temperatures, these hybrid systems use the thermal component to passively cool PV cells while capturing low-grade heat [11]. This recovered heat can be directly utilised for low-temperature applications or used as a preheating stage for higher-temperature processes, ultimately reducing overall thermal energy demand. Numerous studies have evaluated different PVT collector configurations under various climatic conditions, consistently reporting higher overall energy efficiency and improved electrical performance when compared to separate PV and solar thermal systems.

For example, Tiwari et al. provide a comprehensive review of PVT technology, highlighting that, while the thermal efficiency of PVT systems may be slightly lower than that of standalone solar thermal systems because of simultaneous heat extraction, their ability to deliver both electricity and heat makes them highly attractive in space-constrained settings [97]. Economic assessments further indicate that despite their higher initial capital cost, the combined energy outputs of PVT systems can result in substantial long-term financial benefits. Nevertheless, significant research gaps persist. First, very few studies have been undertaken in Southern Africa, where conventional PV and solar thermal technologies are already widely deployed and have demonstrated effectiveness. In Lesotho specifically, the PVT system adoption remains negligible, with only 48 m^2 of collector area installed to date, producing approximately 21 kW of thermal energy and 8 kW_{peak} of electricity [98]. Crucially, no performance evaluations or techno-economic analyses of PVT systems have been conducted in this context. This leaves a clear gap in understanding their feasibility under local climatic, economic and operational conditions.

Second, the existing literature predominantly focused on residential, commercial, or industrial applications. For instance, studies conducted in Kenya and Ghana have shown that the PVT systems can achieve higher overall efficiency and lower LCOE compared to standalone PV systems; however, these investigations have been confined to household and manufacturing settings [10], [15]. Despite the significant electricity and hot water demand in educational institutions, particularly in student residences, research on the viability of PVT systems in these settings remains limited.

Therefore, this study aims to address these critical gaps by evaluating the technical performance and economic feasibility of PVT systems in the educational sector, using the NUL as a case study. By comparing the performance of the PVT systems with that of solar thermal installations under Lesotho's climatic conditions, the research will generate context-specific evidence on the suitability of PVT technology for Southern Africa's educational institutions. The findings are expected to inform energy planning for environments where space constraints, rising energy costs and the demand for sustainable solutions underscore the value of hybrid energy systems.

3. Methodology

3.1 Overview

This chapter presents the methodological framework employed to assess the potential analysis of PVT systems in educational institutions, with a particular emphasis on the student residences at the NUL. A simulation-based methodology was adopted to enable a detailed and data-driven analysis of system performance under realistic conditions. The approach is structured around four key stages: (1) conducting an energy audit to evaluate current energy consumption patterns, (2) designing optimised SWH and PVT systems tailored to site-specific conditions, (3) modelling the systems using POLYSUN simulation software and (4) performing a comparative analysis of technical, economic and environmental performance. These stages are visually summarised in Figure 17**.**

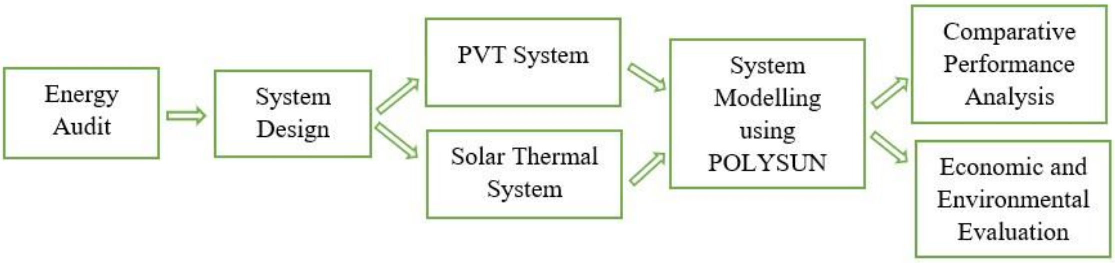


Figure 17: Methodology framework for PVT system modelling and analysis at the NUL residences

3.2 Study Area and System Context

This study is centred on the NUL campus, located in Roma, Maseru. The site benefits from good solar potential, with an average solar radiation of 5.5-7.2 kWh/m^2, which makes it wellsuited for the adoption of solar energy technologies. At the same time, the student residences face substantial electrical and thermal energy demands, driven largely by inefficient energy use practices. These high consumption levels translate into significant energy costs for the university, which relies exclusively on grid electricity to meet both its electrical and hot water needs.

The dependence on the grid not only increases operational expenses but also exposes the university to supply instability and the broader challenges of energy security. In light of these conditions, the NUL student residences present an ideal setting for evaluating the feasibility, performance and potential benefits of integrating PVT systems. These systems offer a promising solution for simultaneously meeting both electricity and hot water demands in a more sustainable and cost-effective manner.

To explore this potential, the study adopts a quantitative, simulation-based case study approach. The quantitative component enables the development of detailed system models based on climate data and energy usage patterns, thus improving the reliability and relevance of performance assessments. Meanwhile, the case study framework enables an in-depth, contextspecific analysis of energy consumption at the NUL, providing valuable insights into how PVT systems could be effectively deployed in similar institutional settings.

3.3 Energy Audit and Data Collection

Before system design and modelling, an energy audit is conducted to assess both the hot water and electrical load profiles of the student residences at the NUL. An energy audit evaluates how much energy a facility consumes, identifies where energy is used and helps justify upgrades aimed at improving efficiency. In this study, an investment-grade energy audit approach has been adopted. This method, commonly applied in commercial or institutional settings, follows a rigorous process to provide a reliable business case for reducing energy consumption, cutting costs and lowering greenhouse gas emissions [99].

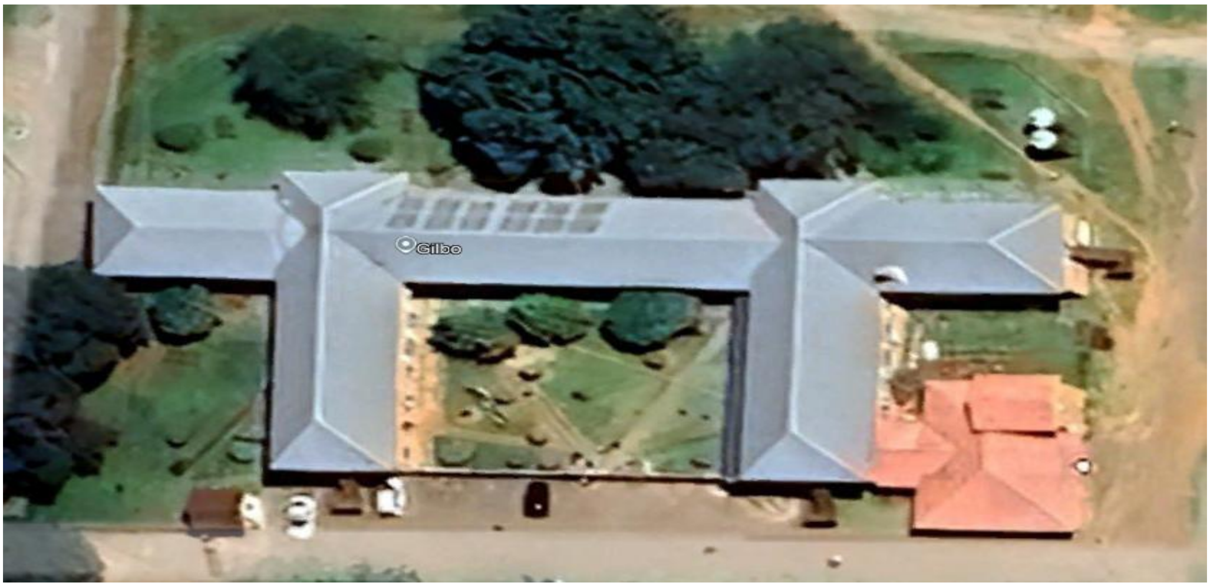


Figure 18: View of the NUL student residence known as Gilbo

As part of the audit, occupancy levels have been assessed by analysing the number of rooms and bed capacity in each residence, as summarised in Table 1. The NUL has thirteen student residences (Table 1), with Gilbo Residence selected as the representative case study for system modelling, shown in Figure 18. This residence was chosen because detailed electricity consumption data from the electric geysers is available. Again, Gilbo houses 108 students and has a rooftop area of approximately 1,386 m², of which around 600 m² is considered suitable for installing solar collectors because of its north-facing attributes. In POLYSUN, this datum is used to define the building’s energy characteristics, guiding the design, sizing and optimisation of the proposed solar thermal and PVT systems. It is also worth mentioning that this datum is critical for modelling the hot water demand profile and estimating energy savings if a solar energy system were implemented.

Table 1: Student residence occupancy at the NUL

Residence	**Occupancy**	**Single rooms**	**Double rooms**
Freedom	104	8	48
Mswati	88	20	34
Mutala	84	0	42
Masenate	608	0	304
Tšepo	120	0	60
Tšepo Extension	150	6	72
Cida	100	0	50
Chancellor	103	19	42
Africa male	102	54	24
Africa female	102	54	24
Gilbo	108	98	5
Khama	32	32	0
German Embassy	14	14	0

3.3.1 Load Assessment

An assessment of the existing water heating system was carried out to evaluate its performance and capacity. At the Gilbo residence, the current setup includes three 1,000-litre electric geysers, collectively supplying a peak daily hot water demand of about 490 kWh. These geysers are designed to provide water at around 50 °C, a temperature suitable for domestic use. However, it has been observed that they often struggle to maintain this temperature, especially from mid-morning to late evening, indicating that the system is undersized. Consequently, users frequently experience hot water shortages during peak demand times, confirming that the current configuration is inadequate for satisfying the daily hot water needs.

Meanwhile, an electrical load assessment was carried out to guide the design of a PVT system intended to reduce part of the student residences' electricity demand, excluding water heating. This assessment started by identifying all the major electrical appliances and devices in use, then reviewing their power ratings. The peak electrical load was estimated by multiplying the wattage of each device by the number of units and a diversity factor, which indicates the likelihood of simultaneous use [33].

For example, continuously operating appliances, such as refrigerators, were assigned a usage frequency (diversity factor) of 1. Frequently used appliances, including lighting and televisions, were assigned a factor of 0.4–0.6, while infrequently used items, such as hair dryers, were assigned a factor between 0.2 and 0.4 [100]. The average daily energy consumption was then calculated by incorporating the typical daily operating hours of each appliance. A summary of this analysis is presented in

Table 2, with a peak load estimated at 137 kW and an average daily load of approximately 1,010 kWh.

Table 2: Gilbo residence load profile

Device/Appliance	Number of Devices	Wattage (W)	Diversity Factor	Peak Load (kW)	Hours in Use (hrs/day)	Average Load (kWh/day)
Mini Fridge	65	90	1	5.85	24	140.40
Iron	108	1600	0.2	34.56	0.50	17.28
Kettle	108	1850	0.2	39.96	0.50	19.98
Hair Dryer	10	1400	0.3	4.20	1	4.20
Television	1	150	0.8	0.12	4	0.48
Lights	142	20	0.6	1.70	8	13.63
Sandwich Maker	30	750	0.2	4.50	0.16	0.72
Baseboard Heater	104	1000	0.4	41.60	6	249.60
Phone Charger	108	20	0.5	1.08	2	2.16
Laptop Charger	108	45	0.7	3.40	3	10.21
Total				**136.98**		**1010.52**

This load assessment is essential to ensure that the PVT system is appropriately sized to cover a share of the residence's electricity demand [101]. Moreover, the derived load provides insights into the building's electricity consumption profile for system optimisation and performance modelling.

3.4 System Design

System design defines the architecture and configuration of the solar energy systems to be modelled. This stage involves selecting and optimally sizing the key components of both the SWH and PVT systems. Various tools can be employed for this purpose, including mathematical tools and design software. In this study, system design was conducted using POLYSUN, a simulation platform that allows the creation of system diagrams and the testing of various configurations by selecting and interconnecting specific components.

The design process is guided primarily by two factors: the availability of solar radiation at the site and the thermal and electrical energy demands of the selected residence. Because solar irradiance varies with location, season and time of the day, an accurate understanding of the local solar resource is crucial for ensuring the system's capacity to convert solar energy reliably into useful energy [54]. This demand-driven and site-specific design strategy enables the development of technically robust and efficient systems that are tailored to the energy needs of the building while optimising overall performance.

Within POLYSUN, system configurations for both the conventional SWH system and the hybrid PVT system have been created and tested. By iteratively adjusting component types and sizes, such as collectors, storage tanks, electric elements, heat exchangers and pumps, the most effective system configurations were identified based on performance metrics, such as energy yield, system efficiency and solar fraction. This approach ensured that the final designs were not only functional but also optimised to improve the systems' efficiency.

3.4.1 Systems Configuration

The system configurations for both the PVT system (Figure 19) and SWH system (Figure 20) are based on flat-plate collector technologies, each connected to a thermal storage tank via a heat exchanger. While the solar thermal system uses conventional flat-plate collectors to harness the solar energy for water heating, the PVT system integrates a PV module with a thermal absorber in a single flat-plate collector. Apart from the type of the collectors employed, the two systems share an identical configuration, enabling a more accurate comparison of their performance.

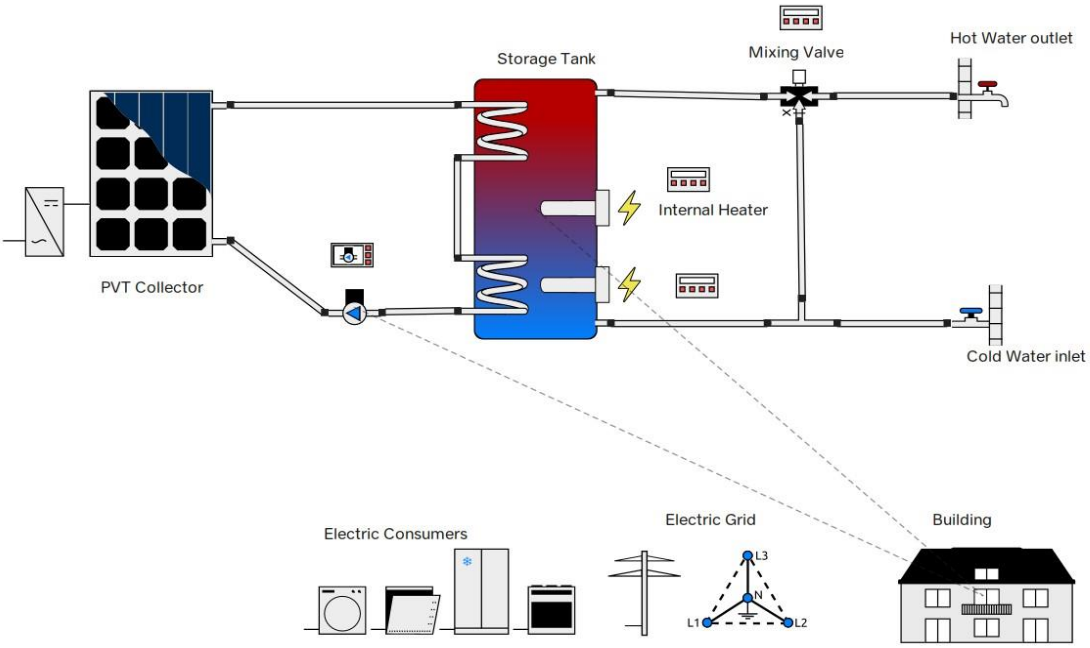


Figure 19: PVT system plus grid diagram

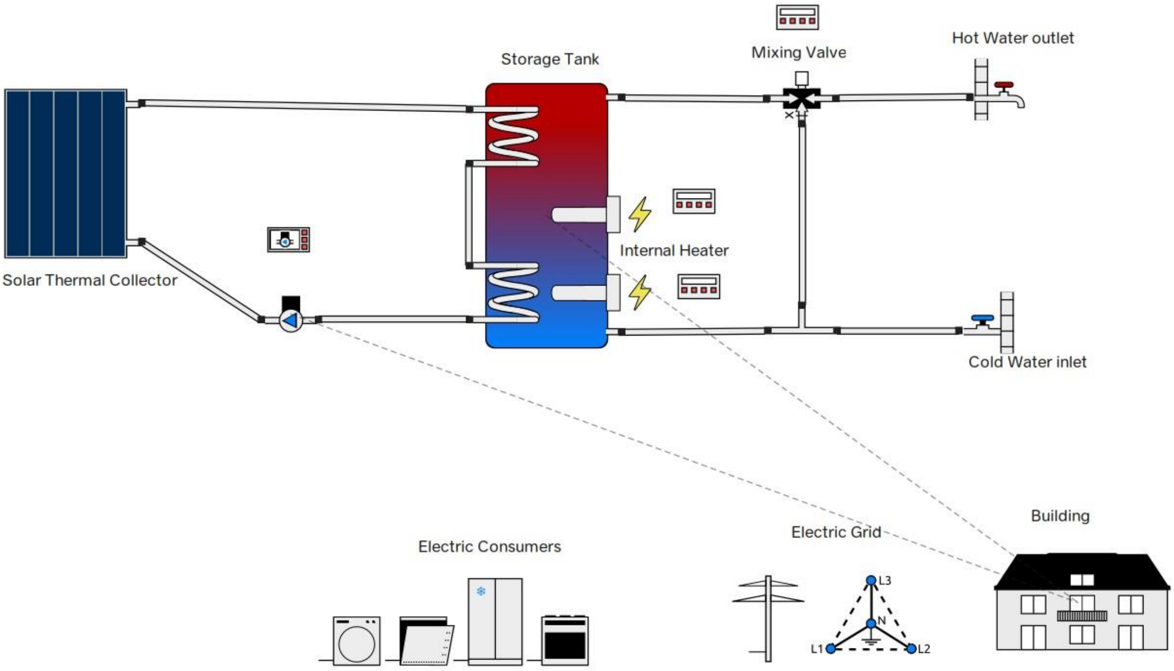


Figure 20: Conventional solar thermal system plus grid diagram

In both systems, solar energy heats a circulating 33.3% propylene glycol fluid within the collectors. This thermal energy is then transferred to the water in a storage tank through a heat exchanger. To ensure a consistent supply of hot water, the storage tank is equipped with auxiliary electric backup heaters (electrical elements), which activate when the temperature of the water falls below a set threshold. Hot water is extracted from the upper section of the tank, where the temperature is the highest and is delivered at approximately 50 °C. A thermostatic mixing valve is used to blend hot water with cooler supply water before it is distributed to endusers, ensuring both safety and comfort.

3.4.2 Tilt Angle and Orientation

Solar energy systems must be operated at their optimal performance, which is largely influenced by the collector's orientation and tilt angle relative to the horizon [102]. The tilt angle (β) is defined as the angle between the collector surface and the horizontal ground plane. A positive β indicates that the collector is facing towards the Equator, while a negative β means that it is facing towards the pole.

The performance of solar collectors is highly dependent on both their tilt angle and orientation with respect to the Equator, as these factors directly influence the amount of solar radiation incident on the collector surface [103]. Therefore, optimising these parameters is essential for maximising energy capture and improving system efficiency.

In the Southern Hemisphere, the optimal orientation is typically north-facing to maximise exposure to solar radiation throughout the year. Moreover, the ideal tilt angle is usually set equal to the site's latitude, as this alignment helps to maintain consistent performance across seasons. Based on these considerations, this study adopts a collector azimuth angle of 180° (true north) and a tilt angle of 29°, corresponding to the latitude of the study location.

3.4.3 Component Selection and Sizing

Proper selection and sizing are critical to achieving the desired balance between electrical and thermal outputs while ensuring cost-effectiveness and optimal performance and efficiency. The criteria used to choose components, such as solar collectors, storage tanks, inverters, and pumps, considering factors like energy demand, climatic conditions and system configuration, is discussed.

3.4.3.1 Solar Collectors

The selection and sizing of solar collectors are crucial to the system's performance and are guided by several design parameters. These include the required outlet temperature, the optical efficiency of the collector, the expected operating temperature range, the available installation area, and the site’s annual solar irradiance. These parameters collectively inform the choice of appropriate collector technology and ensure optimal system configuration for efficient energy conversion.

To enhance thermal performance, both the solar thermal and PVT collectors are primarily connected in series. This arrangement promotes a uniform temperature profile across the collectors and reduces pressure losses within the system [82]. In addition, a parallel flow layout may be employed where necessary. This would be done to improve fluid distribution, minimise thermal stratification and enhance heat transfer efficiency. Therefore, a series-parallel configuration has been adopted in this study to strike a balance between uniform heat distribution, system reliability and thermal efficiency.

Flat-plate collectors are selected for both systems because of their reliability and relatively low cost. They have also proven suitability for domestic and institutional water heating applications. Furthermore, their ability to operate at temperatures up to 200 °C makes them ideal for meeting the hot water demands of student residences.

Once the energy requirements and solar resource availability are clearly defined, the required collector area is determined using Equation 16 [32].

$A_{th} = \frac{Q_{HWD}}{\eta_{th}\times G_T}$

$$A_{th} = \frac{Q_{HWD}}{\eta_{th}\times G_T} \qquad \textit{Equation 16}$$

where **A_{th}** represents the area of thermal collectors (**m^2**); **Q_{HWD}** is the total thermal energy demand (***kWh***) and is equal to the useful energy **Q_u**; and **η_{th}** is the efficiency of thermal energy conversion.

Based on this approach, the SWH system is sized to include 25 Solartek flat-plate collectors, each with a gross area of 2 m², resulting in a total collector area of 50 m². These collectors operate with an optical efficiency of approximately 75%, which supports reliable energy capture and delivery.

In contrast, the thermal performance of PVT collectors is inherently lower because of the integrated design that accommodates both photovoltaic and thermal functions. Hence, a larger surface area is required to meet the same thermal output as that of a standard SWH system [75]. In this study, the PVT system includes 38 Abora aH72SK collectors, each with a gross area of

1.96 m², covering a total area of 74.5 m². Moreover, these collectors provide a thermal optical efficiency of 66% and an electrical efficiency of 17.8%, enabling them to supply both heat and electricity to the residence. These collectors were selected as they represent the only available flat-plate collector option in the simulation software, with comparatively higher thermal efficiency.

3.4.3.2 Storage Tank

The sizing of the storage tank considers factors including the daily hot water demand, the desired water temperature levels, solar radiation availability, and the required storage duration. Vst = HWD x P x 1.2 Equation 17 has been used to determine the appropriate storage tank volume (V_{st}), enabling adjustments to account for fluctuations in solar energy availability. This ensures that the system can reliably meet hot water needs while optimising the benefits of solar energy storage.

In the regions with high solar radiation levels, such as Southern Africa, the volume of the hot water storage tank, V_{st}, can be expressed using V_{st} = HWD x P x 1.2 Equation 17 [32].

$$V_{st} = HWD \times P \times 1.2 \qquad \text{Equation 17}$$

where **HWD** is the daily hot water demand per person (***Litres***) and ***P*** is the number of people in the household or beds in the residence.

Based on this sizing method, the calculated storage volume requirement is 5,184 litres; therefore, a 5,000-litre thermal storage tank was selected for each system. Since manufacturers do not produce tanks in every possible size, a selection must be made from commercially available capacities. It is recommended that the storage tank capacity be within 90–120% of the calculated volume, a range within which the selected capacity falls. The tank is designed to operate at a maximum temperature of 100 °C, allowing for effective thermal energy accumulation during the periods of high solar irradiance. In addition, the tank has a height of two metres and is insulated with 100 millimetres of rigid polyurethane (PU) foam, a material chosen for its excellent thermal performance. Specifically, PU foam has a low thermal conductivity (approximately 0.018 to 0.024 ***W/m·K***), which significantly reduces heat losses and enhances energy efficiency.

Further, each system includes two auxiliary electric heaters, each rated at 10 kW to supply backup thermal energy during the periods of low solar radiation and at night. Thus, they ensure that the system can meet the target hot water temperature under all conditions. These heaters are regulated by an auxiliary heating controller, which automatically activates them when tank temperatures fall below 40 °C and switches them off once the temperatures exceed 60 °C.

To further optimise energy use, the operation of the auxiliary heaters is time-controlled. Specifically, they are set to be available during early morning hours (1:00 am to 8:00 am) and late afternoon to evening (3:00 pm to 9:00 pm). Conversely, the heaters are disabled between 9:00 am and 2:00 pm, a period when solar radiation is typically at its peak and solar energy can be utilised more effectively. Thus, the selected storage tank and associated control strategy were designed to ensure reliable hot water delivery, improve energy efficiency and reduce dependency on grid-supplied electricity.

3.4.3.3 Circulation Pump

Effective flow regulation is essential for balancing the thermal functions of both the SWH and PVT systems. Each system incorporates a circulation pump controlled by a solar loop controller, which dynamically manages fluid flow between the storage tank and the solar collectors based on temperature measurements. The controller monitors temperature variables, namely the collector outlet temperature, the temperature at layer 5 of the storage tank and the collector aperture temperature, to obtain optimal operating conditions. In addition, it is programmed to maintain a specific flow rate of 200 litres/hour per m^2 of collector area. This ensures that the heat transfer fluid circulates efficiently, allowing for consistent energy collection and delivery. To prevent system overheating and improve safety, the pump is configured to remain active as long as the tank temperature is below 90 °C and the collector temperature is below 120 °C. These limits help to maintain system reliability.

Moreover, the solar loop controller employs a temperature differential control strategy to determine when to activate or deactivate the pump. Specifically, the pump is switched on when the temperature difference between the collector and the tank exceeds 6 °C, indicating that useful heat can be transferred. Conversely, it is turned off when the temperature difference drops below 2 °C, thus avoiding unnecessary circulation and thermal losses. This control strategy ensures that the system operates efficiently under varying solar and load conditions, optimising energy utilisation while protecting system components from thermal stress.

3.4.3.4 Inverter

An inverter is a vital component of the PVT system, serving the essential function of converting the direct current (DC) produced by the PV modules into alternating current (AC) suitable for grid use [104]. To facilitate this, a grid-tied inverter has been selected, enabling efficient integration of the PVT system with the existing electrical grid infrastructure. Through advanced power electronics, the inverter ensures that the AC output adheres to the grid's voltage, frequency and operational standards, thereby allowing seamless and reliable energy transfer to the grid [105]. In addition, it plays a critical role in maintaining system stability and compliance with utility requirements.

Furthermore, the inverter must be properly matched to the electrical characteristics of the PVT array, particularly under standard test conditions (STC). This includes aligning the inverter's nominal power rating with the system's maximum expected output to avoid underperformance or energy clipping due to overloading. Each PVT collector in the system has a nominal power rating of 350 watts. To accommodate the total electrical load and ensure optimal performance, three inverters, each rated for a maximum DC input power of 5 kW, are incorporated into the system. This configuration ensures that the electrical energy generated is efficiently converted and transferred without overloading the inverters, enhancing the performance, safety and reliability of the PVT system.

3.4.4 Grid Setup

The external electricity grid in Lesotho operates at a frequency of 50 Hz, with 400 V provided for three-phase systems and 230 V for single-phase connections, following standard voltage regulations. This grid serves as a reliable supplementary energy source, supporting the designed systems in meeting their energy needs during the periods of low solar availability. The grid also provides backup power for auxiliary water heating elements, general electrical loads, particularly during night-time or overcast conditions when solar energy generation is insufficient. This ensures that the systems can maintain continuous operation and meet user demands regardless of solar input fluctuations.

The integration of both the solar thermal and PVT systems with the national grid enables efficient energy management. In addition, the grid-tied configuration allows for enhanced selfconsumption of generated solar energy while reducing dependence on grid electricity. Thus, the systems not only support energy security but also contribute to cost savings and sustainable energy utilisation.

3.5 Case Study Simulation Modelling

The case study at the NUL focuses on the Gilbo student residence, where both a SWH system and a PVT system are modelled and analysed using POLYSUN software. This analysis aims to evaluate the feasibility and performance potential of PVT systems in educational institutions. POLYSUN offers a modern, user-friendly interface that facilitates the input of system parameters through an intuitive graphical environment [106]. Both systems are grid-connected, and their components are optimally configured to meet the residence's hot water demand. Key inputs include site-specific meteorological data and detailed electrical and thermal load profiles. The primary outputs assessed in the simulation include thermal and electrical energy yield, solar fraction and overall system efficiency, providing a comprehensive understanding of the systems' performance under local conditions.

3.5.1 POLYSUN Input Data

3.5.1.1 Solar Radiation Data

The NUL student residences are located in Roma, Maseru, at coordinates 29.4° S latitude and 27.72° E longitude. These coordinates were entered into the POLYSUN simulation software to generate location-specific solar radiation data, as illustrated in Figure 21. POLYSUN accesses this data through an integrated web-based service, ensuring accurate and up-to-date meteorological and solar irradiance information essential for reliable system modelling [12]. By incorporating precise geographical inputs, the software accounts for local climatic variations and solar resource availability, enabling simulations that closely mirror real-world site conditions.

New project
Polysun is creating a new project. Define a new name and location for the project.

Project
Project name: GILBO
Comments:

Location selection
○ From database ● From map

Location
Latitude: -29.447
Longitude: 27.724
Elevation: 1,673
Location name: Roma
Map: Open map

Figure 21: Meteorological Data Input in POLYSUN

3.5.1.2 Hot Water Demand Profile

A consistent supply of hot water is vital for essential domestic activities such as showering, dishwashing, and laundry. The total hot water energy demand can be estimated using Equation 18, which relates the volume of water used to the required temperature rise. Daily hot water consumption is determined based on standard usage patterns specific to the type of facility.

At the NUL student residences, hot water demand typically peaks in the early morning as the students prepare for class, decreases significantly during midday (when usage is limited to cleaning), and rises again in the late afternoon after recreational activities. For this study, the residences were classified as medium-demand facilities, with an average estimated consumption of 40 litres per student per day. Given the student population of 108, this corresponds to a total daily demand of approximately 4,320 litres. However, to accommodate potential fluctuations and ensure adequate sizing, a rounded figure of 5,000 litres per day is used, as derived using V_{st} = HWD x P x 1.2 Equation 17. The daily hot water demand can further be used to calculate the thermal energy required to raise the water from its initial temperature to the desired supply temperature for the residence, as expressed in $Q_{HWD} = mC_p\Delta T$ Equation 18 [32].

$$Q_{HWD} = mC_p\Delta T \qquad \text{Equation 18}$$

where, ***m*** is the daily hot water consumption (***m^3***); ***C_p*** is the heat capacity of water (***1.16 kWh/m^3K***); and ***ΔT*** is the temperature difference between the outlet water and inlet water in Kelvin (***K***).

Drawing on the results of the energy audit, a detailed daily hot water demand profile for Gilbo Residence has been developed and is presented in Figure 22. This profile reflects the temporal variation in demand throughout the day. Notably, the pattern differs from the typical student residence profile (Figure 23). The profile shows a pronounced morning peak between 06:00 and 08:00 hours, minimal midday use, and a secondary peak between 17:00 and 19:00 hours, aligning with students returning from classes. This typical profile was adopted as the reference for system design and modelling, serving as a key basis for accurate performance assessment.

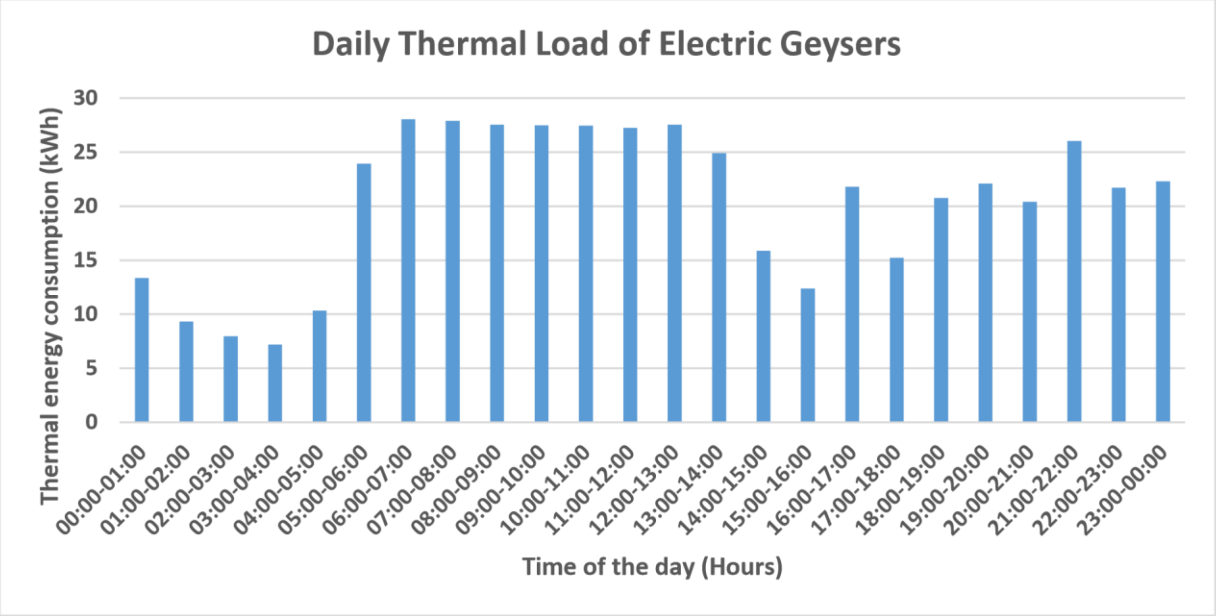


Figure 22: Gilbo residence's daily hot water demand profile

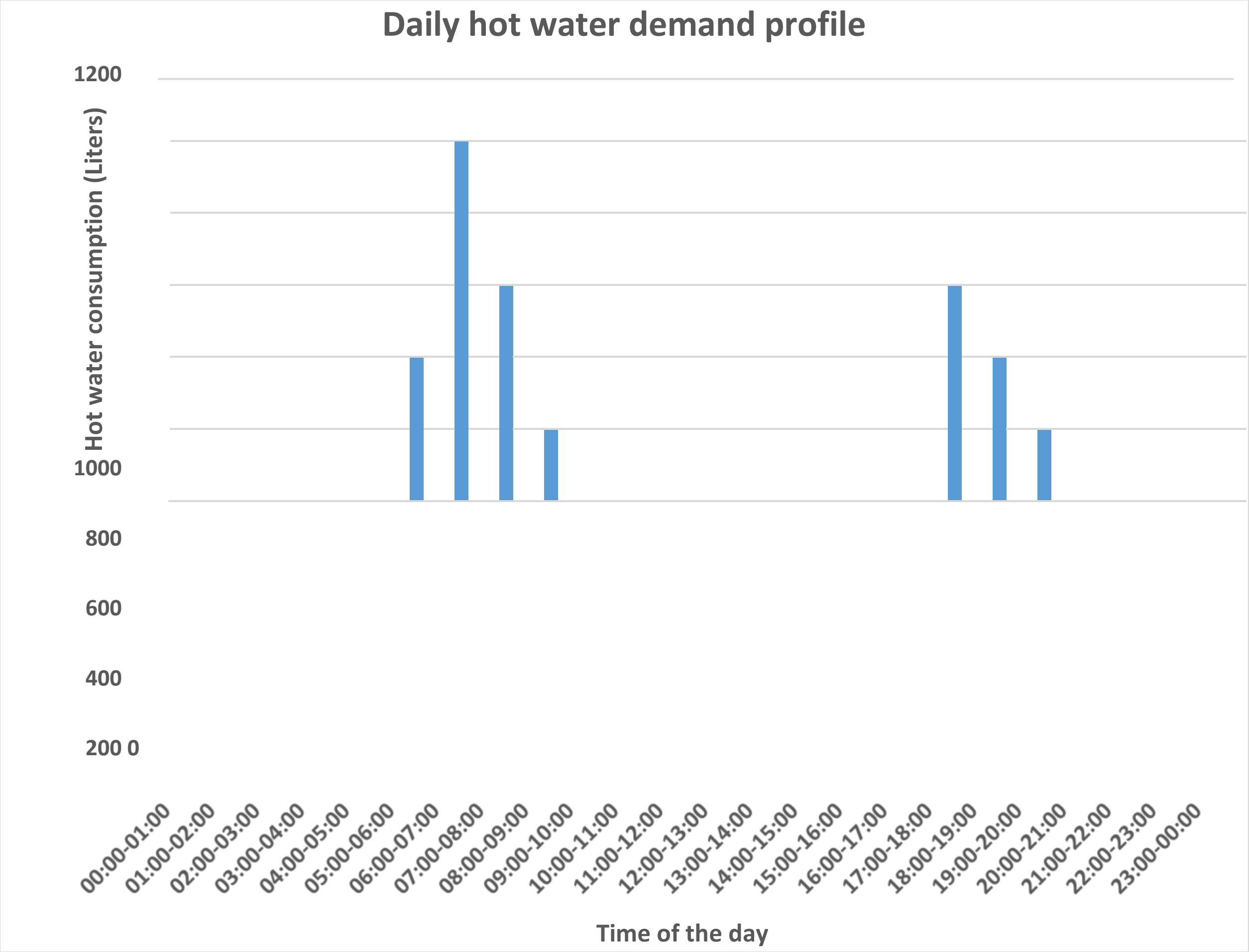


Figure 23: Typical daily hot water demand profile for a student residence

Monthly hot water demand varies seasonally, reflecting changes in student occupancy and activity levels throughout the academic calendar, including breaks and holidays. As illustrated in Figure 24, a significant reduction in hot water usage occurs during the winter academic break (end of academic year) from the last week of May to the last week of August. Notably, hot water demand drops to zero in June and July, as the student residences are unoccupied during this period. Additionally, a one-week university closure in December, at the end of the first semester, leads to a further decline in hot water demand for that month. These variations are essential for accurate system modelling, as the quantified daily and monthly hot water demand inputs form the basis for estimating the thermal energy output and assessing the overall system efficiency of both the standalone solar thermal and PVT systems.

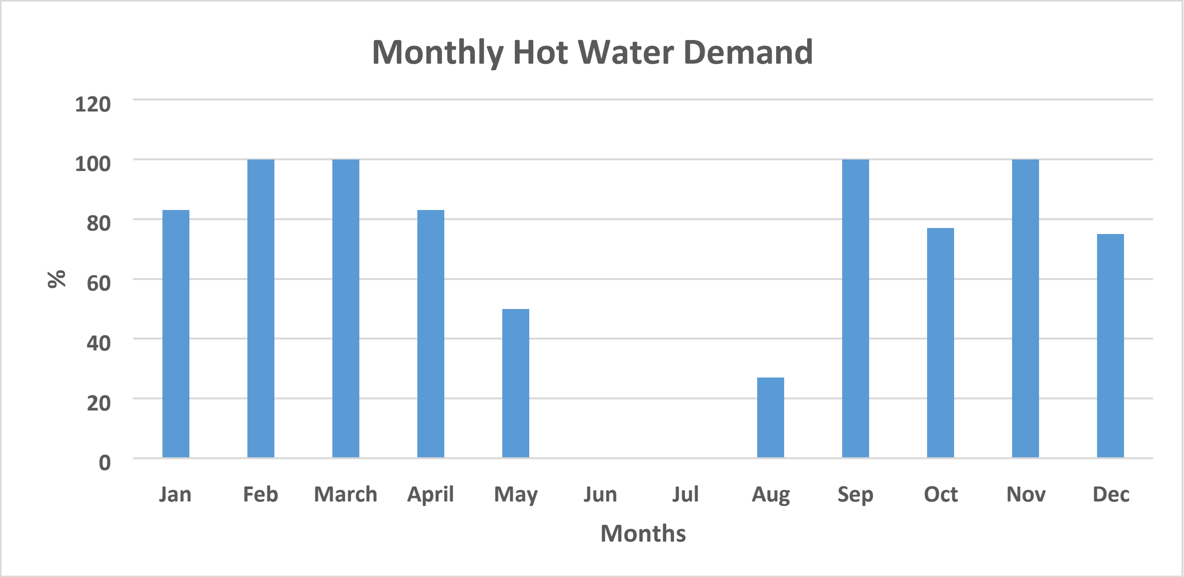


Figure 24: Monthly hot water demand for Gilbo residence

3.5.1.3 Electrical Load Profile

An accurate electrical load profile is developed by identifying and quantifying the major electricity-consuming appliances within the student residences. These include lighting, space heating, plug loads, and shared equipment located in communal areas. Both daily and seasonal variations in electricity usage are considered reflecting fluctuations in demand throughout the day and across the academic calendar. This level of detail is essential for the precise modelling and optimisation of the PVT system, both from technical and economic perspectives.

As shown in Table 2, the estimated average daily electricity consumption at Gilbo Residence is approximately 1,010 kWh, with a peak demand of around 137 kW. The peak load is assumed to occur at approximately 6:00 AM, aligning with the start of daily student activities. It remains relatively high until around 5:00 PM, after which it gradually declines. The lowest energy consumption is expected between midnight and 5:00 AM, consistent with reduced activity levels during these hours, as illustrated in Figure 25. These assumptions are informed by typical student routines and appliance usage patterns within the residence.

Moreover, as depicted in Figure 26, the monthly electricity load profile mirrors the seasonal trends observed in hot water demand. The periods of reduced occupancy, such as semester breaks and holidays, are associated with lower electricity consumption, reinforcing the importance of aligning energy system design and performance modelling with the academic calendar.

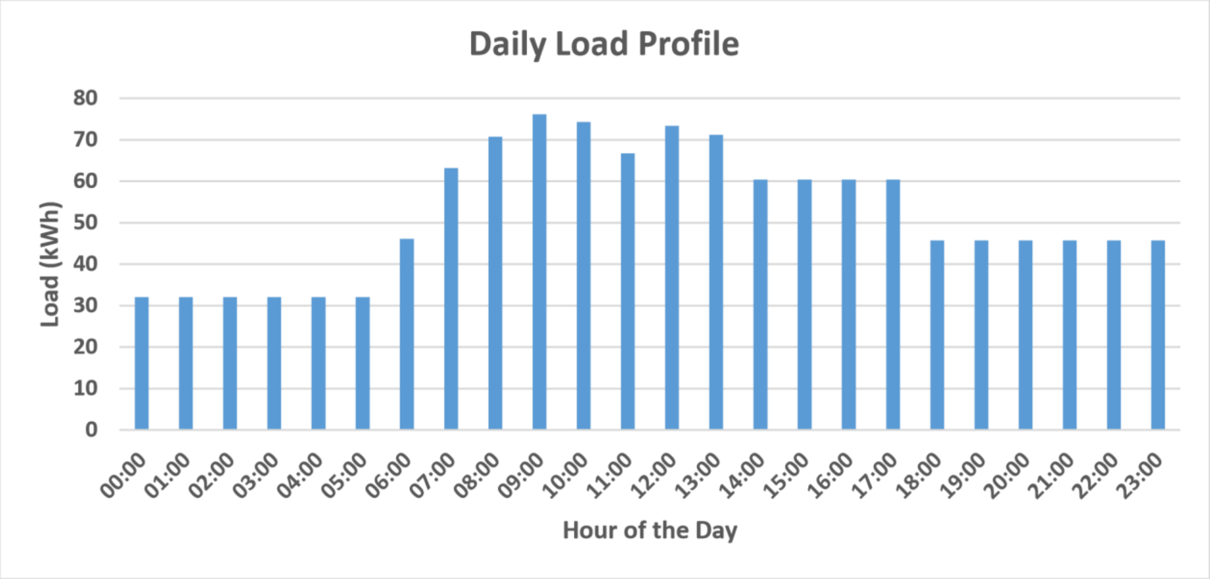


Figure 25: Gilbo's daily load profile

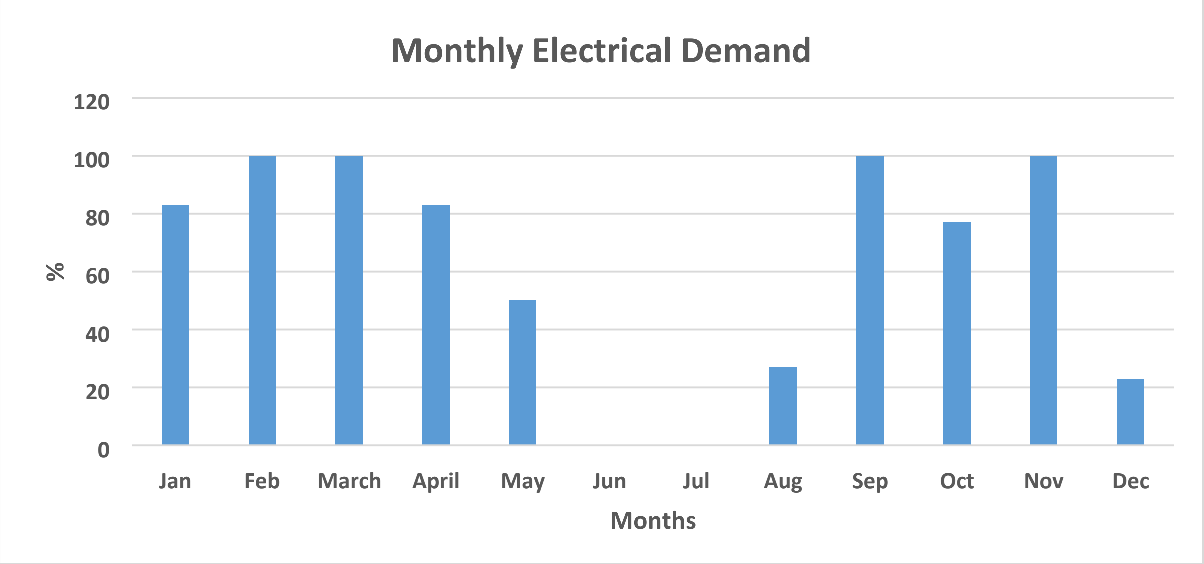


Figure 26: Gilbo's monthly electrical demand profile

3.5.2 Expected Outputs

The performance of the proposed systems is assessed using a set of key performance indicators, including thermal energy output, PV energy yield, overall system efficiency, solar fraction, cost-effectiveness and potential for carbon dioxide emissions reduction. Owing to the dualgeneration capability of the PVT collector, its evaluation includes both thermal and electrical performance metrics. To assess the feasibility and effectiveness of the PVT system, its performance is benchmarked against that of a conventional SWH system. This comparative analysis forms the basis for evaluating the potential of PVT technology to meet both thermal and electrical energy demands efficiently.

3.5.2.1 Thermal and Electrical Yield

Thermal energy output is a key parameter in determining the system's ability to meet domestic hot water demand. In this study, useful thermal energy was calculated as a function of the total collector surface area, which directly influences the system's heat generation capacity. The thermal output of both the standalone solar thermal system and the PVT system was evaluated to compare their effectiveness in fulfilling the residence's thermal load.

Besides the thermal output, the PV energy yield of the PVT system was analysed. This metric represents the amount of electrical energy generated by the PV component and serves as a critical indicator of the system's contribution to the building's electricity demand. By examining both the thermal and electrical outputs, the study assesses the overall capability of the PVT system to support the residence's energy needs.

3.5.2.2 Solar Fraction

The solar fraction represents the proportion of total energy demand (thermal and/or electrical) that is met by the solar energy system. It is a vital performance metric, indicating the system's level of dependence on solar energy. A higher solar fraction reflects greater energy selfsufficiency and reduced reliance on grid-based energy sources. In this study, solar fractions are calculated for both the conventional SWH system and the integrated PVT system and are compared to determine the more effective solution.

3.5.2.3 System Efficiency

System efficiency refers to the percentage of incident solar energy that is converted into useful thermal or electrical energy. This parameter is critical in evaluating how effectively each system utilises the available solar resource. The efficiency of the PVT system is compared to that of the SWH system. Higher efficiency indicates better system performance and improved utilisation of collector area, making it a preferred option in terms of energy output per unit area.

3.5.3 Economic and Environmental Analysis

This subsection evaluates the economic viability and environmental impact of the designed systems. It considers cost-related factors, including investment, operation and maintenance expenses, alongside key economic indicators and potential energy savings. Furthermore, it assesses environmental performance by examining metrics such as carbon emission reductions to provide a view of the system's sustainability within its intended application.

3.5.3.1 Economic Analysis

A comprehensive financial analysis has been conducted to evaluate the economic viability of the proposed PVT and SWH systems. The objective is to identify the most cost-effective solution to meet the building's hot water demand over a 25-year project horizon. The profitability assessment incorporates a wide range of economic parameters outlined in Table 3, including the prevailing electricity tariffs, projected annual tariff escalation, interest and inflation rates, and the cost of capital.

Table 3: Financial Parameters and Input Assumptions

Financial Parameter and Inputs	**Value**	**Source**
Time under Observation	25 Years	Assumed project life
Effective Interest Rate	7.25%	https://www.centralbank.org.ls/
Inflation Rate	4.20%	https://tradingeconomics.com/lesotho/inflationcpi
Interest Rate on Debt	11.21%	https://tradingeconomics.com/lesotho/interestrate
Electricity Price	M2.3429/ kWh	https://www.lewa.org.ls/approved-electricitytariffs-charges/
Electricity Price Increase	9.3%	https://www.lewa.org.ls/approved-electricitytariffs-charges/
PV Price Change Technology	-7%	https://www.pvxchange.com/Price-Index and https://www.irena.org/Data
PV Degradation	0.5 %/ year	https://solarmagazine.com/solar-panels/solarpanel-degradation/

Investment costs are calculated using $Investment\ cost(I_c) = A_c \times Average\ Costs$ Equation 11 and input into the simulation software for further economic evaluation. For the solar thermal system, the investment cost is estimated at M16,000.00 per m² of collector area. In contrast, the PVT system has a higher upfront cost, estimated at M19,000.00 per m², reflecting its dual-generation capability. Furthermore, operational and maintenance (O&M) costs are accounted for at 2% for each system to ensure a realistic long-term performance outlook. The financial model also includes debt servicing obligations, the potential availability of government subsidies and any ancillary costs related to energy supply.

POLYSUN simulates energy production and evaluates financial performance metrics, including energy cost savings, LCOE, NPV, ROI and IRR. These indicators, along with the calculated payback period, are used to assess the long-term cost-effectiveness of each system. The system that delivers the required energy services at the lowest total cost is considered the optimal solution. This holistic approach ensures that both the PVT and SWH systems are evaluated not only in terms of technical performance but also in terms of financial sustainability and investment risk.

3.5.3.2 Environmental Evaluation

The reduction of carbon dioxide (CO_2) emissions is a key indicator of the environmental benefits associated with renewable energy technologies. In this study, avoided CO_2 emissions are used to assess the contribution of the PVT system to greenhouse gas reduction. The analysis quantifies the emissions offset by the PVT system and compares them directly with those achieved by the SWH system. By calculating the amount of CO_2 displaced through the substitution of grid electricity and conventional water heating with solar-based systems, the study highlights the comparative environmental impact of each configuration.

The study adopts a systematic approach to evaluate PVT and SWH systems at the selected NUL student residence (Gilbo). It commences with data collection and an energy audit to establish detailed electricity and hot water demand profiles. This was followed by system design encompassing component selection and sizing to ensure both technical and operational efficiency. The designed systems were subsequently modelled using POLYSUN to simulate and optimise their energy output and thermal performance under local conditions. Finally, an economic and environmental assessment was conducted to evaluate cost-effectiveness, potential energy savings, and overall sustainability. This structured methodology provides a robust foundation for the next chapter, which presents the results and discussion.

4. Results and Discussion

4.1 Overview

This chapter presents and critically discusses the results obtained from the system simulations conducted using POLYSUN, in alignment with the study’s research objectives. The analysis encompasses three key dimensions: technical performance, environmental impact, and economic viability. Each aspect is examined to evaluate and compare the effectiveness of a PVT system with a conventional SWH system.

4.2 Technical Performance Analysis

This section presents and discusses the technical performance of the PVT and SWH systems based on key performance indicators. It evaluates metrics such as solar fraction, energy outputs, electric heater consumption, system efficiencies, energy savings and overall system performance. The results are compared to identify the system that demonstrates the best technical performance under the given operating conditions.

4.2.1 Solar Fraction

The solar fraction is a key performance indicator that measures the proportion of total thermal energy demand supplied by a solar thermal system. In this study, two systems were evaluated: a PVT system and a conventional SWH system (SWHS). The PVT system achieved a higher annual average solar fraction of 88%, compared to 76% for the SWHS, as shown in Figure 27 and Figure 28, respectively. This indicates that the PVT system uses more solar energy to meet hot water demand and relies less on auxiliary electric heating.

Seasonal changes significantly influence system performance. Both systems achieved higher solar fractions during months with low hot water demand, especially in May, August and December, which coincide with school holidays. During these times, low occupancy and reduced thermal load enable the available solar energy to fulfil nearly all hot water needs.

In contrast, the solar fraction decreases during months with high hot water demand, as the solar system covers a smaller percentage of the increased energy requirement. The lowest monthly solar fractions occurred in September: 74% for the PVT system and 64% for the SWHS. September is characterised by full occupancy, 100% hot water demand and relatively low ambient temperatures, which reduce the inlet water temperature and increase the heating load. Although February, March and November also experience full demand, the higher ambient temperatures during these months reduce the required thermal input, resulting in slightly better solar fraction performance compared to September.

One of the key reasons for the PVT system's superior performance is its larger collector area of 75 m² compared to 50 m² for the SWHS. A larger collector surface enables the system to harvest more solar energy, convert it into useful heat, and supply a greater share of the hot water demand. This correlation between the collector area and solar fraction is supported by

Huang et al. in a feasibility study on solar district heating in China, which concluded that higher solar fractions are typically achieved by increasing the collector area [107]. This underscores the importance of proper collector sizing when designing systems to maximise solar energy utilisation.

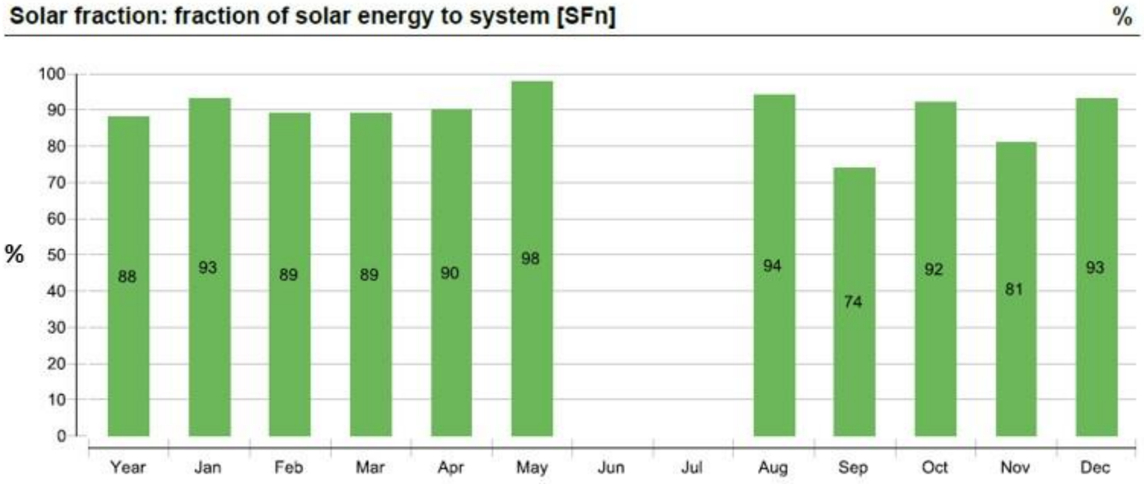


Figure 27: Annual solar fraction of the PVT system

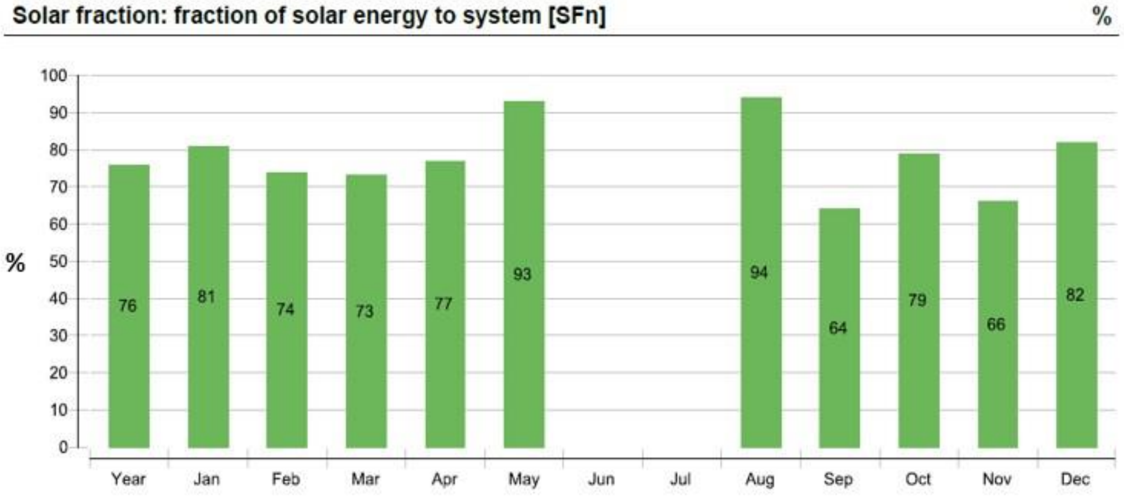


Figure 28: Annual solar fraction of the SWH system

Additionally, solar fraction varies geographically and temporally and is influenced by local solar radiation levels and usage patterns [79]. Solar fractions tend to peak during the summer months when solar irradiance is high and daylight hours are long. Conversely, during winter, lower sun angles and shorter days reduce the available solar resource, resulting in lower solar fractions. For this reason, it is recommended that solar thermal systems be designed based on the month with the lowest solar radiation and the highest hot water demand to ensure consistent year-round performance.

Finally, a logical pattern emerges: the months with low hot water demand consistently result in higher solar fractions, while the months with greater demand yield lower solar contributions. For both the PVT and SWH systems, school break periods, such as May, August and December, exhibit the highest solar fractions because of reduced thermal load. This demonstrates that, when demand is low, the system's solar energy production is more than sufficient to meet requirements. In contrast, higher demand months challenge the system's capacity, leading to a greater reliance on auxiliary electric heating.

4.2.2 Solar Thermal Output

The PVT system demonstrates a higher annual solar thermal energy output compared to the conventional SWHS, primarily because of its larger collector area and higher solar fraction. The PVT system yields 46,398 kWh/year of thermal energy, which is 4,618 kWh more than the 41,780 kWh/year produced by the SWHS. Although both systems are designed to meet the same hot water demand, the PVT system's 75 m² collector area enables it to harvest more solar energy than the SWHS with a 50 m² area, as shown in Figure 29.

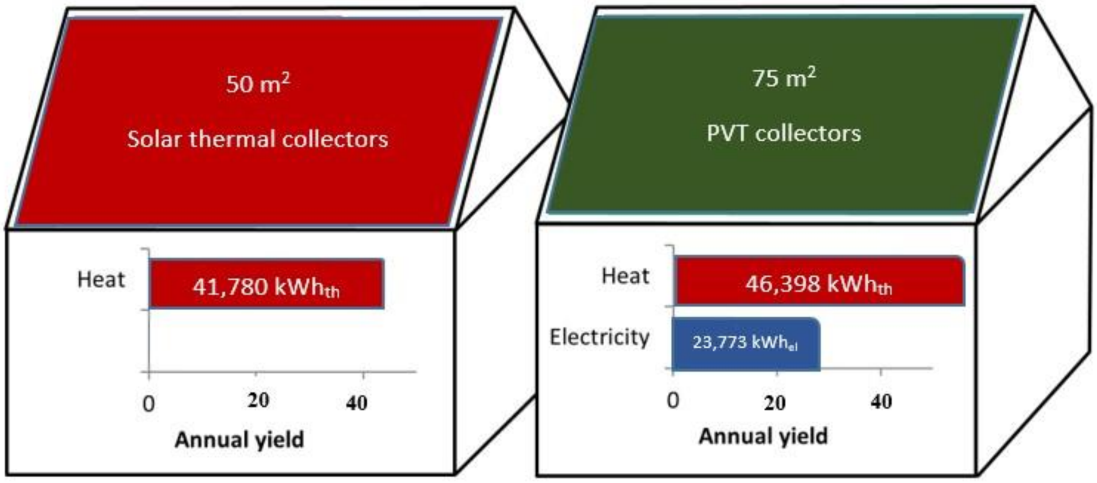


Figure 29: Comparative diagram illustrating the annual energy yields of the SWH system and the PVT system

Both systems follow a similar seasonal trend, generating higher thermal outputs from September to November. This corresponds to the periods of higher solar radiation. The maximum thermal output is observed in October for the PVT system (5,283 kWh) and in

November for the SWHS (4,723 kWh). Conversely, August records the lowest output because of the reduced demand during school holidays, 2,501 kWh for the PVT system and 2,523 kWh for the SWHS, as indicated in Figure 30 and Figure 31 respectively. This seasonal variation closely mirrors the trend in available solar irradiance onto the collector area, resulting in higher thermal output during spring and early summer months.

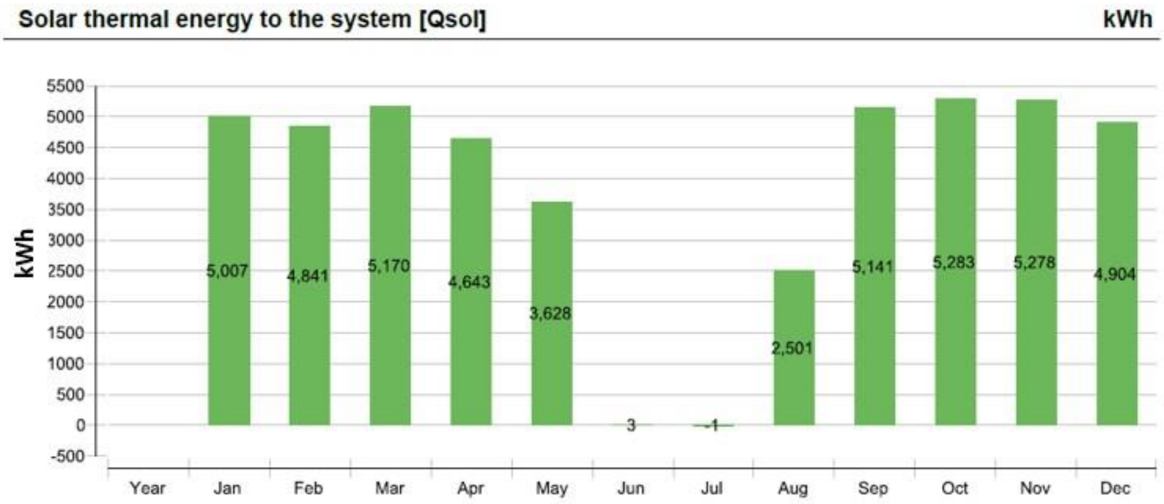


Figure 30: Annual thermal output of the PVT system

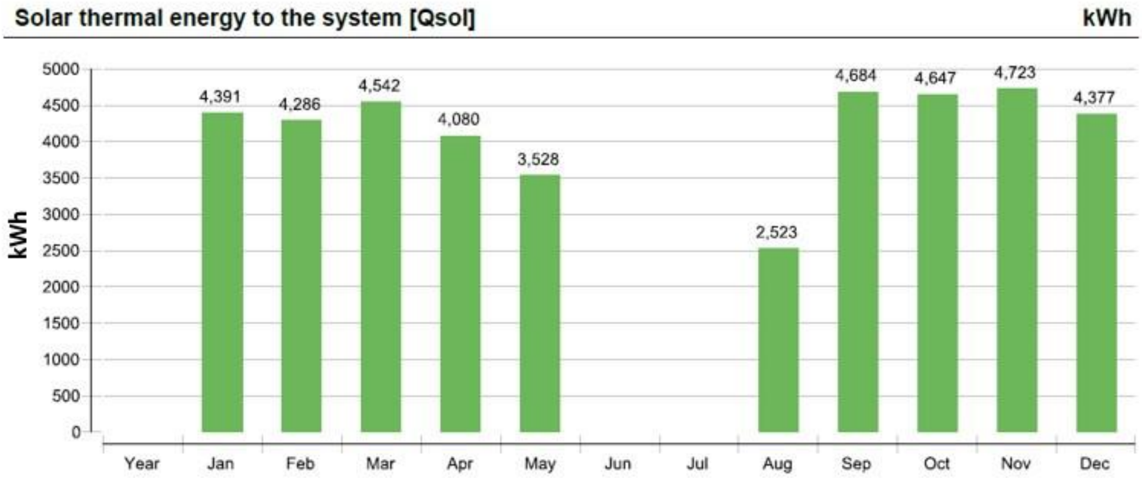


Figure 31: Annual thermal output of the SWH system

When normalised to collector aperture area, the collector field yield for the SWHS is 880 kWh/m²/year, compared to 611 kWh/m²/year for the PVT system. This confirms that the SWHS collectors are more thermally efficient per unit area in meeting the hot water demand. However, the larger collector area of the PVT system compensates for its lower per-area efficiency, resulting in a higher overall thermal energy output. Since thermal yield is directly influenced by the amount of solar radiation incident on the collector, the increased surface area of the PVT system enables it to capture more energy, contributing to its superior output.

In terms of solar irradiation, the PVT system receives 175,665 kWh annually, while the SWHS receives 110,651 kWh, reflecting the difference in collector area. The highest monthly irradiation occurs in October, with 15,921 kWh received by the PVT system and 10,029 kWh by the SWHS. From April to July, both systems experience their lowest irradiance levels, with minima of 13,048 kWh (PVT) and 8,219 kWh (SWHS), contributing to the lower thermal outputs during these months. Notably, system outputs are lowest in August, following the inactive period during June and July because of zero occupancy and no hot water withdrawal.

The larger collector area and higher irradiation levels received by the PVT system also result in higher collector temperatures. Daily average collector temperatures for the PVT system reach 70°C from January to April and again in November and December as indicated in Figure 32. On the other hand, the SWHS averages around 60°C during the same periods as shown in Figure 33. In June and July, with no hot water draw-off, both systems reach stagnation temperatures because of heat build-up. The PVT system stagnates at around 200°C, while the SWHS reaches 135°C. This reflects the thermal performance differences.

The stagnation temperature characteristics of PVT collectors can differ significantly from those of conventional solar thermal collectors, primarily due to variations in design, insulation, and heat loss mechanisms. Chow et al. and Brahim et al. reported that the stagnation temperature of a solar thermal collector absorber with advanced spectrally selective coatings can reach up to 220 °C. In contrast, the stagnation temperature of a PVT absorber is often lower, around 150 °C, owing to its typically higher solar reflectance and greater infrared emission compared to conventional solar thermal absorbers [108], [109]. In the present study, however, the PVT collectors demonstrate higher stagnation temperatures than flat-plate solar thermal collectors. This outcome is attributed to reduced convective heat losses, which result from enhanced rear insulation as well as the PV module itself acting as an additional glass cover. The combination of high solar absorption, enhanced insulation and lower overall heat losses enables a PVT collector to retain heat more effectively than a standard SWHS collector. While this design is advantageous for minimising operational heat losses, it also means that, in the absence of cooling flow, the PVT collector can attain significantly higher stagnation temperatures.

Despite its higher thermal output, it is important to note that if both systems had the same collector area, the SWHS would outperform the PVT system in thermal energy production. This is because the PVT collectors are subject to a trade-off between thermal and electrical performance. While PV cells operate optimally at lower temperatures, thermal collectors benefit from higher operating temperatures. To preserve electrical efficiency, PVT systems are often designed to operate at moderate temperatures. This reduces the temperature gradient and the rate of heat transfer to the fluid, which in turn lowers the overall thermal efficiency.

In addition, the SWHS collectors are purpose built for optimal thermal performance, typically featuring direct contact between the absorber and heat transfer fluid. In contrast, the PVT collectors must accommodate PV modules, which introduce thermal resistance due to air gaps, adhesive layers or limited contact area between the PV back-sheet and the absorber. These design limitations impair the heat transfer process in the PVT collectors and reduce their thermal efficiency compared to the SWHS units.

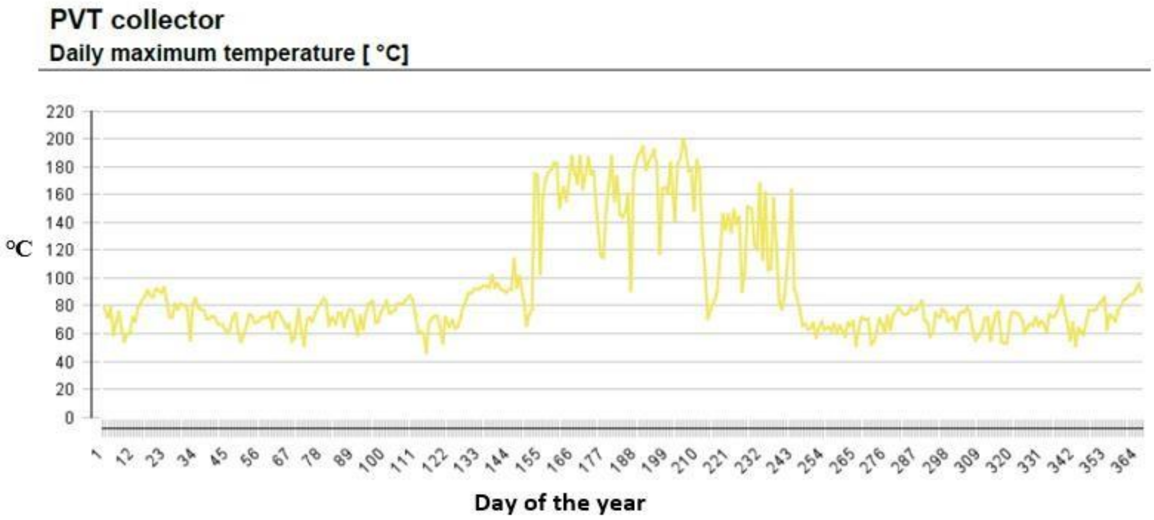


Figure 32: Daily maximum temperatures of the PVT collector

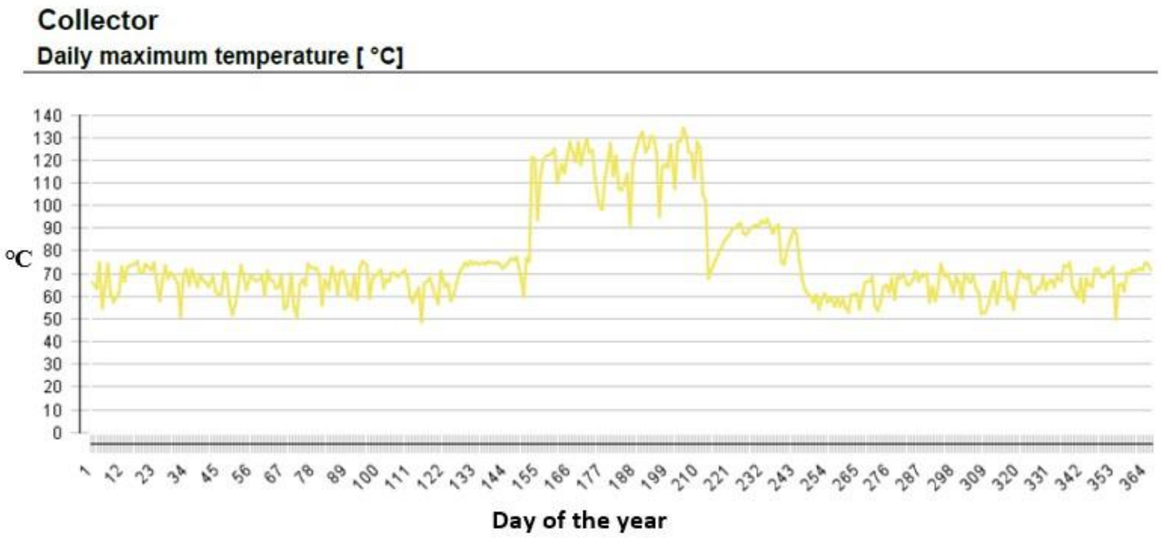


Figure 33: Daily maximum temperatures of the thermal collector

Because of these mentioned differences, the PVT system was intentionally designed with a larger collector area to meet the same hot water demand as the SWHS in this study. This strategic sizing explains why the PVT system ultimately delivers a higher total thermal output, despite its inherent thermal efficiency limitations.

4.2.3 Electricity Consumption of Heat Generators (Electric elements)

Despite both systems achieving relatively high solar fractions, they do not fully meet the thermal demand throughout the year. As a result, auxiliary heating provided by electric elements in the storage tanks is required to supplement solar thermal energy, especially during the periods of increased demand or lower solar availability.

Most of the annual thermal demand is supplied by the solar thermal systems, with the electric elements playing a supportive role. However, during colder months, the demand for hot water tends to rise. This is because of the lower inlet water temperatures, which increase the energy needed to reach the setpoint temperature of 50°C, even though collector efficiency may improve under cooler conditions. Consequently, the electric elements are required to operate more frequently and for longer durations during these months.

Notably, the conventional SWHS exhibits significantly higher auxiliary electricity consumption than the PVT system, 18,773 kWh compared to 11,825 kWh annually. This suggests that the PVT system is more effective in covering thermal demand through solar energy. The outcome is likely a result of the system’s larger collector area and higher overall solar contribution.

The months with the highest auxiliary energy consumption for both systems are September and November, aligning with the periods of full academic activity and increased occupancy, which naturally lead to higher hot water demand. In contrast, May, August and December correspond to school holidays and reduced campus activity. During these months, thermal energy demand is lower, and the majority of it is covered by solar energy alone, resulting in the lowest usage of electric elements.

As indicated in

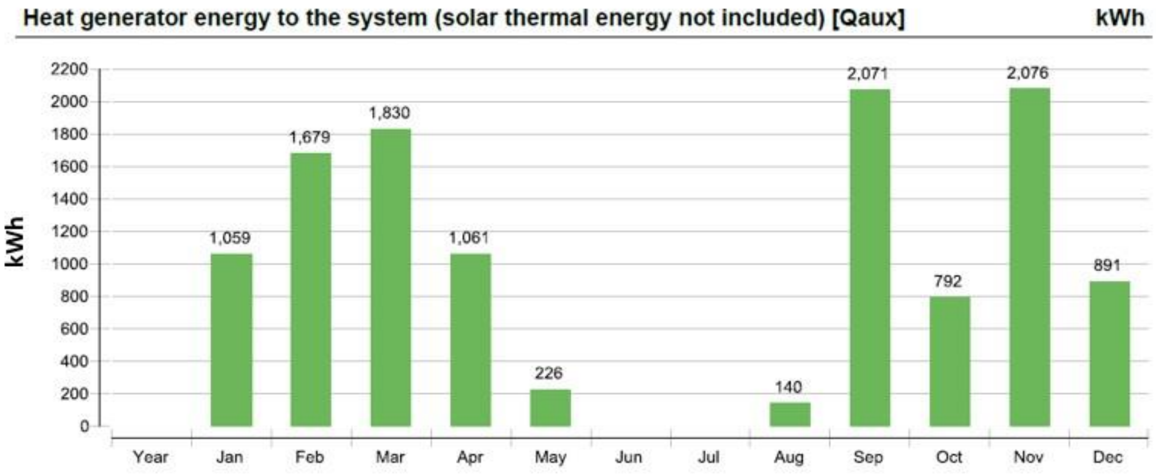


Figure 34, the PVT system records its lowest auxiliary electricity consumption at 140 kWh in May. Contrarily, the highest occurs in November, reaching 2,076 kWh. In comparison, the SWH system shows the lowest auxiliary electricity use in August at 150 kWh, and the highest in November, with a peak of 2,915 kWh, as illustrated in Figure 35. During warmer months, both systems require less auxiliary heating because higher ambient temperatures elevate inlet water temperatures, reducing the heating load and decreasing energy consumption by the electric elements. Overall, the energy supplied by the electric heaters closely follows an inverse trend to the solar fraction: when solar contribution is high, reliance on electric backup is low, and vice versa. This pattern highlights the importance of optimising solar system design and sizing to minimise dependency on auxiliary heating and reduce electricity use.

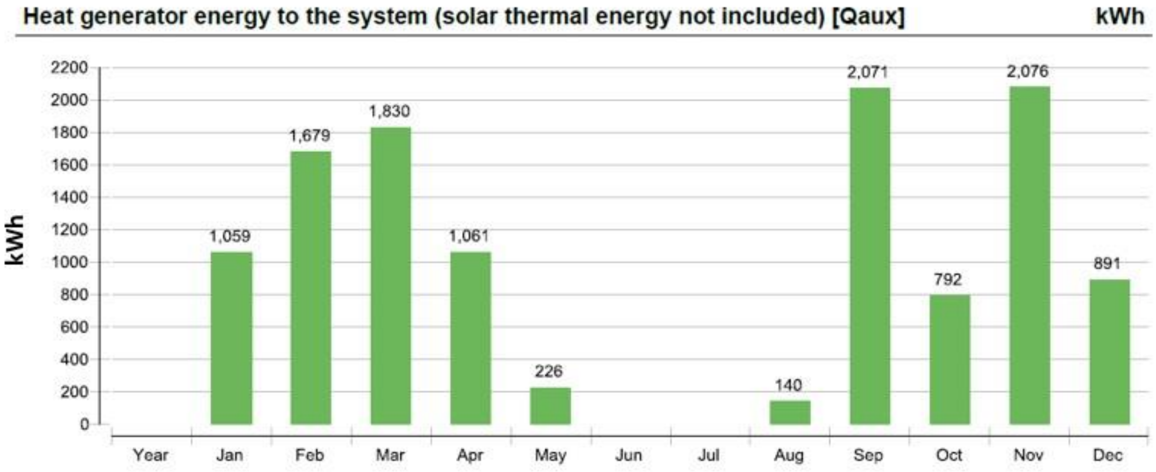


Figure 34: Auxiliary electric energy consumption in the PVT system

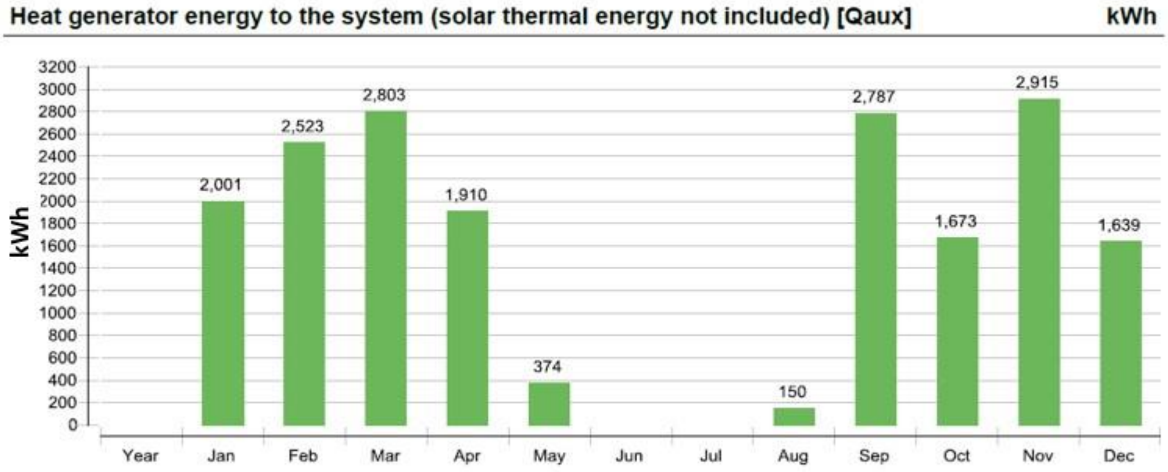


Figure 35: Auxiliary electric energy consumption in the SWH system

4.2.4 PV Electricity Yield of the PVT System

Besides thermal energy generation, the PVT system also produces electricity through its integrated PV modules. Over the course of the year, the system yields 23,773 kWh (1,787 kWh/kWp) of electricity, which can be utilised to supplement the building's electrical demand, thereby reducing dependency on grid-supplied electricity.

The PV electricity yield follows a seasonal pattern similar to that of the thermal output. The highest generation is observed between September and November, coinciding with the periods of high solar irradiance. October's recorded peak output is 2,253 kWh. In contrast, the lowest yield occurs in June at 1,419 kWh, as indicated in Figure 36. These variations are primarily driven by changes in solar radiation levels and ambient conditions. Both actors directly influence PV efficiency. Efficiency is higher during the spring months (September to November) when irradiance is ample and temperatures are moderate. Under these conditions, PVT systems achieve optimal PV performance.

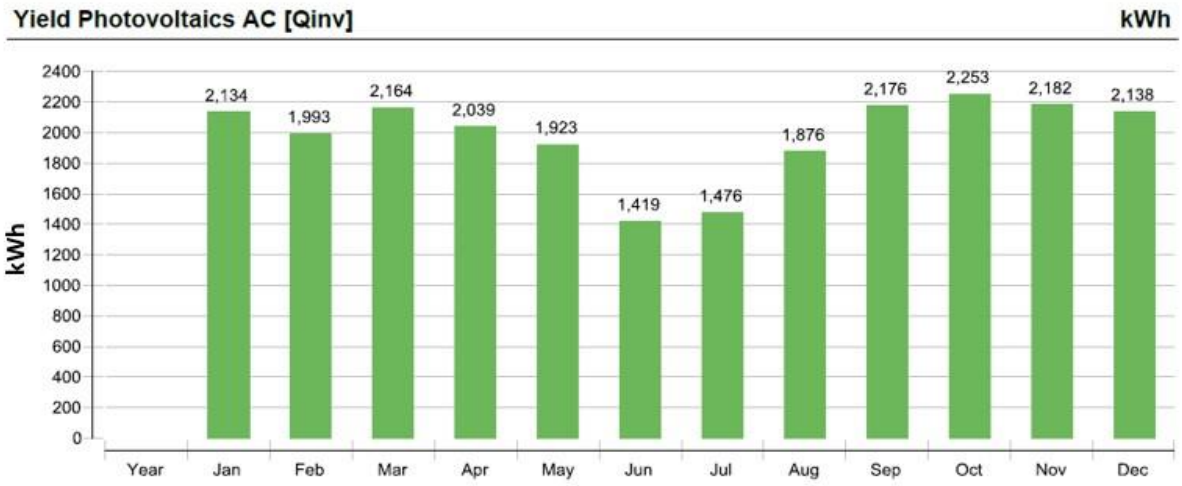


Figure 36: Monthly PV yield of the PVT system

Self-consumption, defined as the portion of PV electricity directly utilised by the system's loads, closely follows the trend of PV generation throughout most of the year, as illustrated in Figure 37. The total annual self-consumption amounts to 20,818 kWh. During the winter break in June and July, self-consumption drops to zero despite continued PV production, as the system's loads are inactive due to campus closure. In all other months, the system achieves 100% self-consumption, meaning that all the PV electricity generated is immediately utilised on-site.

Compared to a conventional SWH system, the PVT system offers the added advantage of electricity generation. While both systems are primarily designed to meet hot water demand, the PVT system's ability to also produce electricity provides additional energy savings. This dual functionality enhances overall system value by partially offsetting the building's electricity demand and reduces grid electricity consumption. In this scenario, where the PVT system is sized and modelled primarily for domestic hot water provision, the electrical output serves as a valuable co-benefit, contributing further to energy efficiency and cost savings.

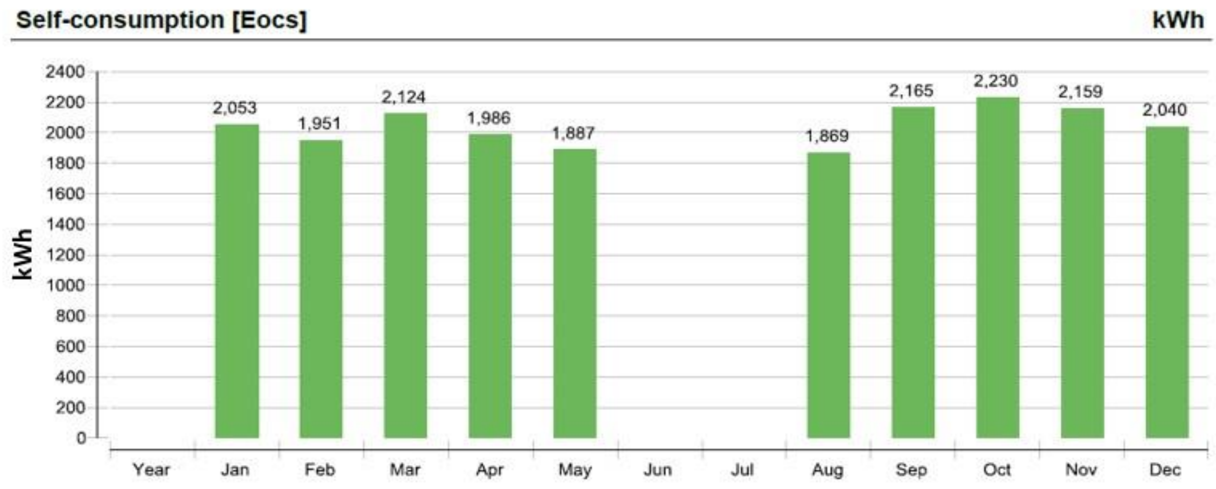


Figure 37:Monthly self-consumption of generated electricity

4.2.5 Energy Savings

Energy savings refer to the reduction in grid electricity consumption achieved through the integration of solar technologies. In this study, the PVT system yields annual energy savings of approximately 72,615 kWh, significantly higher than the 43,979 kWh achieved by the standalone SWH system. These savings are directly linked to the total energy output of each system. Unlike the SWH system, which only provides thermal energy, the PVT system delivers both thermal and electrical outputs, leading to greater overall energy savings. Further, the extent of energy savings varies by geographical location and seasonal weather patterns. The regions with high solar resource potential and months with elevated solar irradiance tend to yield higher energy savings, while overcast or winter months result in reduced performance. The superior thermal output of the PVT system, combined with its contribution to electricity generation, underscores its enhanced potential for energy savings compared to conventional solar thermal technologies.

4.2.6 System Performance

System performance serves as a key indicator of how effectively a solar system converts input energy into useful thermal and electrical output. For the PVT system, the annual system performance factor is calculated at 4.5, meaning that the system delivers 4.5 units of useful energy (thermal and electrical) for every unit of auxiliary energy consumed by electric heaters and parasitic loads, such as pumps and controllers. This high value reflects the strong operational efficiency of the PVT system, driven by its dual-function capability and lower reliance on auxiliary heating.

In comparison, the SWHS demonstrates a significantly lower system performance of 3, indicating it produces only 3 units of useful thermal energy for every unit of auxiliary energy input. The reduced performance is largely because of greater dependence on electric heating elements, particularly during the periods of high hot water demand. Unlike the PVT system, the SWHS lacks photovoltaic components, thereby forfeiting the additional energy generation and efficiency gains provided by PV electricity production and heat recovery.

Monthly trends show that system performance fluctuates with seasonal variations in thermal load and auxiliary energy usage. Performance is typically highest in months, such as May and August, when auxiliary heating demand is lowest. This is due to reduced campus occupancy during holidays, so most of the hot water demand is met by solar energy, as shown in Figure 38. Conversely, performance declines during high-demand months such as September, when the increased use of electric heaters to maintain hot water setpoint temperatures reduces overall system efficiency. These findings highlight the comparative advantage of PVT systems in optimising energy use and minimising auxiliary energy consumption. The PVT system also contributes to greater overall sustainability and cost-effectiveness.

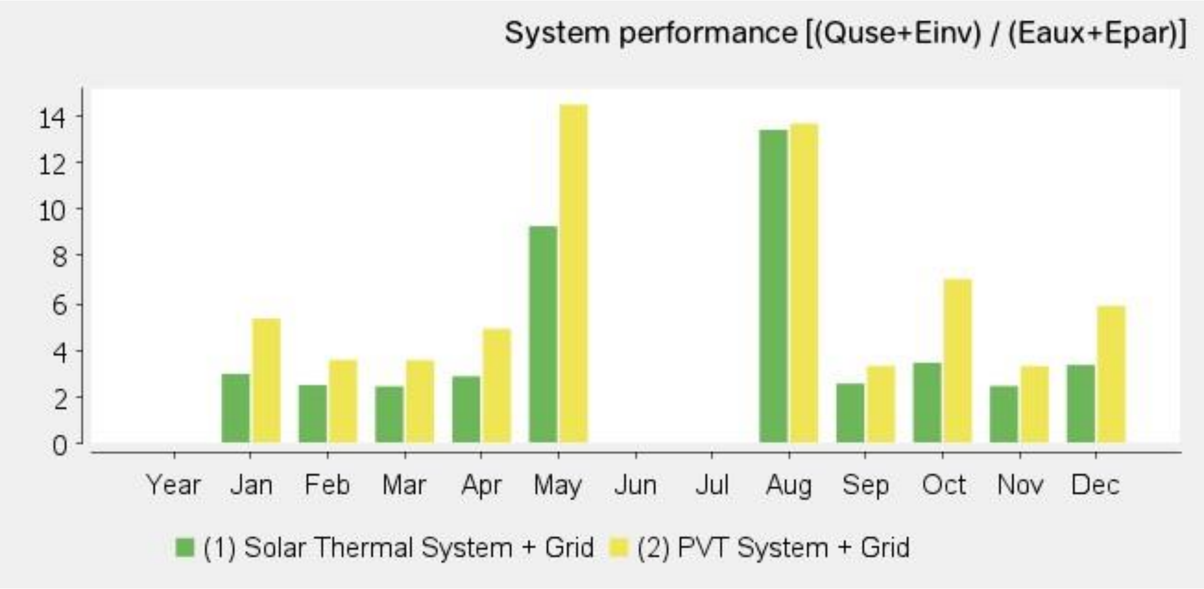


Figure 38: Annual system performance of the PVT and SWH systems

4.2.7 System Efficiency

System efficiency refers to the proportion of incident solar energy on a collector surface that is effectively converted into useful output, either thermal, electrical or both. In this study, the SWHS is designed with a collector area of 50 m², receiving a total solar irradiance of 110,647 kWh. The PVT system, with a larger collector area of 74.5 m², receives 175,665 kWh of solar energy.

The SWHS achieves a thermal energy output of 41,780 kWh, which corresponds to a system efficiency of approximately 37.8%. In comparison, the PVT system yields a thermal output of 46,398 kWh and an electrical output of 23,773 kWh. The combined useful energy output results in an overall system efficiency of approximately 40%. Within the PVT system, the thermal efficiency is calculated at 26.4%, while the electrical efficiency of the PV modules is 13.5%.

These results are consistent with some findings in the literature. Tripanagnostopoulos et al. conducted an experimental study on hybrid PVT systems in Greece and have reported electrical efficiencies ranging between 11% and 17%, while Aste et al. found thermal efficiencies between 22% and 29% and electrical efficiencies ranging from 6% to 14% in a theoretical performance comparison of PVT water collectors [54], [110]. Their study reported an overall efficiency of 42.3% for a covered PVT collector, which closely aligns with the simulated results of this study.

The higher overall efficiency of the PVT system can be attributed to its dual energy generation capability. Unlike the SWHS, which only provides thermal energy, the PVT system harnesses both electrical and thermal energy from the same surface area [97]. Additionally, the thermal component of the PVT system serves to cool the PV cells, maintaining their operating temperature within an optimal range. This cooling effect reduces electrical losses caused by overheating and improves electrical performance while also capturing low-grade thermal energy.

According to manufacturer specifications, flat-plate solar thermal collectors typically have thermal efficiencies of up to 75%, while PVT collectors may exhibit thermal efficiencies around 70% and electrical efficiencies as high as 17%. These potentially lead to a combined theoretical efficiency of up to 87%, as shown in Figure 14. However, actual system efficiencies, especially after simulation and optimisation under real-world conditions, are lower because of the factors, such as available solar radiation, collector orientation, system design, and parasitic losses.

It is worth noting that the thermal efficiency of the PVT system is somewhat lower than that of the SWHS. This is primarily due to the trade-off inherent in the PVT systems, where some thermal performance is sacrificed in favour of electrical output. The thermal component of the PVT system is primarily designed to manage the temperature of the PV module rather than maximise thermal energy production. Nevertheless, the combined output of electricity and usable heat results in a higher overall system efficiency for the PVT system compared to a conventional standalone SWHS.

4.3 Environmental Impact Analysis

The integration of solar energy systems contributes significantly to the reduction of carbon dioxide (CO_2) emissions by displacing electricity that would otherwise be generated from fossil fuels, particularly coal-based power. In this study, the SWH system achieves a maximum annual CO_2 emissions reduction of 23,590 kg. In contrast, the PVT system offers greater environmental benefits, with reductions of CO_2 emissions of approximately 26,199 kg from its thermal component and an additional 12,752 kg from its PV contribution.

Seasonal variations play a notable role in emissions reduction. Both systems exhibit their highest CO_2 savings between September and November, corresponding to the periods of increased solar irradiance and energy yield. The SWHS records its peak monthly emissions reduction in November at 2,667 kg, while the PVT system reaches its maximum in October at 2,983 kg as shown in Figure 41 and Figure 39, respectively. For August, the SWHS has the lowest reductions at 1,425 kg, with the PVT system’s thermal portion at 1,412 kg. The PVrelated CO_2 savings from the PVT system peak in October at 1,208 kg and drop to their minimum in June at 761 kg, as illustrated in Figure 40.

CO_2 emissions reductions are proportional to the energy output of the system and inversely related to the reliance on auxiliary electric heating. The months with higher grid electricity consumption, particularly through electric elements, tend to exhibit lower emissions reductions. However, this relationship is often outweighed by the system’s thermal and electrical generation, which drives higher CO_2 savings during the periods of strong solar resource availability. Overall, the combined thermal and electrical performance of the PVT system results in superior environmental benefits compared to the conventional SWHS.

Figure 39: Monthly CO_2 emission reductions achieved by the thermal component of the PVT system

Figure 40: Monthly CO_2 savings through the PV component of the PVT system

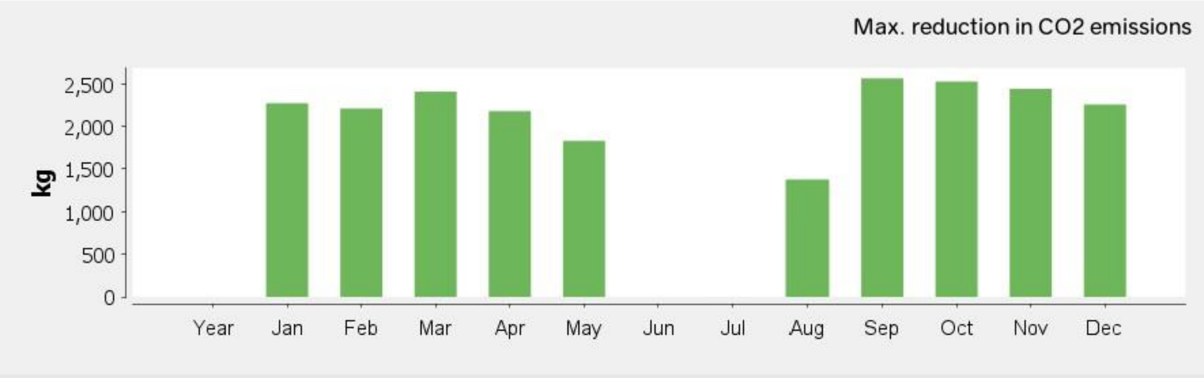


Figure 41: Monthly CO_2 emissions reduction achieved by the SWH system

4.4 Economic Analysis

For financial analysis, both the PVT and SWHS systems are assumed to be financed through a mixed structure comprising 60% equity and 40% debt. This financing model reflects the reality that full upfront funding through the university resources is often impractical because of the high capital requirements of renewable energy infrastructure. By leveraging debt, the investment becomes more financially accessible and appealing to potential investors, as a portion of the risk is transferred to the lender. Furthermore, this structure can enhance the return on equity for the investor by spreading financial exposure.

As indicated in Figure 42, the PVT system requires a higher initial capital investment of M1,425,000.00, which is financed through M855,000.00 in equity and M570,000.00 in debt. In contrast, the SWH system has a lower initial investment of M800,000.00, financed through M480,000.00 in equity and M320,000.00 in debt.

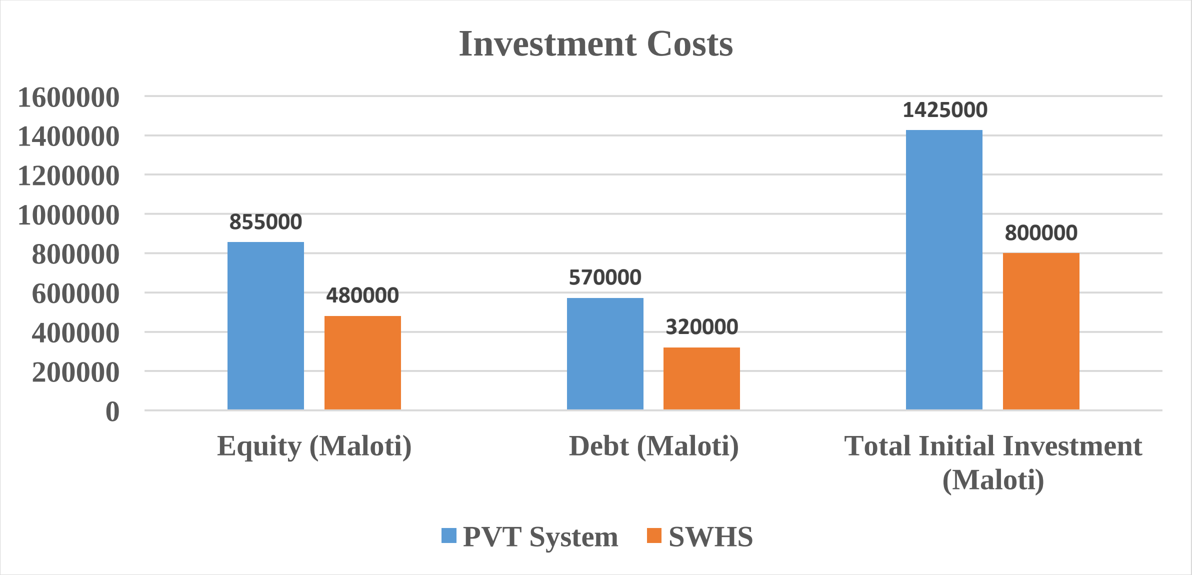


Figure 42: Investment costs of the PVT and SWH systems

The higher capital cost of the PVT system is primarily attributed to the advanced and integrated design of the PVT collectors. These are inherently more expensive than conventional flat-plate solar thermal collectors. The PVT collectors combine photovoltaic modules with thermal absorbers, resulting in a more complex and costly manufacturing process. Additionally, as an emerging technology, PVT systems have not yet benefited fully from the economies of scale. In contrast, flat-plate thermal collectors are widely produced by numerous manufacturers, which fosters competitive pricing and mass production, thereby reducing their unit cost.

Moreover, the larger collector area required for the PVT system further increases its total investment cost. The integration of electrical and thermal functions in a single collector leads to a higher cost per square meter compared to standalone flat-plate collectors. Consequently, despite the operational advantages of the PVT system, its initial capital cost remains significantly higher than that of a conventional SWHS.

Table 4: Economic analysis results of the PVT system and SWH systems

System	**PVT System**	**SWH System**
LCOE (M/kWh)	1.62	1.26
NPV (M)	1,546,935.60	971,128.60
ROI (%/year)	8.7	9.4
Payback Period (Years)	9	8
IRR (%)	17.7	18.9
Energy cost savings (M/annum)	170,129.68	103,038.40

The LCOE reflects the average cost of generating one kWh of usable energy over the system's lifetime and measures system profitability. The SWH system has a lower LCOE of M1.26/kWh compared to M1.62/kWh for the PVT system, as shown in Table 4. This difference is mainly due to the higher initial capital cost of the PVT system relative to its additional energy output. Although it is greater than that of the SWH system, it does not entirely offset the extra investment. Nonetheless, both the systems are economically viable since their respective LCOE values are below the current grid electricity tariff of M2.3429/kWh. The lower LCOE of the SWH system indicates that it provides energy at a reduced cost per unit, making it more costcompetitive.

The NPV measures the difference between the present value of all the future cash inflows and the initial capital investment. Since money available today is more valuable than the same amount received in the future due to the factors, like inflation, the time value of money, and opportunity costs, future cash flows are discounted to their present value. This makes NPV a reliable indicator of a system's long-term economic viability. Both systems have positive NPVs, and this confirms their financial feasibility. The PVT system achieves an NPV of M1,546,935.60, which is higher in absolute terms than the SWH system's NPV of M971,128.60, reflecting a difference of M575,807.00, as shown in Table 4. However, when these NPVs are considered relative to the initial investment, the SWH system performs better. Its NPV indicates an increase of M171,125.60 above its initial investment over 25 years, compared to the PVT system's increase of M121,935.60. This suggests that, despite the PVT system's higher absolute NPV, the SWH system offers a relatively greater return on its capital.

The payback period analysis shows that the SWH system has a shorter investment recovery time of 8 years compared to 9 years for the PVT system. This one-year difference is mainly due to the PVT system's higher initial capital expenditure, which takes longer to offset through energy cost savings. This indicates that the SWH system recovers its initial investment more quickly. However, the slight difference in payback periods is balanced by the superior longterm performance of the PVT system. Over its operational lifetime, the PVT system produces more total energy and achieves greater energy cost savings. This makes it economically attractive despite its slightly longer payback period.

In terms of annual ROI, the SWH system achieves a value of 9.4%, exceeding the PVT system ROI of 8.7%, as shown in Table 4. Both systems perform competitively, approaching the 10% average ROI benchmark for solar energy reported by Forbes [111]. Although the PVT system generates a higher absolute profit (M3,095,559.00) compared to the SWH system (M1,885,590.20), its relatively higher initial capital expenditure and longer payback period lead to a lower ROI. In contrast, the SWH system's lower upfront investment and shorter payback period enhance its overall profitability, demonstrating that the SWH system is more financially viable than the PVT system.

The IRR for both systems exceeds the assumed interest rate of 11.21%, confirming the financial attractiveness of both technologies. As shown in Table 4, the SWHS, with an IRR of 18.9%, appears more appealing from a long-term investment perspective than the PVT system, which has an IRR of 17.7%. Nevertheless, both IRRs indicate strong potential for financial return.

The PVT system results in annual energy cost savings of M170,129.68 in the initial year. It significantly exceeds the M103,038.40 saved by the SWH system, as detailed in Table 4. This difference is because of the PVT system's higher combined thermal and electrical energy output. The additional electricity generated increases both the cost savings and the system's role in reducing grid dependence, thus improving its long-term economic and operational benefits.

Overall, the economic indicators highlight the long-term potential of the PVT system for deployment in the NUL student residences. The SWH system demonstrates a lower LCOE, shorter payback period, and higher IRR and ROI values. Nonetheless, the PVT system's greater absolute NPV and significantly higher cumulative energy cost savings indicate that it will provide more substantial financial benefits over its lifetime. Although the SWH system appears more financially viable when considering initial investment costs, the dual energy generation capability of the PVT system offers a clear advantage, especially in settings with high grid reliance, such as educational institutions. Producing both thermal and electrical energy, the

PVT system reduces dependence on grid electricity and results in greater long-term cost savings, which can offset its higher upfront cost. Therefore, even though its returns are lower than those of the SWH system, the PVT system remains a sustainable and economically feasible option in the long run.

4.5 Comparison with Previous Studies

The performance analysis indicates that the PVT system demonstrates higher overall performance compared to the SWH system, largely due to its greater collector area. The PVT system achieved an annual thermal yield of 46,398 kWh, corresponding to 610.7 kWh/m². Energy generation, however, is highly dependent on the geographical location of the installation. For instance, when compared with the study by Bianchini et al. in Central Italy, which evaluated the PVT performance under different inlet cooling fluid temperatures, the system in this work achieved a higher thermal yield than the reported range of 6,176–10,246 kWh/year (267.01–442.97 kWh/m²) [95]. Similarly, the yield obtained here exceeds the values reported in three other European locations, which ranged between 218–535 kWh/m². However, it remains slightly lower than the maximum thermal yield of 637 kWh/m² reported in Athens by Lämmle et al., who conducted a systematic assessment of PVT systems using a novel characteristic temperature approach in residential buildings [75]. These results reinforce the suitability of PVT systems for domestic hot water applications, particularly in temperature ranges of 40–50 °C.

The electrical performance of the PVT system in this study is also noteworthy. Due to the cooling effect of the thermal subsystem, the PV modules achieved an electrical yield of 1,787 kWh/kWp (23,773 kWh/ year). This is significantly higher than the range of 76–159 kWh/kWp reported in a Nigerian feasibility study on the PVT systems for the residential buildings in SubSaharan Africa [112]. Similarly, Dupeyrat et al. have reported electrical yields between 91.15– 128 kWh/kWp for PVT collectors integrated into solar thermal systems in Paris, Lyon, and Nice, with the highest performance observed in Nice, where it reflected regional variations in solar irradiance [55]. In terms of overall system efficiency, the PVT system once again outperformed the SWH system. Abdul-Ganiyu et al. have reported a PVT overall efficiency of 42.5%, including a thermal efficiency of 34.69%, which is higher than the 26% thermal efficiency obtained in the present study [15]. However, the electrical efficiency reported by Abdul-Ganiyu et al. was lower than the 14% achieved in the current study.

Despite these technical advantages, the economic viability of the PVT system for the student residences remains constrained by its high initial investment cost. Although the LCOE of the PVT system in this study was relatively low at 0.092 $/kWh (1.62 M/kWh), it remains less attractive than the SWH system if the upfront capital expenditure is considered. When compared to the literature, this value is substantially lower than the range of 0.2518–0.3838 $/kWh, as reported by Adun et al. in West Africa for simulated PVT systems designed for a typical four-person household [112]. It is also below the 0.33 $/kWh reported by Abdul-Ganiyu et al. in Ghana, who assessed the techno-economic performance of a hybrid water-based monocrystalline silicon PVT module against a conventional PV module [15]. Moreover, the LCOE obtained in this study aligns closely with the 0.082–0.092 $/kWh range reported by Bianchini et al., who analysed the performance and economics of the PVT systems under varying inlet cooling fluid temperatures [95]. These findings underscore the potential of the PVT systems for deployment in educational institutions, particularly within the environmental context of Lesotho.

5. Conclusions and Recommendations

5.1 Overview

This chapter presents the conclusions drawn from the results and aligns them with the study's objectives and research questions. It also provides recommendations aimed at enhancing the adoption of PVT systems and outlines the limitations encountered during the research. The potential areas for future work are also highlighted, which offer insights that can guide subsequent studies seeking to optimise the performance and integration of PVT systems in similar contexts.

5.2 Conclusions

University buildings are amongst the highest energy consumers in the institutional sector, highlighting the increasing need to adopt sustainable energy solutions like solar technologies to meet rising energy demands and enhance institutional sustainability. Photovoltaic-thermal (PVT) systems present a promising renewable energy option that can be implemented in educational environments to decrease electricity use, improve energy efficiency, and reduce operational costs. This study examined the potential of a PVT system at the National University of Lesotho (NUL), using the Gilbo student residence as a case study. A comparative analysis was performed between a 75 m² PVT system and a 50 m² solar water heating (SWH) system, with both systems simulated and optimised using POLYSUN software to satisfy the building's hot water needs. The evaluation focused on technical performance, economic feasibility and environmental advantages.

The technical performance analysis revealed that the PVT system achieved a higher solar fraction of 88%, compared to 76% for the SWH system. Thermal energy output was also higher for the PVT system (46,398 kWh) relative to the SWH system (41,780 kWh. However, the SWH system exhibited higher auxiliary electricity consumption (18,773 kWh versus 11,825 kWh). Notably, the PVT system produced 23,773 kWh of electricity annually, of which 20,818 kWh was directly self-consumed on-site. The PVT system achieves significantly higher maximum annual energy savings of 72,615 kWh, compared to 43,979 kWh for the SWH system. The system performance factor was also greater for the PVT system at 4.5, compared to 3.0 for the SWH system. In terms of efficiency, the PVT system achieved an overall efficiency of 40%, comprising 26.7% thermal and 14% electrical efficiency. Conversely, the SWH system attained a thermal efficiency of 37.8%. Additionally, the PVT system maintained higher average daily outlet temperatures (70°C compared to 60°C for the SWH system). These findings are consistent with the existing literature and they underscore the benefits of cogeneration. The superior technical performance of the PVT system is attributed to the larger collector area and the synergistic relationship between the PV and thermal components.

The environmental analysis revealed that the SWH system achieved a maximum annual CO_2 emissions reduction of 23,590 kg, while the PVT system achieved a combined reduction of 38,951 kg, comprising 26,199 kg from the thermal component and 12,752 kg from the PV component. These reductions were most pronounced during the periods of high solar radiation and energy output.

The economic analysis assumed a financing structure of 60% equity and 40% debt for both systems. The PVT system required a higher capital investment of M1,425,000.00 (M855,000.00 equity and M570,000.00 debt), compared to M800,000.00 for the SWH system (M480,000.00 equity and M320,000.00 debt). The increased investment cost for the PVT system is mainly due to the larger collector area and the integration of dual-generation functionality. Despite the higher upfront costs, the PVT system demonstrated better long-term financial performance. It achieved a higher levelized cost of energy of M1.62/kWh, compared to M1.26/kWh for the SWH system. Both systems showed financial viability with positive net present values, but the PVT system produced a higher NPV of M1,546,935.60 compared to M971,128.60 for the SWH system. Additionally, the SWH system yielded a greater annual return on investment of 9.4%, compared to 8.7% for the PVT system.

Although the SWH system had a shorter payback period (8 years versus 9 years) and a higher internal rate of return of 18.9% (compared to 17.7% for the PVT system), the PVT system offered greater annual cost savings, M170,129.68 versus M103,038.40. These results indicate that, while the SWH system may be more attractive for long-term returns, the PVT system provides more significant long-term energy cost savings, especially in environments like student residences, where rooftop space is available and energy demand remains relatively steady. In conclusion, PVT systems are a technically feasible, economically viable and environmentally beneficial solution for enhancing energy performance in educational institutions.

5.3 Limitations of the Study

This study is subject to several limitations. First, there is a lack of year-round data on electric geyser consumption to inform the design and modelling of the proposed systems. Consequently, hot water consumption assumptions were necessary, which may affect the accuracy of the results. In addition, the use of POLYSUN software presented challenges, particularly because of its reliance on static consumption profiles that represent daily averages rather than detailed hourly patterns. The available profiles are predominantly derived from developed countries, with limited data for developing countries, including those in Africa. This lack of context-specific consumption data poses a further constraint on model accuracy. Another limitation is the restricted availability of PVT collectors compared to solar thermal collectors, thus narrowing the options for system modelling and optimisation.

Further, the economic analysis is sensitive to fluctuations in key parameters such as interest rates, electricity tariffs, and inflation. An increase in interest rates tends to reduce the NPV and increase both the payback period and the LCOE. In contrast, higher inflation rates increase the NPV, payback period, and IRR. Changes in electricity tariffs have a relatively smaller effect but can still lead to reductions in IRR, NPV, and absolute profit. This implies that the economic feasibility outcomes are not entirely robust and can change significantly if real-world conditions shift.

Final, the absence of experimental validation represents an important limitation. The findings of this research are entirely based on theoretical simulations, and no empirical testing was undertaken to account for potential modelling errors or to verify the simulation outputs.

5.4 Recommendations

To strengthen the case for PVT adoption in educational institutions, future research should prioritise experimental installations of PVT systems across campuses. Real-time performance monitoring of these installations would serve to validate the theoretical modelling results presented in this study and provide critical insights into system behaviour under actual operating conditions. While the current analysis focused on the student residences, it is recommended that subsequent investigations extend to other campus facilities, such as lecture halls, libraries, and administrative offices, which also present significant and diverse energy consumption profiles. Again, side-by-side installations of standalone PV and SWH systems versus a PVT system should be considered in future studies. Such comparative analysis under identical environmental and operational conditions would enable more accurate evaluation of each system’s thermal and electrical efficiency, energy output and economic feasibility, especially in institutions with sufficient rooftop space.

Besides their functional role in enhancing energy performance, the PVT systems offer substantial educational value. Their integration into engineering and environmental science curricula would provide the students with hands-on learning opportunities, fostering awareness and technical understanding of renewable energy technologies. Final, to encourage wider adoption of PVT systems, supportive policy interventions are essential. Governments and relevant educational stakeholders should consider implementing targeted measures, such as subsidies, tax incentives and low-interest financing schemes to reduce upfront costs and mitigate investment risks. These incentives would not only accelerate the deployment of PVT technologies in the education sector but also contribute to broader national and institutional sustainability goals.

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