A COMPARATIVE PERFORMANCE ANALYSIS OF SELECTED REFRIGERANTS TOWARDS SUSTAINABLE COOLING

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A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN ADVANCED MANUFACTURING SYSTEMS ENGINEERING OF KYAMBOGO UNIVERSITY

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DECLARATION

I, Orit Anthony, candidate for the Master of Science in Advanced Manufacturing Systems Engineering Degree of Kyambogo University, declare that this research dissertation is my original work and has never been presented for a degree in any other university and no part of this dissertation is plagiarized work.

Sign: .... Date: ....

APPROVAL

This Master of Science Dissertation titled "A Comparative Performance Analysis of selected Refrigerants Towards Sustainable Cooling", prepared and submitted by Orit Anthony in partial fulfilment of the requirements for the Master of Science in Advanced Manufacturing Systems Engineering Degree of Kyambogo University, has been supervised and is ready for examination.

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DEDICATION

To my parents, the late Mr. Onyinge and Ms. Anyango, my wife Mrs. Orit, and our children Sasha, Rapha and Jireh in appreciation of their moral and financial support that has enabled me to attain this academic achievement.

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LIST OF ACRONYMS

AC	Air Conditioner
ASHRAE	American Society for Heating, Refrigeration and Air Conditioning Engineers
BTU	British Thermal Units
COP	Coefficient of Performance
CI	Confidence Interval
EER	Energy Efficiency Ratio
ELISA	Environmental Lifecycle Impacts of Solar Air-conditioning Systems
EPD	Environmental Product Declaration
GHG	Green House Gases
GWP	Global Warming Potential
HCs	Hydrocarbons
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
HRS	Hours
HVAC	Heating, Ventilation and Air Conditioning
IPCC AR6	Intergovernmental Panel on Climate Change's Sixth Assessment Report
LCC	Life Cycle Cost
NEMA	National Environmental Management Authority
ODP	Ozone Depleting Potential
RAC	Refrigeration and Air Conditioning
RMS	Root Mean Square
SEER	Seasonal Energy Efficiency Ratio

TEWI	Total Equivalent Warming Impact
UNARA	Uganda National Association of Refrigeration and Air Conditioning
U4E	United for Efficiency

DEFINITION OF TERMS

R290	Propane
R410A	It is a blend, with R-32 and R-125 each comprising 50% of the mixture with the chemical names Difluoromethane (R-32) and Pentafluoroethane (R-125).
Temperature glide	Refers to the range of temperatures a refrigerant undergoes during a phase change (boiling or condensation) at a constant pressure.

ABSTRACT

The increasing demand for air conditioning to maintain room comfort, product quality, safety, and process efficiency especially in pharmaceutical industries worldwide and in developing countries like Uganda combined with the associated high electricity costs is contributing to global warming. Studies focusing on energy efficiency ratios in East Africa have provided limited information on seasonal energy efficiency of air conditioners using different refrigerants. Additionally, there is little information on a comprehensive assessment integrating energy consumption, environmental impact, and economic factors to support stakeholders in decision-making. This study investigated the comparative performance of air conditioner systems using R-290 and R-410A refrigerants by tracking the set room temperature, energy consumption, environmental impact, and operational life cycle costs over a 6-day experimental period. It was observed that the R-290 and R-410A air conditioner systems were both capable of closely tracking the set room temperature, with R-410A air conditioner system achieving closer adherence to the set room temperatures. Additionally, their energy consumption showed that R-290 air conditioner system consumed 4% less energy in descending set room temperature pattern (from 26℃ to 24℃ to 22℃), whereas R-410A system consumed 11% less energy in ascending set room temperature pattern (from 22°C to 24°C to 26°C). Generally, the R-410A air conditioner system consumed 2% less energy compared to the R-290 air conditioner system. In terms of environmental impact, the R-290 air conditioning system exhibited a significantly lower Total Equivalent Warming Impact (TEWI), with a difference of 142% compared to R-410A air conditioner system. However, R-410A air conditioner system demonstrated marginally lower total life cycle costs with a difference of 0.36% compared to the R-290 air conditioner system. Furthermore, the comparative analysis suggests that R-290 air conditioner system is more advantageous in terms of environmental sustainability and long-term viability, when considering commitment to the Montreal Protocol and the Kigali Amendment, which necessitate a reduction in the use of hydrofluorocarbons (R-410A) refrigerants. Six days of the experiment showed no significant difference in daily energy consumption between R-290 and R-410A air conditioner systems, presented no statistical difference in energy performance. Longer-term studies are recommended to assess performance across seasons and locations, while environmental impact, safety, and lifecycle costs remain important considerations.

Keywords: Natural Refrigerants, Hydrocarbons (HC), Hydrofluorocarbons (HFC) Climate Change, Energy Efficiency, Direct Emissions, Indirect Emissions, Air Conditioning

CHAPTER ONE

INTRODUCTION

1.0 Introduction

This chapter introduces the study through a presentation of the status of air conditioning globally and in Uganda, the environmental implications of air conditioners and their refrigerants, problems related to sustainable cooling in Uganda and the purpose of this study. The justification of the study, research questions to guide this study, and a conceptual framework for this study are also explained.

1.1 Background

The phenomenon of global warming, characterized by the steady rise in the earth's average surface temperature due to greenhouse gas emissions, has precipitated a marked increase in the demand for cooling systems worldwide, with a remarkable trend in developing countries, where rapid urbanization and economic growth compound the effects of rising temperatures (Mastrucii, 2022). The direct correlation between global warming and the escalating need for air conditioning to maintain comfort and preserve food quality in hotter climates. Furthermore, the International Energy Agency (International Energy Agency, 2018) forecasts a significant surge in global energy demand for cooling, projecting that by 2050, the energy required for space cooling will double, posing substantial challenges for energy sustainability and environmental protection. With average temperatures rising, the demand for air conditioners has seen a notable increase globally (Sherman, 2022) and in Uganda, particularly in urban areas like Kampala. The findings of Jamil, et al. (2023) underscore the urgent need for efficient and sustainable cooling solutions in developing countries. The situation is exacerbated by the relatively high cost of electricity and the environmental implications of conventional air conditioning systems which have high energy consumption and rely heavily on refrigerants with high Global Warming Potential (GWP) (Ali & Akkas, 2023). Addressing the burgeoning demand for cooling in a sustainable manner requires a multifaceted approach, incorporating advancements in air conditioner technology, adoption of energy-efficient practices, and exploration of alternative cooling methods (Petrovic & Williams, 2023).

The surge in air conditioning systems, particularly in developing countries like Uganda can be attributed to escalating global temperatures and rapid urbanization, necessitating efficient and sustainable cooling solutions to mitigate environmental and economic impacts (International Energy Agency, 2018). Electrical energy consumption in space cooling is growing faster than any other energy dependent service in buildings (International Energy Agency, 2018) resulting in increasing indirect emissions. The energy demand for buildings cooling accounts for 20% of the total electric energy consumption worldwide and is expected to reach up to 40% in 2050 (International Energy Agency, 2018). Another reason is that global temperatures are rising, with an increase of 1.5°C or more over pre-industrial levels expected by 2035 (IPCC, 2018). Both reasons are likely to cause an increase in the demand for cooling appliances, especially with rising standards of living in developing countries. The increasing global temperatures and rapid urbanization in developing countries have been accompanied by a growing need for air conditioning systems, creating enormous environmental and economic problems (IPCC, 2021). While high outdoor ambient temperatures and economic growth in Uganda have made the country an attractive market for effective cooling solutions (National Planning Authority, 2020) . Yet, due to their operation and refrigeration use, air conditioning systems are responsible for a large share of total energy consumption by buildings negatively impacting the environment (Davis & Gertler, 2015).

Given the fact that further development of energy-efficient and environmentally friendly cooling technologies is a high priority around the world (Jamil, et al., 2023). There is a multifaceted relationship between air conditioning systems energy consumption, their environmental implications, and the pursuit of sustainable cooling solutions. Some studies have been directed to establishment of the energy efficiency of various air conditioning models, their operational emissions, and the implementation of life-cycle cost analysis (LCC) to enable a sustainable approach in selecting cooling technologies (Hellweg et al., 2023). Furthermore, there are regulatory frameworks governing air conditioner efficiency, refrigerant usage (Petrovic & Williams, 2023) and viable sustainable cooling alternatives are explored (Ali & Akkas, 2023; Jamil et al., 2023; McQuiston et al., 2023).

This study aims to fill the identified gap by conducting an analysis of the performance of selected refrigerants in the common air conditioner models available globally and in the Ugandan market, focusing on energy efficiency, environmental impacts and life cycle costs with an emphasis on the Ugandan context seasonal energy efficiency. By evaluating the energy consumption patterns, associated operational costs, and environmental footprints of two different refrigerants in the various air conditioner models, this research seeks to carry out a comprehensive assessment that considers energy consumption, environmental impact, and cost implications (Bordbar et al., 2023). This assessment serves as a vital tool for consumers, policymakers, and manufacturers, aiding in the selection of sustainable air conditioning systems.

1.2 Problem Statement

Uganda, which is a developing country has an increasing demand on room cooling and according to the third national development plan (National Planning Authority, 2020) the electricity cost remains higher than the national target of 178 Uganda shillings per unit within the country. The critical role of air conditioners in modern living standards (McQuiston et al., 2023) and their potential environmental impact is underscored (Hellweg et al., 2023). Existing studies predominantly concentrate on energy efficiency without adequately addressing the environmental implications of air conditioner usage. Furthermore, there's a lack of a holistic approach that integrates energy consumption, environmental impact, and economic factors to guide stakeholders in making informed decisions. This gap hinders the development of effective policies (Petrovic & Williams, 2023) and consumer choices toward sustainable cooling solutions in Uganda and similar contexts. Therefore, an analysis of the refrigerants used in air conditioners available in the Ugandan local market is necessary in order to estimate the energy, their environmental impact and to carry out a comparative life cycle assessment of the two air conditioner systems that can guide decision makers in selecting the best refrigerant in the air conditioner system to be recommended for use in Uganda's cooling sector.

1.3 Objectives

1.3.1 Main Objective

To conduct a comprehensive analysis of the performance of selected refrigerants in air conditioner models available globally and in the Ugandan local market.

1.3.2 Specific Objectives

The specific objectives of the study are:

(i) To determine the performance characteristics of selected air conditioner refrigerants used globally and in Uganda.

(ii) To examine the environmental impact of the selected refrigerants.

(iii) To carry out a comparative life cycle cost assessment of the two air conditioner systems under study.

1.4 Research Questions

(i) What are the performance characteristics of air conditioner refrigerants used globally and in Uganda, comparing hydrofluorocarbons and hydrocarbons.

(ii) What are the environmental impacts of the selected air conditioner refrigerants

(iii) What is the comparative variation of life cycle costs of the selected air conditioner refrigerants.

1.5 Conceptual Framework

The conceptual framework is presented in figure 1-1. The independent variables included energy efficiency of air conditioners, environmental impact, and operational life cycle costs. The moderating variables relate to policy and regulatory framework and market dynamics. The dependent variable includes sustainable cooling solutions.

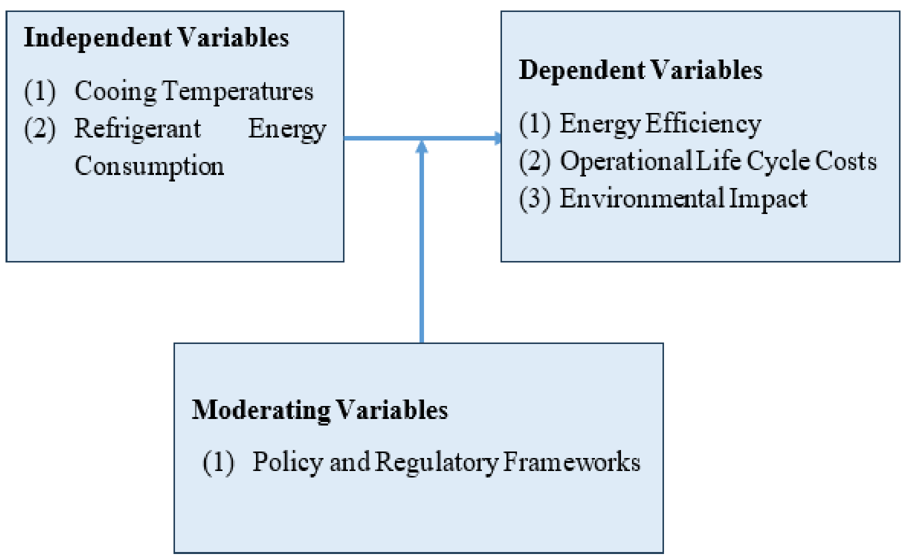

Figure 1.1: Conceptual Framework

1.6 Justification

There is a growing demand for cooling solutions globally and in Uganda, particularly for comfort in buildings, food, product quality, process efficiency especially in pharmaceutical industries and beverages, due to increased global temperatures and urbanization. With notable environmental and economic challenges, the possibility of high energy consumption, increased greenhouse gas emissions, and consumer energy cost burdens underpin the significance of an in-depth analysis of air conditioners with emphasis on energy efficiency and environmental impact (Kian Jon, 2021). Moreover, global sustainability goals and Uganda's national development plan aim to mitigate the adverse effects of climate change while ensuring energy security and environmental sustainability (Petrovic & Williams, 2023). The study specifically seeks to identify refrigerants with low energy consumption for sustainable cooling. A life cycle costs assessment that is developed through this study has the potential to inform stakeholders and decision makers on efficient and eco-friendly cooling. This study provides actionable insights for a sustainable advancement of the cooling sector, while emphasizing its significance in the current global and local environmental challenges. The study could inform policy towards sustainable cooling, thereby contributing to addressing the global challenge of responsible climate action.

1.7 Contribution of the Study

This study contributes to the body of knowledge on sustainable cooling solutions and aligns with Uganda's national development plans and global sustainability goals.

SDG 13 (Climate Action), which calls for urgent action to combat climate change and its impacts, including reducing greenhouse gas emissions and building resilience. Relatedly, the Global Cooling Pledge has specific targets to address cooling-related emissions; including a

68% reduction by 2050, increase access to sustainable cooling by 2030, and improve the average efficiency of new air conditioners by 50%. Sustainable cooling is also linked to other SDGs, such as those promoting health (SDG 3), sustainable cities (SDG 11), and economic growth (SDG 8).

The research provides actionable insights for a sustainable advancement of the cooling sector and emphasizes the significance of sustainable cooling in addressing the current global and local environmental challenges. While the body of research on air conditioning efficiency, environmental impact, and sustainable cooling solutions is extensive, several gaps remain that provide opportunities for further investigation and development. Identifying these gaps is crucial for advancing knowledge in the field and guiding future research efforts toward areas that can significantly contribute to the sustainability and efficiency of cooling technologies.

One notable gap is the lack of comprehensive studies focused on the unique climatic, economic, and infrastructural contexts of specific regions, particularly in developing countries like Uganda. While general trends and technologies have been well-explored in global literature, region-specific studies that consider local environmental conditions, energy sources, and consumer behaviour are scarce. Such research is essential for developing tailored solutions that address the specific challenges and opportunities in these areas. Although there are studies on the technological, economic, and environmental aspects of air conditioning, research that integrates these dimensions into a unified model is limited. The complexity of balancing energy efficiency, cost-effectiveness, and environmental sustainability calls for integrated approaches that consider the interdependences between these factors. A holistic assessment of air conditioner options based on a comprehensive set of criteria remains a critical need.

1.8 Scope

This research was conducted within the time frame of eight months, starting with a preliminary review to identify gaps in the refrigeration and air conditioning sector in Uganda. The study was conducted in Mukono, Uganda, with a focus on the most bought split air conditioners. In this study, an experiment was set-up to assess the room cooling temperatures of two refrigerants (R-290 and R-410A) in two different air conditioner models available globally and in the Ugandan market in order to identify the most energy efficient refrigerant with low environmental impact; and subsequently, a lifecycle costs assessment for sustainable cooling was done.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter gives a reflection on the air conditioner systems, refrigerants, performance parameters, environmental impact, air conditioner efficiency, sustainable cooling solutions, life cycle cost analysis approach and air conditioning environmental regulations.

2.1 Categorization of Air Conditioners

The air conditioners primarily provide building cooling, product quality, process efficiency especially in pharmaceutical industries and are also used in cold rooms to ensure food and beverages are kept at an appropriate temperature (World Health Organization., 2018). The air conditioners are categorized according to their cooling capacity, the refrigerant used, energy efficiency ratio, the inverter and non-inverter, and finally the lifespan of 15 years (Zhang et al., 2021).

2.1.1 Split Air Conditioners

Split air conditioners are a popular choice for cooling and heating individual rooms or areas within a building. They consist of two main components: an indoor unit and an outdoor unit, an example of the outdoor units are shown in figure 2.1. These units are connected by refrigerant pipes and electrical cables, allowing the system to transfer heat between the inside and outside of a building efficiently (Setyawan et al., 2022).

The indoor unit is typically mounted on a wall inside the room to be cooled or heated. It contains the evaporator coil, blower fan, and air filter. The evaporator coil absorbs heat from the indoor air, which is then blown back into the room by the fan, resulting in a cooling effect. Some advanced models come with features like adjustable louvers, remote controls, and air purifiers to enhance comfort and air quality.

The outdoor unit houses the compressor, condenser coil, and a fan. The compressor pumps the refrigerant through the system, which carries the absorbed heat from the indoor unit to the outdoor unit. The condenser coil releases the heat into the outside air, assisted by the fan, which blows air over the coil.

Split air conditioners have varying types, known for their energy efficiency, quiet operation, and ease of installation, as they do not require extensive ductwork like central air conditioning systems. They are available in various capacities, measured in British Thermal Units (Btu), to suit different room sizes and cooling/heating requirements (Bhandari & Fumo, 2022).

Overall, split air conditioners provide a versatile and efficient solution for maintaining comfortable indoor temperatures in both residential and commercial settings.

Split air conditioners are the most common type of split systems, consisting of one indoor unit and one outdoor unit. These systems are designed to cool or heat a single room or area, making them ideal for homes, small offices, or individual rooms within larger buildings. The indoor unit is mounted on the wall and contains the evaporator coil and fan, while the outdoor unit houses the compressor and condenser coil and it is usually installed outside of the building.

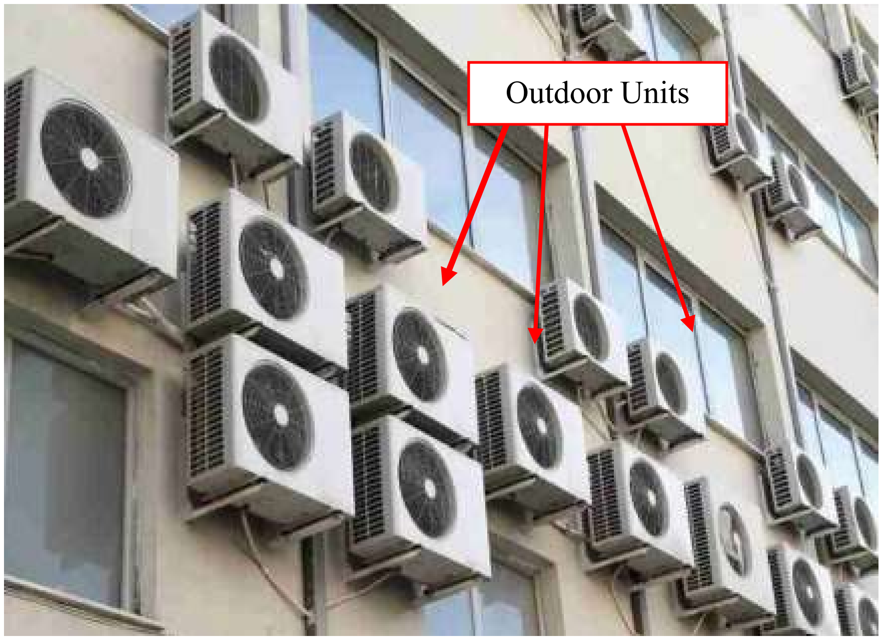

Figure 2.1: Outdoor units of split air conditioners installed for building cooling

2.1.2 Multi-Split Air Conditioners

Multi-split air conditioners are similar to single-split systems but can connect multiple indoor units to a single outdoor unit. This allows for the cooling or heating of multiple rooms or areas independently. Each indoor unit can be controlled separately, providing customized comfort for different spaces. Multi-split systems are ideal for larger homes, apartments, or commercial spaces where individual room control is desired. They offer space-saving benefits and reduce the need for multiple outdoor units (Tamseel et al., 2017).

2.1.3 Inverter Split Air Conditioners

Inverter split air conditioners utilize advanced inverter technology to regulate the compressor's speed, allowing for precise temperature control and energy efficiency. Unlike traditional air conditioners that operate at a fixed speed, inverter models can adjust their cooling or heating capacity based on the room's temperature. This leads to significant energy savings, reduced wear and tear on the compressor, and a more consistent indoor climate. Inverter split systems are available in both single and multi-split configurations (Elsayed, 2020).

2.1.4 Cassette Split Air Conditioners

Cassette split air conditioners are designed for ceiling installation, with the indoor unit mounted within the ceiling space. They are ideal for large open areas or rooms with limited wall space. The cassette unit distributes air evenly in four directions, providing uniform cooling or heating throughout the room (Deye Solar, 2024) . These systems are commonly used in commercial settings such as offices, retail stores, and restaurants. Cassette units are discreet, blending seamlessly with the ceiling, and offer efficient and quiet operation.

2.1.5 Floor Mounted Split Air Conditioners

Floor mounted split air conditioners feature an indoor unit that is installed at floor level, making them suitable for rooms with limited wall or ceiling space. These systems are an excellent choice for attics, basements, or spaces with sloped ceilings. The floor-mounted unit can be easily accessed for maintenance and cleaning (Zhang et al., 2022). They provide effective cooling or heating and can be a more aesthetically pleasing option for certain room layouts.

2.1.6 Ducted Split Air Conditioners

Ducted split air conditioners use a network of ducts to distribute conditioned air throughout multiple rooms or areas from a central indoor unit. The indoor unit is typically installed in the ceiling or under the floor, with ducts running to vents in each room (Fernández-Hernández et al., 2022). This type of system is ideal for whole-house or large commercial space cooling and heating. Ducted systems offer a seamless and unobtrusive solution, with only the vents visible in each room. They provide consistent temperature control and can be zoned to allow for individual room control.

2.1.7 Portable Split Air Conditioners

Portable split air conditioners offer the flexibility of a portable unit with the efficiency of a split system. These units consist of a portable indoor unit and a separate outdoor unit connected by a flexible hose. The indoor unit can be moved from room to room, providing cooling or heating where needed. Portable split systems are ideal for rental properties, temporary cooling needs, or spaces where permanent installation is not feasible. They offer ease of installation and the convenience of mobility (Ravindra, 2016).

2.2 Air Conditioner Refrigerants

Air conditioner refrigerants are substances used in cooling systems to absorb heat from the indoor environment and release it outside, thereby cooling the indoor space. Refrigerants play a crucial role in the functioning of air conditioners, and their selection and use have significant environmental implications (Sinche Chele et al., 2024). There are several categories of refrigerants based on their chemical composition and environmental impact.

2.2.1 Chlorofluorocarbons (CFC) Refrigerants

CFCs, such as R-12, were among the first refrigerants used extensively in air conditioning systems. However, they were found to have a high ozone depletion potential (ODP) and contribute significantly to global warming. Due to their harmful environmental impact, the production and use of CFCs have been largely phased out under the Montreal Protocol.

2.2.2 Hydrochlorofluorocarbons (HCFC) Refrigerants

HCFCs, like R-22, were introduced as transitional replacements for CFCs. They have a lower ODP compared to CFCs but still pose environmental risks. HCFCs are also being phased out gradually under international regulations, with deadlines for complete phase-out set in various countries.

2.2.3 Hydrofluorocarbons (HFC) Refrigerants

HFCs, such as R-134a and R-410A, are commonly used in modern air conditioning systems and refrigerators. They do not deplete the ozone layer, making them a better option than CFCs and HCFCs. However, HFCs have a high global warming potential (GWP) and contribute to climate change. Efforts are underway to reduce the use of HFCs through regulations like the Kigali Amendment to the Montreal Protocol.

2.2.4 Hydrofluoroolefins (HFO) Refrigerants

HFOs, such as R-1234yf, are newer refrigerants designed to have low GWP while being non-ozone-depleting. They are seen as environmentally friendly alternatives to HFCs and are increasingly being adopted in air conditioning systems. HFOs offer comparable performance to HFCs with significantly reduced environmental impact.

2.2.5 Natural Refrigerants

Natural refrigerants, including ammonia (R-717), carbon dioxide (R-744), and hydrocarbons like propane (R-290) and isobutane (R-600a), are gaining popularity due to their low environmental impact. These refrigerants have very low or zero GWP and ODP, making them sustainable choices for cooling applications (Varshney, 2024). Natural refrigerants are used in various systems, including commercial and industrial refrigeration. Among the natural refrigerants R-290 is widely used in modern room air conditioners and R-744 is mainly limited to heat pumps.

2.3 Performance Parameters of Air Conditioners

The parameters that define the performance of air conditioners include energy consumption, energy efficiency ratio (EER), environmental impact, and life-cycle costs.

2.3.1 Energy Consumption of Air Conditioning Systems

The operation of air conditioning systems accounts for a significant portion of global energy consumption, particularly in regions experiencing high temperatures and rapid urban development. Air conditioners are pivotal for ensuring indoor comfort in residential and commercial settings; they are also among the largest consumers of electricity in buildings. Porras et al. (2023) assesses the benefits of strengthening minimum energy performance standards (MEPS) for ACs, and reports on Seasonal Energy Efficiency Ratio (SEER) improvements and emission reductions. Energy Efficiency Ratio (EER) and SEER are key metrics used to evaluate the energy efficiency of air conditioning units. These ratios provide insights into how effectively an air conditioner converts electrical energy into cooling power, with higher values indicating more efficient units. The shift towards air conditioners with higher EER and SEER ratings is essential for reducing energy consumption and, by extension, operational costs for consumers (McQuiston et al., 2023).

Furthermore, advancements in technology, such as the introduction of inverter air conditioners, have been instrumental in enhancing energy efficiency. Inverter technology allows the compressor to operate at variable speeds, significantly reducing energy consumption compared to traditional fixed speed compressors (Hellweg et al., 2023). Despite these technological advancements, the widespread use of air conditioners with suboptimal efficiency continues to contribute to high energy demand, particularly in developing countries where newer, more efficient models are less accessible due to higher upfront costs. This issue is compounded by the lack of stringent regulatory frameworks for air conditioner efficiency in many of these regions, leading to a market flooded with less efficient units (Petrovic & Williams, 2023).

2.3.2 Energy Efficiency Ratio (EER)

The Energy Efficiency Ratio is a measurement of how efficient an air conditioning unit uses electrical energy to remove heat from an area. An EER rating is determined by dividing the cooling capacity that is measured in British Thermal Units per hour (Btu/h) by the power input, measured in watts (Hu & Shen, 2024). Therefore, if an air conditioner has an EER rating of 3.5, it implies that for every watt of electricity it consumes, it can remove 3.5 Btu of heat per hour from the indoor air. An EER is calculated at an outdoor temperature of 35°C and an indoor return air temperature of 27°C, with 50% relative humidity (International Organization for Standardization, 2017). A higher EER means that the air conditioner is more energy efficient, which may translate to savings on electric bills (Shah et al., 2021). From a practical perspective, the EER-rating enables customers to understand which air conditioning units are more energy-efficient and, therefore, cheaper to operate. Furthermore, it is possible to derive the maximum theoretical EER from the Coefficient of Performance (COP), which is a metric of the performance of both cooling and heating appliances. By applying the first law of thermodynamics, the maximum EER of a perfect air conditioner can be calculated. It is also important to note that in real-life EER ratings are significantly lower due to the inefficiencies attributed to the compression and expansion of gases in air conditioning systems. Another related metric is the Seasonal Energy Efficiency Ratio (SEER) is a measure of the energy efficiency of an air conditioner over a typical cooling season with consideration of the electric input during the same period (Martin, 2024) . This provides a more detailed view of an air conditioner's energy efficiency over a time period compared to the EER which is measured at a single operating point.

2.4 Environmental Impact of Air Conditioning

The use of air conditioning systems, while providing essential relief from heat, also brings significant environmental concerns that extend beyond their direct energy consumption (Agarwal et al., 2018). These concerns primarily revolve around the emissions generated during electricity production for air conditioner operation and the environmental impact of the refrigerants used in air conditioner systems. Indirect emissions resulting from the generation of electricity consumed by air conditioner units contribute to their overall environmental footprint. Given the reliance on fossil fuels for electricity production in many parts of the world, the operation of air conditioners plays a notable role in global greenhouse gas emissions, highlighting the urgent need for a transition towards renewable energy sources and more energy-efficient cooling technologies (Ali & Akkas, 2023). Therefore, the energy consumption of air conditioning systems presents a dual challenge in managing the rising demand for cooling in a warming world while minimizing the environmental impact of increased energy use. This challenge is addressed through use of energy-efficient air conditioner models, improving regulatory standards, and exploration of alternative, sustainable cooling solutions.

2.4.1 Greenhouse Gas Emissions from Electricity Generation

Air conditioning systems are substantial electricity consumers, especially in regions experiencing high temperatures. The electricity needed to power these systems often comes from fossil-fuel-based power plants, which are major sources of greenhouse gas (GHG) emissions. The International Energy Agency (International Energy Agency, 2018) highlights that as the demand for air conditioning soars, particularly in developing countries, the associated GHG emissions from power generation are projected to increase substantially. This elevation in emissions intensifies global warming, creating a feedback loop where higher temperatures lead to increased air conditioning demand, further increasing GHG emissions.

2.4.2 Impact of Refrigerants

Beyond energy consumption, air conditioners impact the environment through the refrigerants they use; refrigerants are substances employed in air conditioning systems to absorb and release heat, enabling cooling. The landscape of refrigerants used in split air conditioners is evolving, primarily driven by environmental concerns and regulatory changes aiming to reduce the global warming potential (GWP) of these substances. Many conventional refrigerants, such as hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), have high Global Warming Potentials (GWPs), making their emissions particularly detrimental to the climate. The leakage of these refrigerants during maintenance, operation, or at the end of an air conditioner's life cycle releases potent greenhouse gases into the atmosphere (Cowan et al., 2015). Ali & Akkas (2023) stress the significance of transitioning to refrigerants with lower GWPs to mitigate the environmental impact of air conditioning systems. Regulatory efforts and innovations in the air conditioning industry are focusing on replacing the high-GWP refrigerants with more environmentally friendly alternatives, such as hydrocarbons (R290) and HFOs (hydrofluoroolefins), which have significantly lower GWPs and reduced ozone-depleting potentials (Cabello & Azapagic, 2024) .

The transition from high Global Warming Potential (GWP) refrigerants like R-22 and R-410A to more environmentally friendly alternative refrigerants is driven by global regulations such as the American Innovation and Manufacturing (AIM) Act, (US Environmental Protection Agency (US EPA), 2025) which aims to reduce the use of hydrofluorocarbons (HFCs) due to their high impact on global warming. Some of the refrigerants considered viable for split air conditioners by the European safety standards, include R-1270, R-290, R-1234yf, and R-152a, all of which have GWPs below 150 (European Union, 2024). The assessment criteria for these alternatives include product safety, cost to the consumer, and environmental impact, considering the extended use of flammable refrigerants enabled by updated safety standards. Table 2.1 provides an overview of the various refrigerant properties, including their environmental impact grading.

Table 2.1: Environmental effect of different groups of refrigerants (Harby, 2017)

Refrigerant Group	Refrigerant Example	ODP	GWP	Atmospheric Lifetime (years)	Flammability
Chlorofluorocarbons (CFCs)	R11, R12, R115	0.6 - 1	4750 - 14,400	45 - 1700	Non-flammable
Hydrochlorofluorocarbons (HCFCs)	R22, R141b, R124	0.02-0.11	400-1800	1-20	Non-flammable
Hydrofluorocarbons (HFCs)	R404A, R32, R134a	0	140-11,700	1-300	Non-flammable
Hydrofluoroolefins (HFOs)	R1234yf, R123ze, R1234yz	0	<0-12	-	Flammable
Hydrocarbons (HCs)	R290, R600, R600a	0	≤ 3	Few days	Flammable

2.4.3 Lifecycle Emissions

A comprehensive environmental impact of an air conditioning system considers its entire life cycle, from production and operation to disposal. Hellweg et al. (2023) advocate for life-cycle assessments (LCAs) to evaluate the total environmental footprint of air conditioning systems, including direct and indirect emissions across all stages. Additionally, international agreements and national regulations play a crucial role in guiding the industry towards lower emissions. The Kigali Amendment to the Montreal Protocol, for example, sets forth a global plan to phase down the use of HFCs in air conditioners and other refrigeration equipment (Petrovic & Williams, 2023).

2.5 Air Conditioner Efficiency

The efficiency of air conditioning systems is a critical factor in reducing their energy consumption and environmental impact. Efforts to enhance air conditioner efficiency are driven by technological innovations and regulatory frameworks that establish minimum energy performance standards (MEPS) and promote the use of environmentally friendly refrigerants (de Melo, 2022) .

2.5.1 Energy Efficiency Metrics

The energy efficiency of air conditioners is commonly measured using the Energy Efficiency Ratio (EER) and the Seasonal Energy Efficiency Ratio (SEER). These metrics evaluate how effectively an air conditioner converts electrical power into cooling capacity, with higher values indicating greater efficiency. McQuiston et al. (2023) underlines the importance of these ratios in guiding consumers towards energy-efficient air conditioner models, which can significantly reduce electricity consumption and associated greenhouse gas emissions over the unit's operational lifespan.

2.5.2 Technological Advancements in Air Conditioners

Technological advancements play a pivotal role in improving air conditioner efficiency. Inverter technology, which allows the compressor to adjust its speed based on the cooling demand, has emerged as a key innovation in this regard. According to Hellweg et al. (2023), air conditioners equipped with inverter technology can achieve substantial energy savings compared to traditional fixed-speed units. Furthermore, the development of advanced heat exchanger designs and low-friction components contributes to reducing energy consumption and enhancing overall system efficiency.

2.6 Sustainable Cooling Solutions

The concept of sustainable cooling refers to solutions that meet growing cooling needs while minimizing energy demand, greenhouse-gas emissions, and environmental impacts. It integrates high-efficiency cooling technologies, climate-friendly refrigerants, passive design, and renewable energy to reduce both direct and indirect emissions. Beyond technology, sustainable cooling also includes policy frameworks, standards, and behavioural measures that support long-term resilience. The Kigali Amendment to the Montreal Protocol aims to phase down hydrofluorocarbons (HFCs), potentially avoiding up to *0.4°C* of global warming by 2100 (Velders et al, 2015). Complementary actions such as enforcing minimum energy performance standards (MEPS), promoting district cooling, and improving urban planning can significantly reduce cooling energy demand. Together, these approaches help countries meet development needs while advancing climate goals, improving energy access, and strengthening grid stability.

As the demand for cooling continues to grow, driven by rising global temperatures and increased urbanization, the exploration of sustainable cooling solutions has become paramount.

2.6.1 Alternative Cooling Technologies

In the quest for sustainability, several alternative cooling technologies have emerged. These include geothermal cooling, which utilizes the earth's stable underground temperature to cool buildings, and evaporative cooling, which uses water evaporation to reduce air temperature. Solar cooling systems, which harness solar energy to power cooling systems, represent another innovative approach, reducing reliance on fossil fuels and decreasing greenhouse gas emissions

(Alahmer & Ajib, 2020; Kamil & Mohmmed, 2022; Chiasson & Shahzad, 2022)

Each of these technologies offers distinct advantages in terms of energy efficiency and environmental impact, though their feasibility and cost-effectiveness can vary depending on geographic and climatic conditions.

2.6.2 Passive Cooling Strategies

Passive cooling strategies involve designing buildings in a way that naturally reduces heat gain and enhances thermal comfort without relying on mechanical cooling systems (Santamouris, 2017). These strategies include using reflective building materials, optimizing window placement and size for natural ventilation, and incorporating thermal mass that can absorb and release heat. Green roofs and shading devices also play a crucial role in reducing building temperatures naturally. Petrovic & Williams (2023) highlight the significance of integrating passive cooling strategies into building design to significantly reduce the need for conventional air conditioning, thereby lowering energy consumption and environmental impact.

2.6.3 Building Energy Efficiency

Improving the energy efficiency of buildings is critical in reducing the overall demand for cooling. This can be achieved through better insulation, sealing leaks, and using energy efficient windows that minimize heat gain. Implementing energy management systems and smart thermostats can further optimize cooling needs, ensuring that air conditioning is used efficiently and only when necessary (Prada, et al., 2020; Hellweg et al., 2023).

2.7 Life-Cycle Cost Analysis (LCC) for Air Conditioners

Life-Cycle Cost Analysis (LCC) is an essential method for evaluating the total cost of owning and operating air conditioning systems over their entire lifespan (Gobinath et al., 2024). This comprehensive approach considers not only the initial purchase and installation costs but also operating, maintenance, and eventual disposal costs, providing a holistic view of the economic implications of air conditioning choices. Consequently, the life cycle cost of air conditioners begins from the purchase cost and installation cost, the maintenance and disposal cost, and finally the country electricity price.

2.7.1 Components of LCC

The LCC for air conditioners encompasses several key components which include (Gobinath et al., 2024):

(i) Initial Purchase and Installation Costs: The upfront expenses associated with acquiring an air conditioner and installing it. These costs can vary significantly depending on the efficiency, capacity, and type of system chosen.

(ii) Operating Costs: The expenses incurred during the use of the air conditioner, primarily electricity consumption. High-efficiency units typically have lower operating costs, highlighting the importance of considering energy efficiency ratios (EER and SEER) when making purchasing decisions.

(iii) Maintenance and Repair Costs: Regular maintenance is necessary to ensure the optimal performance of air conditioning systems. Additionally, repair costs can accrue over the unit's life, affecting the overall cost-effectiveness of different models.

(iv) Disposal Costs: At the end of their service life, air conditioners must be properly disposed of or recycled, incurring certain costs. Environmental regulations, especially concerning the disposal of refrigerants, can influence these costs.

2.7.2 LCC and Sustainable Cooling Solutions

The LCC framework can significantly contribute to the adoption of sustainable cooling solutions by highlighting the economic and environmental advantages of energy-efficient and low-GWP air conditioners (California Energy Commission, 2024) . By accounting for the full range of costs associated with air conditioning, LCC analysis encourages a shift towards more sustainable practices and technologies in the cooling sector.

2.7.3 Importance of LCC in Decision Making

Incorporating LCC into the decision-making process allows consumers, businesses, and policymakers to make more informed choices regarding air conditioning systems. Bordbar et al. (2023) emphasize that a model integrating LCC with energy consumption and environmental impact considerations provides a more accurate assessment of the true cost and sustainability of cooling solutions. This approach supports the selection of air conditioners that, while potentially more expensive upfront, offer lower long-term costs and environmental benefits.

2.7.4 Challenges and Considerations in LCC Analysis

One of the challenges in applying LCC analysis is the variability in electricity prices, maintenance costs, and the lifespan of different air conditioner models. Additionally, accurately estimating the disposal costs and the environmental impact of refrigerant leakage requires comprehensive data and assumptions. Petrovic & Williams (2023) highlight the need for standardized methodologies in LCC analysis to ensure comparability and reliability of results.

2.8 Integrative Models for Air Conditioner Selection

The decision-making process for selecting air conditioners has evolved to consider not just the initial purchase price but also the broader implications of energy consumption, environmental impact, and overall life-cycle costs. Integrative models that combine these aspects offer a more comprehensive approach to evaluating air conditioning systems, guiding stakeholders toward choices that align with sustainability and efficiency goals.

2.8.1 Frameworks and Decision-Support Tools

Various frameworks and decision-support tools have been developed to facilitate the holistic assessment of air conditioners. These models typically integrate metrics such as Energy Efficiency Ratio (EER), Seasonal Energy Efficiency Ratio (SEER), Global Warming Potential (GWP) of refrigerants, and Life-Cycle Cost Analysis (LCC) to provide a multi-dimensional evaluation of cooling options. Litardo et al. (2023) discusses the application of such models in comparing the long-term economic and environmental benefits of different air conditioning units, emphasizing their potential to assist consumers, policymakers, and manufacturers in making informed decisions.

One practical application of integrative models is a consumer-focused decision-support system, such as an online tool or mobile app, that simplifies the comparison of air conditioners. For instance, the" EcoCooling" app could integrate data on EER, SEER, GWP, and LCC to rank air conditioners based on their overall sustainability and cost-effectiveness. By inputting their local electricity rates, room dimensions, and cooling needs, consumers could receive tailored recommendations for the most efficient and environmentally friendly air conditioners available in their region. On the policy level, an integrative model could be used to evaluate the potential impact of different regulatory scenarios on air conditioner efficiency and environmental outcomes. For example, the" Cool Policy Simulator" tool could model the effects of implementing stricter energy efficiency standards or incentives for low-GWP refrigerants on national energy consumption and GHG emissions. By incorporating data from market studies, environmental reports, and energy forecasts, this tool would help policymakers visualize the long-term environmental and economic benefits of various regulatory strategies, facilitating evidence-based policymaking in line with Hellweg et al. (2023) recommendations for using multi-criteria analysis in environmental decision-making.

Manufacturers could adopt integrative models to optimize the design of new air conditioners, balancing performance, cost, and environmental impact. The" GreenCool Design Suite" could use algorithms to simulate different component configurations, refrigerants, and efficiency technologies to identify the most sustainable and cost-effective designs. This approach would allow manufacturers to assess the life-cycle costs and emissions of proposed models before production, as discussed by Petrovic & Williams (2023).

2.8.2 Importance of Multi-Criteria Analysis of Air Conditioners

Multi-criteria analysis (MCA) is a key component of integrative models, allowing for the consideration of multiple factors and stakeholders' values in the selection process. This approach ensures that decisions reflect a balance between economic, environmental, and social priorities. Li et al. (2021) illustrate the use of MCA in evaluating air conditioner choices, highlighting how it can accommodate diverse criteria, including cost-effectiveness, energy efficiency, and the reduction of greenhouse gas emissions.

2.8.3 Challenges in Model Implementation for Air Conditioners

While integrative models offer a comprehensive framework for selecting air conditioners, their implementation faces several challenges (Khosla, et al., 2021). These include the availability and reliability of data, the complexity of modelling different impact categories, and the need for stakeholder engagement in the decision-making process. Furthermore, Petrovic & Williams (2023) note the difficulty in standardizing models across different geographic and climatic contexts, which can influence the performance and environmental impact of cooling solutions.

2.8.4 Life Cycle Assessment of Air Conditioning Systems

Advancements in data analytics and the increasing availability of life-cycle assessment data are expected to enhance the accuracy and usability of integrative models. Additionally, the incorporation of artificial intelligence and machine learning techniques can further refine these models, providing personalized recommendations based on specific user needs and environmental conditions. McQuiston et al. (2023) suggests that as these models become more sophisticated and user-friendly, they will play a crucial role in advancing sustainable cooling practices and informing policy development. To overcome challenges in model implementation, efforts must be made to standardize data collection and reporting methodologies, ensuring that the inputs to these models are accurate and comparable across different contexts. Collaboration between industry stakeholders, governmental bodies, and academic institutions can facilitate the development of comprehensive databases and modelling tools that reflect the latest advancements in air conditioner technology and environmental science. Furthermore, user education and engagement are crucial for increasing the adoption of these tools and integrating sustainable cooling solutions into mainstream practices.

2.9 Environmental Regulations on Air Conditioning

Various regulations and standards have a profound impact on the air conditioning market, pushing manufacturers to develop more efficient and environmentally friendly products (Polonara, 2017).

2.9.1 Global and Local Perspectives of Environmental Regulations

The Kigali Amendment to the Montreal Protocol, for instance, aims to phase down the use of high-GWP refrigerants in air conditioning systems (Petrovic & Williams, 2023). Similarly, national and regional regulations, such as those implemented by the European Union and the United States, set minimum energy performance standards that air conditioners must meet to be sold within their jurisdictions. These regulatory measures not only encourage innovation in the industry but also help reduce the environmental footprint of cooling technologies.

While international agreements and regulations provide a framework for progress, the implementation of energy efficiency standards and refrigerant management policies varies significantly across countries. Developing nations, in particular, face challenges in adopting and enforcing stringent standards due to economic and infrastructural constraints. In Uganda, the adoption of energy-efficient air conditioning systems is hindered by the high upfront costs of advanced models and a lack of consumer awareness about the long-term benefits of energy efficiency (Jamil et al., 2023). Efforts to enhance the energy efficiency of air conditioning systems and reduce their environmental impact must therefore be tailored to local contexts, involving a combination of regulatory measures, consumer education, and incentives to promote the adoption of efficient technologies.

2.9.2 The Role of Policy and Consumer Awareness

The transition to sustainable cooling requires supportive policies, including incentives for energy-efficient technologies and standards mandating passive cooling designs (Ford, 2022).Raising consumer awareness about sustainable cooling's environmental benefits and long-term cost savings is crucial (McQuiston et al., 2023). As a result, education can empower informed choices aligning with sustainability goals. Consumer behaviour in sustainable cooling informs policy and educational initiatives; hence the relevance for the air conditioning technologies to adapt to changing environmental conditions and energy landscapes. Collaboration among researchers, policymakers, and industry stakeholders can advance sustainable cooling solutions.

2.10 Summary of Reviewed Literature and Research Gaps

The reviewed literature highlights the evolution of air conditioners, refrigerants, energy efficiency metrics, and sustainable cooling strategies. However, there is a major gap in systematic comparative performance analysis of refrigerants, especially under conditions relevant to developing countries like Uganda. Integrating technical, environmental, and economic metrics into a unified assessment framework remains largely unexplored. Addressing these gaps is essential for guiding sustainable refrigerant transition pathways and informed policy formulation.

CHAPTER THREE

METHODOLOGY

3.0 Introduction

This chapter describes how the research addressed the objectives of the study. The specification of the tools used, the methods used to collect and analyse data regarding the life-cycle costs and emissions analysis of air conditioners in Uganda for sustainable cooling solutions.

3.1 Research Approach

The research employed an experimental research design in which six-day experiments were conducted on two split air conditioners using two types of refrigerants. The air conditioner performance when using different refrigerants was determine under various outdoor ambient temperatures in the tropical region of Uganda during the period of 18^{th} to 23^{rd} of October 2024. Two split air conditioner units with a standard cooling capacity of 3.5kW were used. The temperature reading was taken using probe thermometers with digital interfaces and energy consumption was logged automatically during the experiment. The operational life cycle cost data was collected from discussion with the leadership of the Uganda National Association of Refrigeration and Air Conditioning.

3.2 Sampling Techniques

The purposive sampling technique was employed in selecting the representative sample of air conditioner models used in the study. The choice of the selected two models was based on the Montreal protocol roadmap national commitment, which emphasises transitioning from Hydrofluorocarbon to Hydrocarbon refrigerants and also their accessibility within the Ugandan market (National Environment Management Authority, 2020). The selection criteria included:

(i) Cooling capacity of 12000 Btu (measured in British Thermal Units, Btu)

(ii) Refrigerant type of R-410A and R-290

(iii) Energy efficiency rating (EER/SEER values)

(iv) Brand and model availability in the market

3.3 Coding of Selected Split Air Conditioners

For purposes of not disclosing the split air conditioner brands used in this study, the two sampled models were assigned identifier codes which were used to identify the units in the investigations that were undertaken in this study. The two air conditioner identifier codes allocated does not mean the hierarchy of superiority, the designations are only for identification purposes. The split air conditioners were coded using capital letters. For example, code R-290, means model using R-290 refrigerant type. The air conditioners were specifically selected, targeting air conditioners using R290 and R410A refrigerants and of the same cooling capacity of 12,000 BTU. Table 3.1 shows the coding of all test specimens used in the experiments.

Table 3.1: **Coding of Test Specimen for Experiments**

Model	Air Conditioner with Refrigerant type
A	R-290
B	R-410A

3.4 Specifications of the Split Air Conditioners Used

The experiment was carried out on two split air conditioners with R-290 and R-410A refrigerants with standard cooling capacity of 3.5kW, further parameters are show in Table 3.2.

Table 3.2: Specifications of the two split air conditioners used for the experiment

Specification	Split type AC 1	Split type AC 2
Refrigerant	R290	R410A
EER	3.6	3.2
Cooling capacity	3.5 kW	3.5 kW
Inverter (variable speed)	Yes	Yes
Refrigerant charge	0.38kg	0.57kg

3.5 Measurement Instruments Used

The experiment employed three key instruments, the energy logger, the five probe temperature thermometer, and a single probe temperature thermometer which are shown in Figures 3.1, 3.2, and 3.3, respectively. The single probe thermometer monitors the room temperature; the room temperature readings are taken using a single probe thermometer screen which is installed outside with its probe in the cooled room. The table 3.3 provides specifications of the instruments used during the experiment.

Table 3.3: Instruments used during the experiment

No.	Item	Specification	Experiment Application
1.	Fluke 1736 energy logger	The fluke 1736 energy logger was suitable for the experiment due to its specifications that aligned with the experiment requirements (Fluke, 2022).  Measured Parameters • Voltage, current, power (active/reactive), power factor, energy (Wh, VAh, varh), frequency. • Harmonics: 2nd to 50th for both voltage and current, plus THD (total harmonic distortion). • Events: captures voltage dips, swells, interruptions, inrush currents; includes waveform snapshots, high-resolution RMS profiles, timestamp, severity. • Uses 4 flexible current probes (Rogowski coils)	Logging the energy consumption of the air conditioners
2.	Full gauge 2825 Penta III portable thermometer with five sensors.	The Full Gauge 2825 Penta III portable thermometer, equipped with five sensors, was suitable for the experiment because its specifications aligned with the experimental requirements (Full Gauge Control, 2023). 	Measuring outdoor ambient temperature.

No.	Item	Specification	Experiment Application
		• Power supply: One 9V battery (The battery does not come with the product) • Temperature range: -50.0 to 105.0ºC -58.0 to 221°F • Operating temperature: 0 to 50°C / 32 to 122°F • Resolution: 0.1ºC between 50.0 to 105.0ºC 0.1ºF between 58.0 to 199.9ºF 1ºF between 200 to221ºF • Accuracy: ±0.3% f.s. • Number of sensors: 5 • Sensors cable: 1 x 26 AWG microphone type - Length: 1.5 m	
3.	Elitech TPM-10 digital thermometer.	The Elitech TPM-10 digital thermometer was ideal in measure room temperature where the air conditioners were installed and being analysed due to the suitability of its specifications (Elitech Brasil, 2019).  • Temperature range: -50℃ to +110℃ • Temperature measurement error: ±1℃ • Resolution: 0.1℃ • Power: Two LR44 button batteries • Probe: Typically comes with a 1-meter waterproof probe • Display: LCD	Measuring experiment room temperature.

3.6 Experimental Set-Up

The setup was done in double-layer plywood enclosure 3.4m (width) x 4.5m (length) and 3.2m (Height), which amounts to 15.75m^2 with a room height of 3.2m. The enclosure has a concrete floor, ceiling and walls. The air conditioning system setup was done as illustrated in Figures 3.1, 3.4 and 3.5 with identical rooms for both R-290 and R-410A air conditioner systems.

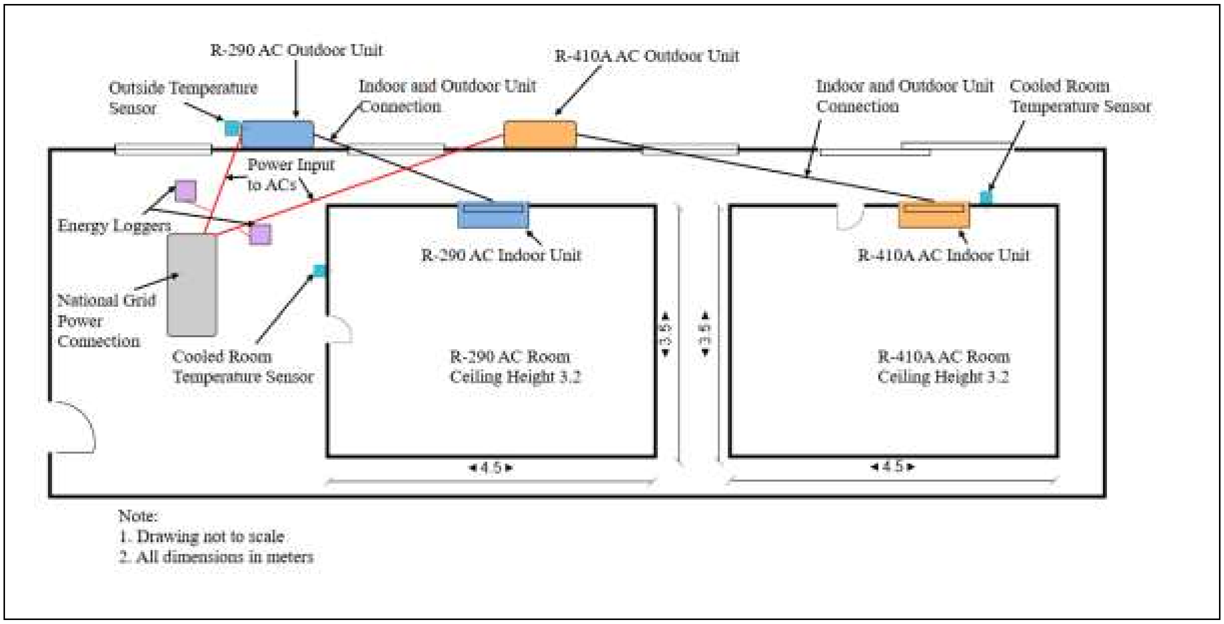

Figure 3.1: Experimental setup for comparative analysis of R-290 and R-410A refrigerants split air conditioners.

Figure 3.2: Installed outdoor units for R-410A and R-290 ACs with temperature sensor on each unit.

Figure 3.3: Mounted Indoor unit of one of the R-410A air conditioner and inside room temperature sensor.

Figure 3. 4: Experiment room setup with timber, plywood and concrete floor/ceiling

Figure 3. 5: Setup of power loggers during the experiment

3.7 Cooling Capacity Sizing

The required cooling capacity, calculated using equation 3.1, is 11,813 Btu, which aligns with the 12,000 Btu of the split-type air conditioners selected and installed for the experiment.

$$\textbf{Required Cooling Capacity (BTU)} = \textbf{Room Area x 3 x 250} \quad \text{-----(3. 1)}$$

$$\textbf{Room Area} = \textbf{3.4 x 4.5} = \textbf{15.75m}$$

$$\textbf{Cooling capacity required} = \textbf{15.75 x 3 x 250} = \textbf{11,813 Btu}$$

3.8 Determination of the Performance Characteristics of Selected Split Air Conditioner Refrigerants

The air conditioners were subjected to energy efficiency tests by logging its energy consumption over the experiment period and system behaviour under various outdoor ambient temperatures, and room temperature.

3.8.1 Evaluation of Temperature Changes of the Air Conditioner System

The comparative analysis and examination of the characteristics of the two different air conditioner systems with refrigerants R-290 and R-410A was performed by monitoring the ability of the two systems to track the set room temperature under similar outdoor ambient temperature. The two air conditioners set room temperatures was varied based on two patterns, A and B. Pattern A was implemented from 18-20 October 2024, with set room temperature varied from 26°C to 24°C to 22°C after every two hours from morning at 9:00 am to afternoon at 3:00 pm. The experiment then adopted Pattern B from 21-23 October 2024, with set room temperature varied from 22°C to 24°C to 26°C within the same time period.

The thermodynamic performance of the R-290 and R-410A refrigerant air conditioners was evaluated by using a five-probe thermometer and single probe thermometer for direct measurement of the indoor temperature variations in the air-conditioned room against outdoor ambient temperature. The temperature measurements were carried out using a five-probe thermometer and a single probe thermometer as shown in Figures 3.3 and 3.4, respectively. The outdoor ambient temperature reading on the five-probe thermometer was taken in the “S5” selector option.

3.8.2 Evaluation of the Energy Efficiency of the Air Conditioner

The energy efficiency of the selected air conditioner models was evaluated by using an energy logger for direct measurement of energy consumption; and then secondary data from energy labels (manufacturer specifications) and existing studies were used to compare energy efficiency ratings. During the six-day experiment, active energy data of the air conditioning systems was collected. This energy metrics were automatically recorded throughout the duration of the experiment using the energy logger shown in Figure 3.5.

3.8.3 Assessment of the Life-Cycle Costs of the Air Conditioners

The dataset of the measured temperature and energy efficiency was used to evaluate the operational life cycle costs and environmental impact within a tropical season in Uganda. Life-Cycle Cost Analysis (LCC) is an essential method for evaluating the total cost of owning an asset.

The approach is based on the total investment costs, energy and maintenance costs (Al-Ghamdi & Al-Gahtani, 2022).

$$\mathbf{LCC = IC + OC} \text{ --------------(3. 2)}$$

Where;

LCC – Life cycle costs

IC – Investment costs

OC – Energy costs + Maintenance costs.

3.9 Data Analysis

This section outlines the various concepts and formulas used to analyse the data acquired during the six-day experiment duration.

3.9.1 The Total Equivalent Warming Impact (TEWI) Concept

The Total Equivalent Warming Impact (Llopis, 2020) concept was employed to calculate the environmental impact of the split air conditioners under study. TEWI was calculated in accordance with equation 3.6; the Table 3.4 indicates the characteristics of the air conditioners under study, and this was acquired from their technical datasheets. Equations 3.5 and 3.4 were used to calculate the direct emissions and indirect emissions of the respective air conditioner systems. The energy consumption used in the calculations is the one obtained specifically from the experiment data of the R-290 and R-410A air conditioner systems.

TEWI = Direct Emissions at lifetime + Indirect Emissions

Direct emissions at lifetime = (L x GWP x m x n) + ((1-R) x m x GWP) --------(3. 3)

Annual Indirect emissions = E x β ---(3. 4)

Annual direct emissions = GWP x m x L --(3. 5)

TEWI = (L x GWP x m x n) + ((1-R) x m x GWP) + (E x β x n) --------- (3. 6)

Where:

TEWI	-	Total Equivalent Warming Impact ($kgCO_2eq$)
GWP	-	Global Warming Potential of the refrigerant ($kgCO_2eq/kg$)
m	-	Initial refrigerant charge (kg)
L	-	Leak rate per year (kg)
R	-	Refrigerant recovery at end of life (%)
n	-	System operating life (years)
E	-	Annual energy consumption (kWh)
β	-	CO2 emissions on energy generation (kg CO_2/kWh)

The direct and indirect emissions were calculated for each air conditioner to compare their environmental impact over the lifetime. Additionally, emissions at the end of life (EOL) are estimated by assuming that 95% of the initial charge is still in the equipment and that no proper disposal is carried out.

Table 3.4: Characteristics of the split air conditioners under study

Specification	Split type AC 1	Split type AC 2
Refrigerant	R-290	R-410A
EER	3.6	3.2
Cooling capacity (kW)	3.5	3.5
Inverter (variable speed)	Yes	Yes
Refrigerant charge (kg)	0.38	0.57
Annual leakage rate (%)	10	10
The annual average leakage rate stipulated by appliance manufacturers of room air conditioners is 10%. For calculation purposes a leakage rate of 10% was adopted. Life expectancy for air conditioning equipment is 15 years		

3.9.2 Global Warming Potential (GWP)

The Global Warming Potential (GWP) is an index that provides a relative measure of the possible climate impact due to a compound which acts as a greenhouse gas in the atmosphere (Brandão, Kirschbaum, & Cowie, 2024). The commonly accepted Integrated Time Horizon (ITH) is 100 years representing a compromise between short-term effects (20 years) and longer-term effects (500 years or longer). For this experiment, two comparisons of 100 years and 20 years were tabulated. Furthermore, the IPCC AR6 report (IPCC, 2021) figures were considered for the global warming potential as seen in Table 3.5.

Table 3. 5: GWP considered (IPCC, 2021)

Refrigerant	GWP 100 years	GWP 20 years
R-410A	2255	4715
R-290	0.02	0.072

3.9.3 CO2 Emissions on Electricity Generation (β)

Electricity is generated from a range of fuels including nuclear, gas, oil and coal and in some cases waste. When the fuel is burnt, energy is produced and carbon dioxide (CO_2) and other chemicals, mostly water, are produced. The ratio of CO_2 emitted to the electricity generated differs according to the type of fuel used. The Life Cycle approach considers both the amount of CO_2 generated during the energy conversion and the amount emitted during the fuel transportation up to the electricity generation plant and during the construction of such power generation plants. The details of national power grid factor for Uganda that were used in this study are based on the United Nations Framework Convention on Climate Change (2022) as shown in Table 3.6.

Table 3.6: **Grid emission factor for Uganda**

Parameter	**Unit**	**Description**	**Applicable project type**	**Applicable Values**		
				First credit period	**Second credit period**	**Third credit period**
EF_{grid}, OM, y	tCO_2/MWh	Operating margin (OM) CO_2 emission factor (EF) for the national power grid of Uganda	All project activities	0.2740		
EF_{grid}, BM, y	tCO_2/MWh	Build margin CO_2 emission factor for the national power grid of Uganda	All project activities	0.0000		
EF_{grid}, CM, y	tCO_2/MWh	Combined margin CO_2 emission factor for the national power grid of Uganda	All project activities except wind and solar power generation	0.1370	0.0685	
EF_{grid}, CM, y	tCO_2/MWh	Combined margin CO_2 emission factor for the national power grid of Uganda	Wind and solar power generation project activities	0.2055		

3.9.4 Limitations

While this study provides relevant insights into the lifecycle costs and emissions of air conditioners in Uganda, certain limitations should be acknowledged.

The experiment was carried out during the rainy season of Uganda from 18th to 23rd October 2024, in Mukono district within the central region of Uganda over a period of six (6) days. The method used considered varying of temperature from ascending order of 26℃, 24℃, 22℃ for the first three days and to descending order of 22℃, 24℃, 26℃ for the other three days over the experiment duration.

On day two (19th October 2024), there was a grid power supply interruption at 12:16 hrs for 14 minutes and 12:47 hrs for 13 minutes, causing a system restart and a spike in room temperature as seen in Figure 4.3. Additionally using an automated temperature logger would have helped in ensuring the time difference in taking temperature readings is eliminated. Furthermore, due to market access and resource constraints, the study only lasted six days and focused on a selected range of air conditioner models; the operational costs were sourced from guided discussions with the experts from the National Association of Refrigeration and Air Conditioning (UNARA).

Despite these limitations, the study provides a crucial baseline for life-cycle cost analysis of air conditioning systems in Uganda and offers guidance for future sustainable cooling initiatives.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Introduction

The experimental study evaluated the performance of split air conditioners with R-290 and R-410A refrigerants. The performance parameters considered in this study were temperature changes in the cooled room and energy consumption. Subsequently, an assessment of the life cycle costs of the conditioner system was developed.

4.1 Results

The performance characteristics of air conditioners using R-290 and R-410A refrigerants in maintaining the set room temperature in this study are presented in this section.

4.1.1 Temperature Changes in the Cooled Space and Energy Consumption

During experimentation period with descending set temperature Pattern A (26℃, 24℃, 22℃), at the start of the day the R-410A and R-290 air conditioner systems started working when the outdoor ambient temperature was 22.5°C which was lower than the set room temperature of 26°C then the outdoor ambient temperature rose later in the day to 28°C toward midday as seen in Figure 4.3. Consequently, the compressors of both R-290 and R-410A air conditioner systems worked minimally at the start of the day and increased later in the day when the outdoor ambient temperature increased, and the set room temperature was reduced. On day 2, there was a power interruption at 12:16 hrs and 14:47 hrs which caused indoor temperatures to spike at 12:30 hrs in Figure 4.3; once power was restored, the compressors of both air conditioner systems had to run longer to bring the room temperature back to the desired set temperature, this in turn caused a general increase in energy consumption. However, the operation temperature of the R-290 air conditioner system was generally lower than the operation temperature of R-410A air conditioner system as can be seen in Figure 4.2 and Figure 4.3.

On the other hand, during the ascending set temperature Pattern B (22℃, 24℃, 26℃), at the start of the day the R-410A and R-290 air conditioner systems started working when the outdoor ambient temperature is approximately 21℃ to 26℃ which was higher than the set room temperature of 22℃; then the outdoor ambient temperature rises later in the day peaking at approximately 29℃ as seen in Figure 4.2 and Figure 4.3.

As a result, the compressors of both R-290 and R-410A air conditioner systems worked at full potential at the start of the day and reduced later in the day when the outdoor ambient temperature increased as the set room temperature also increased.

While the operation temperature of R-290 AC system is generally lower than the operation temperature of R-410A air conditioner system as can be seen in Figure 4.3, the R-410A air conditioner system consumed less energy than the R-290 air conditioner system by 11% as seen in Figure 4.1. In general, an observation of pattern A and B set temperature variation shows that, R-410A air conditioner system consumed a total of 5.8kWh over a duration of 6 days as compared to 5.9kWh energy consumption of R-290 air conditioner system over the same duration signifying a percentage difference of 2%.

Table 4.1:Summary of energy (kWh) consumption during the six-day experiment duration

Date	Active Energy R-290 (kWh)	Active Energy R-410A (kWh)
18.10.2024	1.131	1.327
19.10.2024	1.176	1.116
20.10.2024	1.2	1.2
21.10.2024	0.8162	0.7618
22.10.2024	0.6603	0.7446
23.10.2024	0.9299	0.6442
Total	**5.9134**	**5.7936**

A paired t-test was carried out against the recorded energy consumption of R-290 and R-410A air conditioner systems based on the data in table 4.1.

The t-statistic was calculated using the formula.

$$t = \frac{\bar{D}}{SD/\sqrt{n}} \text{ --------------------------------- (4. 1)}$$

Where;

$\bar{D}$ - The mean difference ≈ 0.01997 kWh

SD - The standard deviation of the differences ≈ 0.1620 kWh

t ≈ 0.302

Comparing with t – critical for α = 0.05 (two-tailed), t-critical ≈ 2.571

Since |t| = 0.302 < 2.571. Hence no statistical difference.

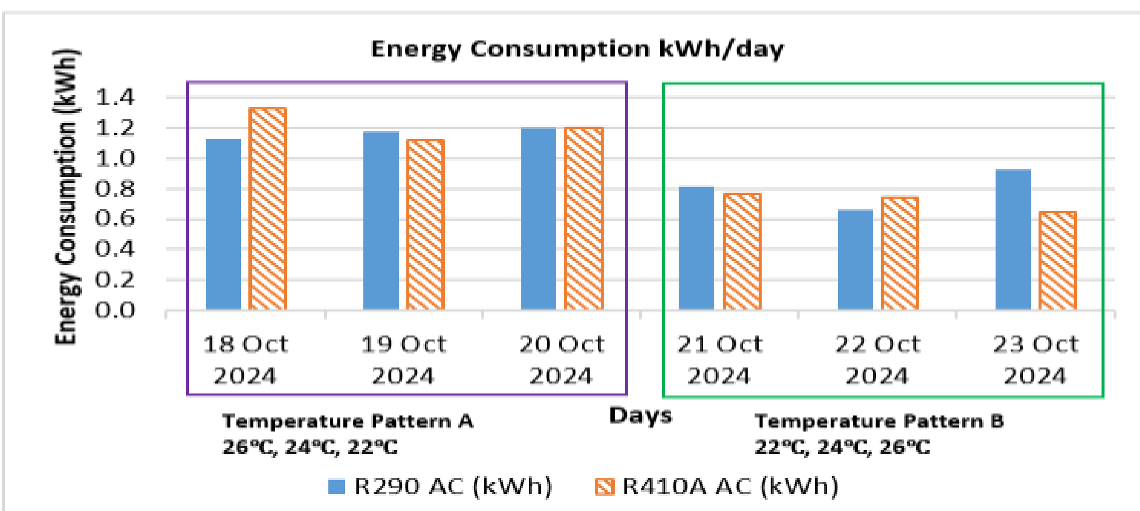

Figure 4.1: Energy consumption during the experiment duration

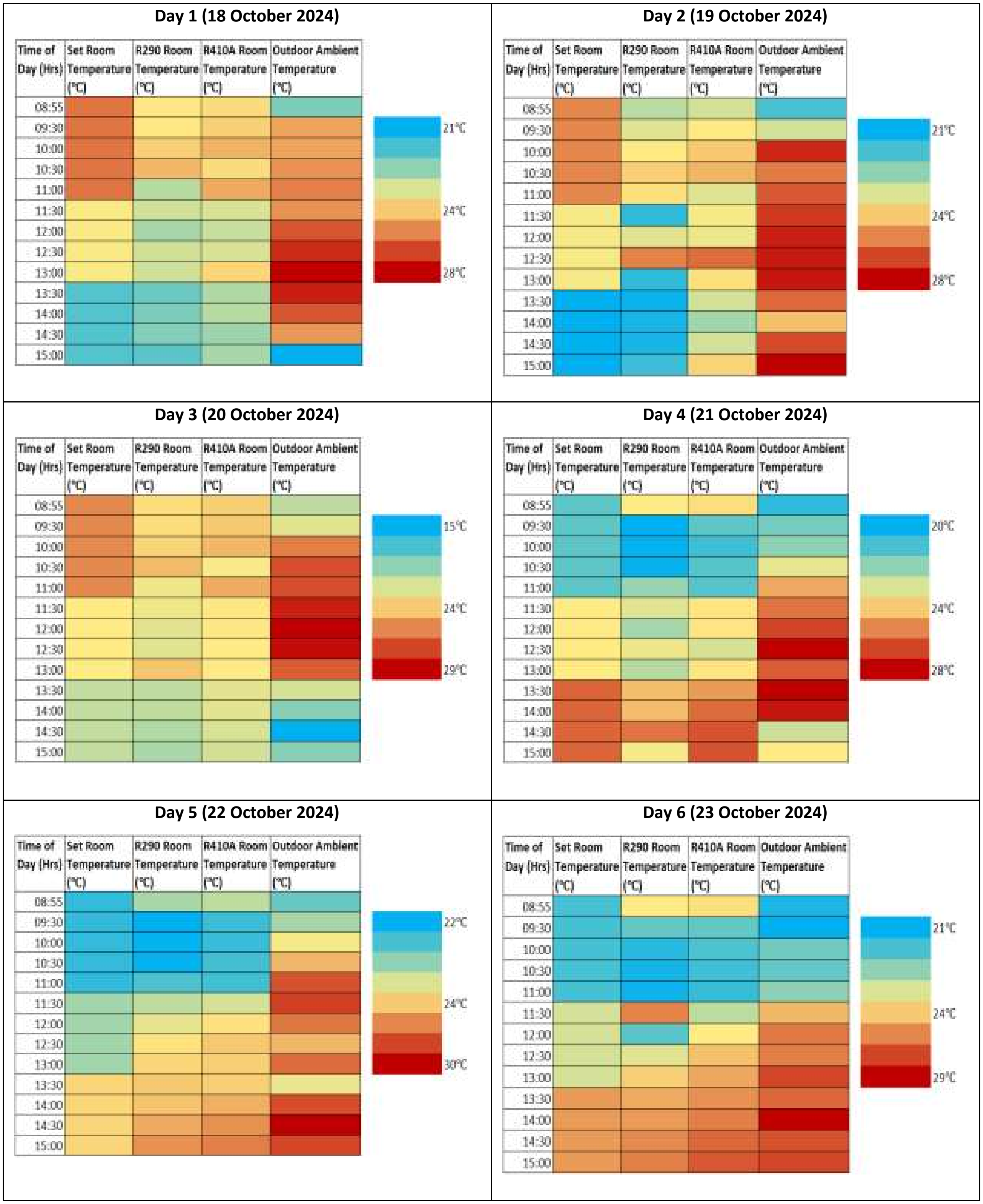

Figure 4.2: R-290 and R-410A air conditioner systems temperature heat-map for pattern A and B

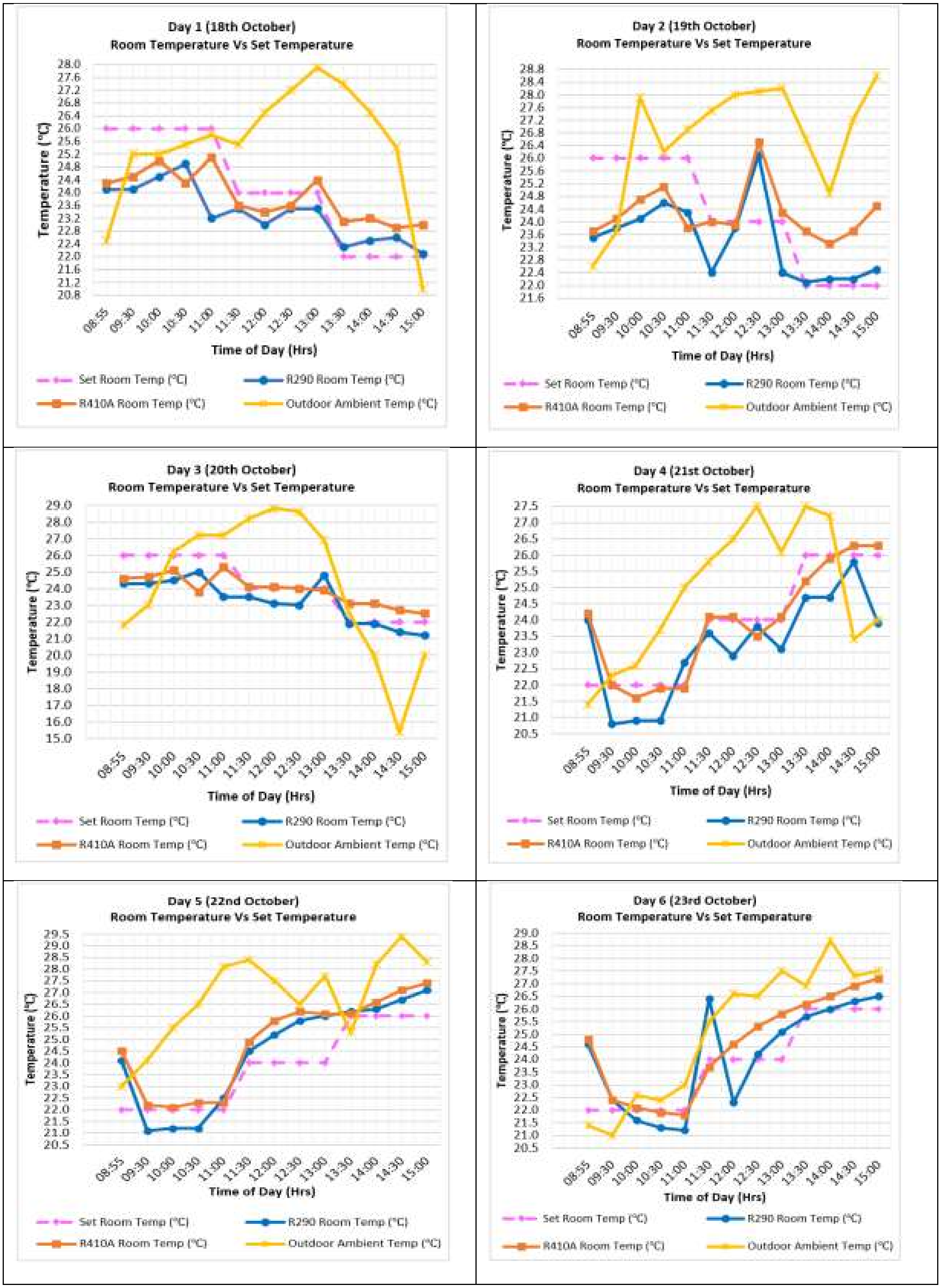

Figure 4. 3: R-290 and R-410A air conditioner systems temperature trend

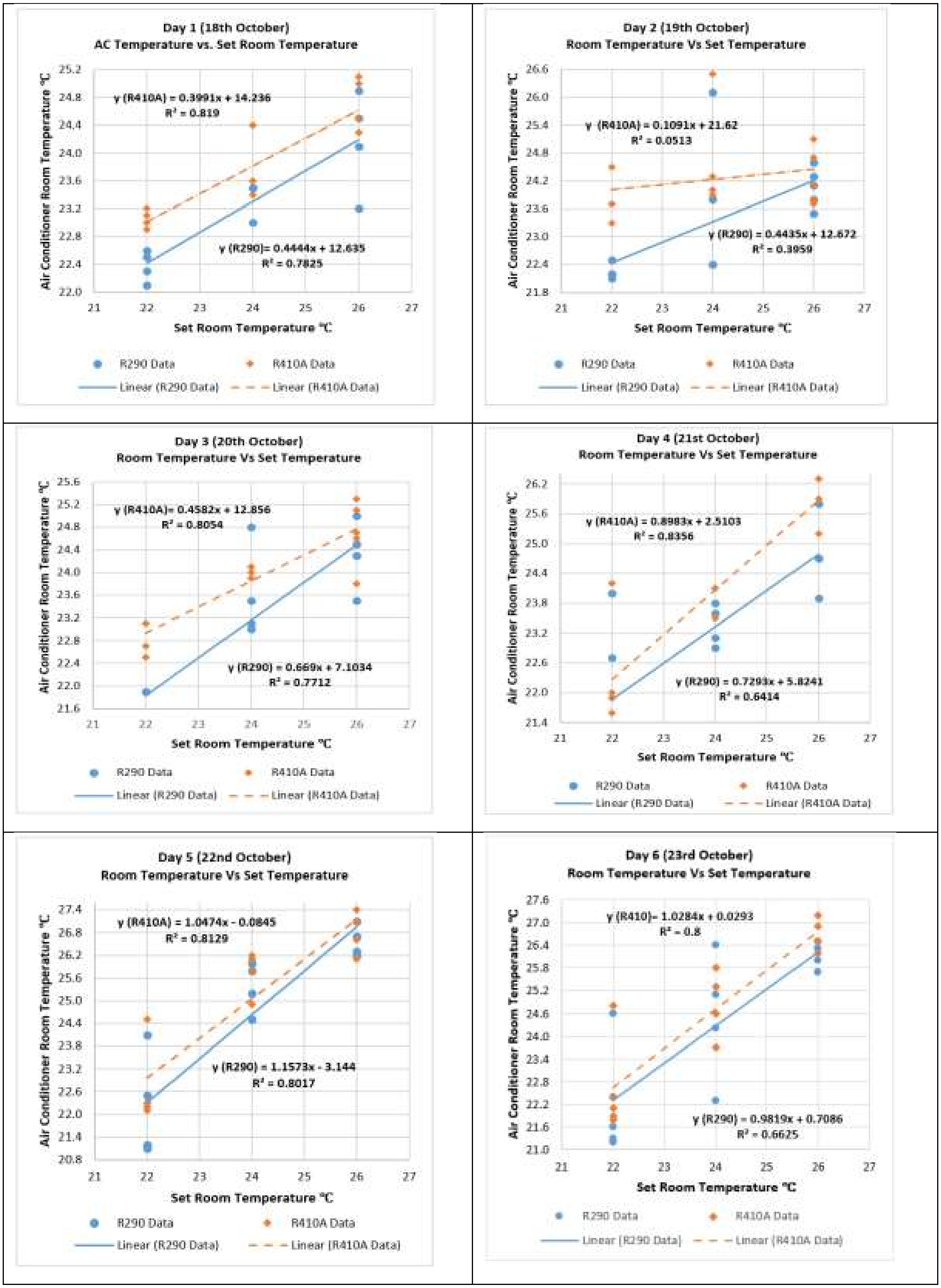

Figure 4. 4: Temperature correlation of R-290 and R-410A air conditioner systems

4.1.2 CO2 Emissions of R290 and R410A AC Systems

Figure 4.5 (a) and (b) presents the calculated emissions for the R-290, and R-410A air conditioner systems investigated in this study, using equations 3.4 and 3.5 for indirect and direct emissions respectively. Considering the 20-year Global Warming Potential (GWP), the R-290 air conditioner direct emissions are 0.000045 $kgCO_2eq$ and 4.418 $kgCO_2eq$ for R-410A air conditioner system. Additionally, the indirect emissions for R-290 air conditioner system are 1.620 $kgCO_2eq$ and the R-410A air conditioner system are 1.587 $kgCO_2eq$. As a result, the total annual emissions considering a 20-year GWP are 1.6203 $kgCO_2eq$ for R-290 air conditioner system and 6 $kgCO_2eq$ for R-410A air conditioner system.

On the other hand, over a 100-year GWP as seen in Figure 4.5 (b), R-290 air conditioner system direct emissions are 0.0000125 $kgCO_2eq$ and R-410A air conditioner system emissions are 2.113 $kgCO_2eq$; furthermore, the R-290 and R-410A air conditioner systems indirect emissions are 1.62 $kgCO_2eq$ and 1.587 $kgCO_2eq$ respectively. Moreover, the total annual emissions based on the 100-year GWP are 1.6203 $kgCO_2eq$ for R290 air conditioner system and 3.7 $kgCO_2eq$ for R-410A air conditioner system.

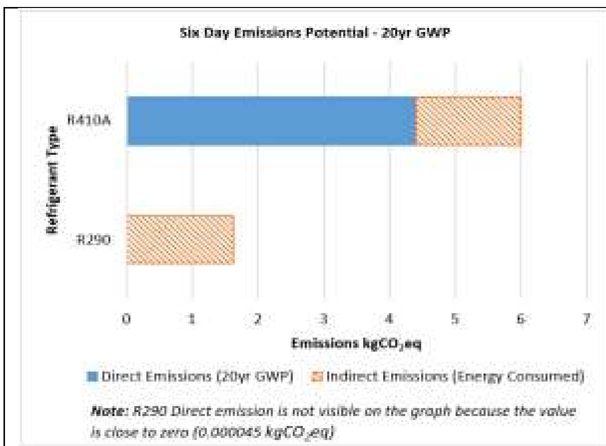	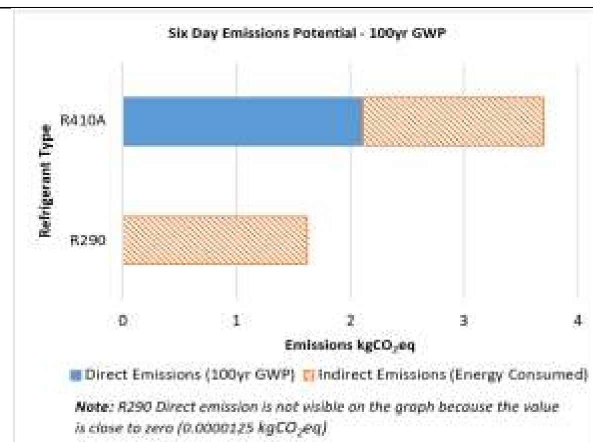
(a)	**(b)**

Figure 4.5: Emissions estimates for 6-days duration, (a) 20yr GWP; (b) 100yr GWP.

4.1.3 Life Cycle Costs for Split Air Conditioners Used

The life cycle cost analysis compared R-290 and R-410A air conditioner systems; over a lifespan of 15 years. The results in Table 4.1 show that R290 air conditioning system had a higher energy demand of 325.90 kWh/year compared to 319.29 kWh/year for the R-410A air conditioner system. The table 4.2 details the respective expenses and the data was sourced from guided discussions with the experts from the Uganda National Association of Refrigeration and Air Conditioning. Overall, the total life cycle cost of the R-290 air conditioner system was 10,309,465.500 Ugx, which is marginally higher than the R-410A air conditioner system at 10,271,848.050 Ugx by approximately 0.36%.

Table 4.2: Life cycle costs for R-290 and R-410A air conditioner systems

Parameters	R-290 AC	R-410A AC
Technical details and data		
Number of devices (devices)	1	1
Energy demand (based on experiment results) (kWh/year)	325.90	319.29
Lifespan of the device, for life cycle cost analysis (year)	15	15
Discount rate for life cycle cost valuation (%)	0	0
Purchase price (according to local market rates)		
Procurement price per device (Ugx)	2,400,000	2,100,000
Installation price per device including accessories (Ugx)	700,000	700,000
Disposal price per device including accessories (Ugx)	200,000	200,000
Delivery costs (Ugx)	0	0
Total procurement costs per device (Ugx)	**3,300,000**	**3,000,000**
Maintenance costs for equipment per year		
Annual maintenance and standard service costs per unit [Ugx]	160,000	160,000
Total maintenance costs of the equipment per year	**160,000**	**160,000**
Refrigerant		
Capacity in kg	0.380	0.570
Annual leakage (kg of refrigerant)	0.038	0.057
Total leakage in 15 years (kg of refrigerant)	0.570	0.855
Price of the refrigerant (Ugx/Kg)	80,000	80,000
Refrigerant replenishment (Annual leakage) (Ugx/year)	**45,600**	**68,400**
Energy costs of the device per year		
Electricity price [Ugx/kWh]	803	803
Energy demand per year per unit (without standby) (kWh/year)	325.90	319.29
Total energy costs per appliance per year (Ugx/year)	**261,697.70**	**256,389.87**
Total maintenance costs per year		
Total maintenance costs per device per year [Ugx/device/year]	421,697.70	416,389.87
Total cost of climate-friendly system (Ugx)	**10,309,465.500**	**10,271,848.050**

4.2 Discussion of Results

The study involved a comparative analysis of the performance characteristics of air conditioners using R-290 and R-410A refrigerants and their environmental impact based on their ability to track the set room temperature. Through the assessment of two air conditioners, a mathematical model that integrates energy consumption, environmental impact and operational life cycle costs is developed.

4.2.1 Temperature Variation and Related Energy Consumption

The observed lower operation temperature and the related lower energy consumption of R-290 air conditioner system at moderate outdoor ambient temperatures shown in Figures 4.1 and Figure 4.3 can be attributed to the higher latent heat of vaporization of R-290 which is 425.60 kJ/kg (Climalife UK, 2022) compared to R-410A at 272 kJ/kg (Climalife UK, 2024). This indicates that R-290 is more efficient at moderate outdoor ambient temperatures leading to reduced compressor work due to high heat absorbed per unit mass of R-290 refrigerant (Zhong et al., 2024). Additionally, R-290 air conditioner system consumed less energy than R-410A by 4% (see Figure 4.1) at the moderate outdoor ambient temperatures because of the smaller temperature difference and gradual load increases such that peak demands occur when the set room temperature is already low (22°C) thus avoiding severe compressor straining. As a result, when outdoor ambient temperature rose the rooms were already at lower temperatures, so even though outdoor ambient temperature peaks at 28°C as seen in Figure 4.3, the high latent heat and superior coefficient of performance (COP) of R-290 at moderate differentials allow it to efficiently handle incremental temperatures. Moreover, the Figure 4.4 indicate that R-410A air conditioner system was able to closely track the set room temperature due to its favourable operating characteristics under varying ambient conditions (Zaki & Abdelaziz, 2024).

During Pattern B where an ascending temperature trend (22°C to 24°C to 26°C) was used, the R-290 air conditioner system consumed 12% more energy than the R-410A air conditioner system. The difference in energy consumption of R-410A and R-290 air conditioner systems in Pattern B was be attributed to the higher outdoor ambient temperatures such that the system pressure increases for both refrigerants in the air conditioning systems. The R-290 air conditioner system operates at lower pressures, for example at a saturation temperature of 21.1°C, the pressure is 760 kPa (Hudson Technologies, 2023), where the R-410A pressure is 1,386 kPa at the same saturation temperature of 21.1°C (Hudson Technologies, 2023). Therefore, maintaining target indoor conditions of 26°C or lower at sustained high outdoor ambient temperatures of 27-29°C as seen in Figure 4-3 forces R-290 air conditioner system to run at higher compressor speeds due to its higher heat absorption rate (Wu et al., 2021).Consequently, this causes frequent cycling after short intervals which increased energy consumption as indicated by Kumar et al. (2024). In contrast, R-410A air conditioner system maintained relatively consistent performance across a wider outdoor ambient temperature range due to its azeotropic nature and higher-pressure stability (Kiliç & Ipek, 2021). It is also notable that R410A handles superheat and subcooling control better at high outdoor ambient temperatures because of its higher operating pressure characteristic and lower temperature glide (Zaki & Abdelaziz, 2024). Furthermore, the variation of the Pearson correlation in Figure 4.4 indicates that R-410A air conditioner system which had a higher Pearson correlation coefficient (R^2) was able to closely track the set room temperature than the R-290 air conditioner system.

The statistical analysis of daily energy consumption over the six (6) day experiment period showed no significant difference between R-290 and R-410A air conditioner systems ($t = 0.302$), indicating that on average both refrigerants consumed similar amounts of energy under the tested conditions. However, the short duration of the experiment limits the generalizability of this finding, as energy performance may vary over longer periods, different seasons, and diverse locations.

4.2.2 Environmental Impact of R-290 and R-410A Refrigerants Air Conditioners

Table 4.3 presents annual and 15-year (lifetime) period direct and indirect emissions for R-290 and R-410A air conditioner systems; the calculations in the table were computed using the 20-years Global Warming Potential (GWP) aligning with Uganda's HFC phase-down dates which indicates a 80% reduction by 2045 (National Environment Management Authority, 2020). Annually R-290 air conditioner system emitted less direct emissions by 200% as compared to R-410A air conditioner system due to its low GWP, which indicated 0.072 CO_2eq and 4,715 CO_2eq respectively. In addition, R-410A air conditioner system annual indirect emissions were 2% lower than R-290 air conditioner system annual indirect emissions due to a higher R-290 air conditioner system energy consumption observed during the experiment. Consequently, over a lifetime of 15 years the Total Equivalent Warming Impact (TEWI) of R-290 air conditioner system was 142% lower than R-410A air conditioner system. These findings show how refrigerant choice affects emissions targets under Ugandan or country regulations context.

Table 4.3:Variable for total equivalent warming impact for R-290 and R-410A air conditioner systems.

Variable	R290 AC	R410A AC	Units	Description
Charge	0.38	0.57	kg	Refrigerant charge
GWP (20yr)	0.072	4715	$kgCO_2eq$	Global warming potential
Leak rate	10	10	%	Annual leakage rate
Lifetime	15	15	Years	Period when AC is used
R	5	5	%	Refrigerant recovery rate at end of life
Energy consumption	325.905	319.292	kWh	Annual energy consumption
Emission factor	0.274	0.274	$kgCO_2/kWh$	Emission factor for Uganda.
Annual direct emissions	0.003	268.76	$kgCO_2eq$	Annual direct emissions
Annual indirect emissions	89.30	87.49	$kgCO_2eq$	Annual indirect emissions
TEWI	1,339.537	7,896.787	$kgCO_2eq$ /lifetime	Total equivalent warming impact over 15 years duration.

4.2.3 Total Life Cycle Costs of the R-290 and R-410A Air Conditioner Systems

The lifecycle costs were considered from the time of purchase of the air conditioner system until disposition. This study as seen in Table 4.1 has established that, the R290 air conditioner had higher total lifecycle costs with a marginal difference of 0.36 %, this can be attributed to the fact that it is a newer entrant to the Ugandan market with its initial procurement cost still high. Additionally various business enterprises, institutions and the service industry are still aligning with strengthening the capacity to support the technology and improving the supply chain (Green Cooling Initiative, 2023). Furthermore, the total annual refrigerant replenishment costs were low for R-290 air conditioner system with a difference of 40 %, due to its low refrigerant charge of 0.38kg as compared to R-410A air conditioner system which required a refrigerant capacity of 0.570kg. It was also observed that the total annual energy costs for R-410A air conditioner system were lower than R-290 air conditioner system by 2%, because of the energy consumption variation logged during the experiment.

In line with the current development plans of Uganda, it is envisaged that through the intervention and alignment of the government of Uganda's national development plans III and IV which focus on climate change adaptation and mitigation (National Planning Authority, 2020). An increased investments towards refrigeration and air conditioning equipment using natural refrigerants will be realised and this will significantly lower the total life cycle costs for the R-290 air conditioner systems (National Planning Authority, 2024).

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.0 Introduction

This chapter concludes the study by summarizing the key research findings in relation to the research aims and questions, highlighting their value and contribution. It also proposes opportunities for future research.

5.1 Conclusions

This study aimed to conduct a comprehensive analysis of the performance of selected air conditioner refrigerants models available globally and also in Uganda local market. This was achieved through an experimental process that revealed the energy consumption and room temperature variations over time. Based on the findings it can be concluded that varying of the room set temperature in descending pattern A and ascending pattern B has a significant effect on energy consumption of the air conditioner systems. Where the R-410A air conditioner system consumed less energy than R-290 air conditioner system by 2%. The R-410A air conditioner system presented closer room temperature values to the set room temperature compared to R-290 air conditioner system. Furthermore, the environmental impact of R-290 air conditioner system indicated a lower Total Equivalent Warming Impact (TEWI) compared to R-410A air conditioner by a difference of 142%. In addition, R-410A air conditioner system presented lower total lifetime costs with a difference of 0.36% compared to R-290 air conditioner system.

The statistical analysis of daily energy consumption of the two air conditioner systems showed no significant difference ($t = 0.302$). This indicates that, under the tested conditions, both refrigerants consumed similar amounts of energy on average. Therefore, conclusions about the relative energy efficiency of these refrigerants should be made cautiously, considering other factors such as environmental impact, and lifecycle costs.

5.2 Recommendations

The study demonstrates how to integrate direct emissions, indirect emissions, and TEWI calculations in a life-cycle framework, which can be used as a model for other developing countries assessing cooling technologies. The R-290 air conditioner systems are significantly better in terms of direct emissions and lifetime TEWI. By linking refrigerant choice to national HFC reduction targets, this work contributes practical, locally relevant evidence that can guide policymakers and stakeholders in developing countries. The study also contributes to the broader field by demonstrating how low-GWP refrigerants can meet both environmental goals and national climate commitments. To compute statistically significant differences there is a need to conduct longer-term studies (at least six months) across different seasons and locations in Uganda to accurately assess differences in energy consumption between R-290 and R-410A air conditioner systems.

Therefore, it is necessary to consider environmental impact, and lifecycle costs alongside energy efficiency when evaluating refrigerants for sustainable cooling solutions.

5.3 Action for Further Research

An examination of the performance of R-290 and R-410A air conditioning system can be accomplished by similar research under various conditions such as.

(i) Other locations in Uganda like the northern part that experiences tropical Savannah climate conditions.

(ii) One set room temperature for the whole duration of the experiment as opposed to the approach of varying temperatures that was used in this study.

(iii) Extended monitoring period of more than six (6) months, since this study's limited financial support reduced the monitoring period to only six (6) days.

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APPENDICES

APPENDIX A

Energy Consumption Data for Air Conditioners Using R-290 and R-410A Refrigerants

This appendix provides detailed energy consumption data for R-290 and R-410A air conditioner systems during the period of the experiment.

20/03/2025 14:47:37

FLUKE ®

RMS Power overview table

R290-1

Logging Information

Study type:	Energy study	Topology:	1-ph with Neutral
Start date:	18/10/2024 09:00:08	End date:	18/10/2024 15:09:11
Duration:	6h 9m 3s		
Averaging interval:	5sec	Number of averaging intervals:	4430

* ... series contained invalid values that have been discarded for the

Active Power [W]	A	B	C	Total
Max	796.1 W 18/10/2024 14:17:45			796.1 W 18/10/2024 14:17:45
linear Avg	183.7 W			183.7 W
Min	-14.3 W 18/10/2024 09:54:45			-14.3 W 18/10/2024 09:54:45
Apparent Power [VA]	**A**	**B**	**C**	**Total**
Max	814.4 VA 18/10/2024 14:17:45			814.4 VA 18/10/2024 14:17:45
linear Avg	288.9 VA			288.9 VA
Min	23.4 VA 18/10/2024 09:55:45			23.4 VA 18/10/2024 09:55:45
Non-Active Power [var]	**A**	**B**	**C**	**Total**
Max	532.8 var 18/10/2024 14:17:25			532.8 var 18/10/2024 14:17:25
linear Avg	213.8 var			213.8 var
Min	21.8 var 18/10/2024 09:55:45			21.8 var 18/10/2024 09:55:45
Power Factor [1]	**A**	**B**	**C**	**Total**
Max	0.98* cap 18/10/2024 12:17:15			0.98* cap 18/10/2024 12:17:15
linear Avg	0.64			0.64
Min	0.53* cap 18/10/2024 12:25:40			0.53* cap 18/10/2024 12:25:40

Averaging interval:

	Configured Interval length
R290-1	5sec

Figure A 1: R-290 AC system RMS power overview table for 18th October 2024

20/03/2025 14:47:37

Demand overview table

R290-1					
Logging Information					
Study type:	Energy study	Topology:	1-ph with Neutral	Cost:	803UGX/kWh, rcv; 0UGX/kWh, dlv
Start date:	18/10/2024 09:00:08	End date:	18/10/2024 15:09:11		
Duration:	6h 9m 3s				
Demand interval:	5min	Number of demand intervals:	74		* ... series contained partial intervals that have been discarded.

Cost of Energy		
Active energy, forward	1.131 kWh	Cost of Energy: standard / advanced (standard selected)
Active energy, reverse	0.001 kWh	
Total active energy	1.130 kWh	Total energy cost: UGX908.375¢
Max. demand	474.0* W 18/10/2024 13:25:00	

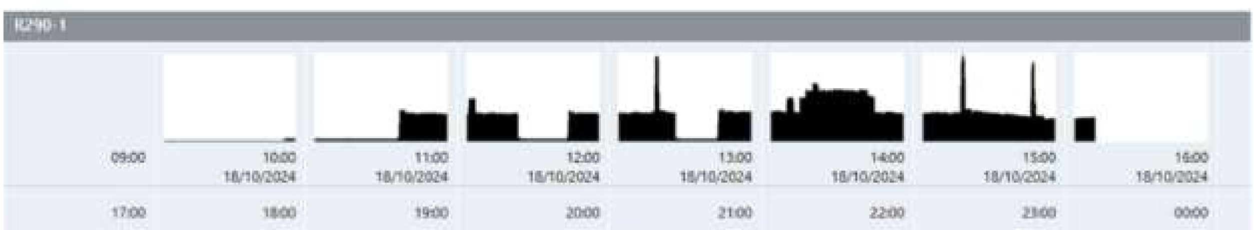
Demand interval:

	Configured Interval length
R290-1	5min

Figure A 2: R290 AC Demand overview table for 18th October 2024

20/03/2025 14:47:37

Calendar overview table



Averaging interval:

	Configured Interval length
R290-1	5sec

Figure A 3: R-290 AC system calendar overview table for R290 for 18th October 2024

20/03/2025 14:59:56

FLUKE

RMS Power overview table

R290-19				
Logging Information				
Study type: **Energy study**	Topology: **1-ph with Neutral**			
Start date: **19/10/2024 09:00:48**	End date: **19/10/2024 14:51:12**			
Duration: **5h 50m 24s**				
Averaging interval: **5sec**	Number of averaging intervals: **4206**	* ... series contained invalid values that have been discarded for the		
Active Power [kW]	A	B	C	Total
Max	**0.909 kW** 19/10/2024 12:36:20			**0.909 kW** 19/10/2024 12:36:20
linear Avg	**0.201 kW**			**0.201 kW**
Min	**-0.0000 kW** 19/10/2024 14:46:45			**-0.0000 kW** 19/10/2024 14:46:45
Apparent Power [kVA]	A	B	C	Total
Max	**1.140 kVA** 19/10/2024 12:36:20			**1.140 kVA** 19/10/2024 12:36:20
linear Avg	**0.287 kVA**			**0.287 kVA**
Min	**0.0000 kVA** 19/10/2024 12:15:20			**0.0000 kVA** 19/10/2024 12:15:20
Non-Active Power [kvar]	A	B	C	Total
Max	**0.722 kvar** 19/10/2024 12:36:20			**0.722 kvar** 19/10/2024 12:36:20
linear Avg	**0.188 kvar**			**0.188 kvar**
Min	**0.0000 kvar** 19/10/2024 12:15:20			**0.0000 kvar** 19/10/2024 12:15:20
Power Factor [1]	A	B	C	Total
Max	**0.98* cap** 19/10/2024 12:36:25			**0.98* cap** 19/10/2024 12:36:25
linear Avg	**0.70**			**0.70**
Min	**0.55*** 19/10/2024 12:12:20			**0.55*** 19/10/2024 12:12:20

Averaging interval:

	Configured Interval length
R290-19	5sec

Figure A 4: R-290 AC system RMS power overview table for 19th October 2024

20/03/2025 14:59:57

FLUKE ®

Demand overview table

R290-19					
Logging Information					
Study type:	**Energy study**	Topology:	**1-ph with Neutral**	Cost:	**803UGX/kWh, rcv; 0UGX/kWh, dlv**
Start date:	**19/10/2024 09:00:48**	End date:	**19/10/2024 14:51:12**		
Duration:	**5h 50m 24s**				
Demand interval:	**5min**	Number of demand intervals:	**71**	* ... series contained partial intervals that have been discarded.	

Cost of Energy		
Active energy, forward	**1.176 kWh**	Cost of Energy ● standard ○ advanced Total energy cost **UGX944.118f**
Active energy, reverse	**0.000 kWh**	
Total active energy	**1.176 kWh**	
Max. demand	**721.4* W** 19/10/2024 12:45:00	

Demand interval:

	Configured Interval length
R290-19	5min

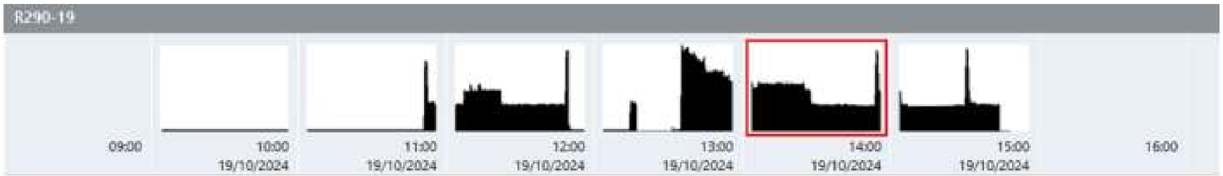
Figure A 5: R-290 AC system demand overview table for 19th October 2024

20/03/2025 14:59:57

FLUKE ®

Calendar overview table

R290-19



Averaging interval:

	Configured Interval length
R290-19	5sec

Figure A 6: R-290 AC system calendar overview table for 19th October 2024

20/03/2025 15:03:24

FLUKE ®

RMS Power overview table

R290-20

Logging Information

Study type:	Energy study	Topology:	1-ph with Neutral
Start date:	20/10/2024 08:59:38	End date:	20/10/2024 15:03:03
Duration:	6h 3m 25s		
Averaging interval:	5sec	Number of averaging intervals:	4362

* ... series contained invalid values that have been discarded for the

Active Power [W]	A	B	C	Total
Max	789.2 W 20/10/2024 12:15:50			789.2 W 20/10/2024 12:15:50
linear Avg	198.1 W			198.1 W
Min	5.9 W 20/10/2024 12:51:00			5.9 W 20/10/2024 12:51:00
Apparent Power [VA]	A	B	C	Total
Max	807.6 VA 20/10/2024 12:15:25			807.6 VA 20/10/2024 12:15:25
linear Avg	295.6 VA			295.6 VA
Min	57.3 VA 20/10/2024 11:03:25			57.3 VA 20/10/2024 11:03:25
Non-Active Power [var]	A	B	C	Total
Max	517.3 var 20/10/2024 10:29:55			517.3 var 20/10/2024 10:29:55
linear Avg	211.4 var			211.4 var
Min	56.6 var 20/10/2024 11:03:25			56.6 var 20/10/2024 11:03:25
Power Factor [1]	A	B	C	Total
Max	0.98* cap 20/10/2024 12:15:10			0.98* cap 20/10/2024 12:15:10
linear Avg	0.67			0.67
Min	0.40* 20/10/2024 10:59:35			0.40* 20/10/2024 10:59:35

Averaging interval:

	Configured Interval length
R290-20	5sec

Figure A 7: R-290 AC system RMS power overview table for 20th October 2024

20/03/2025 15:03:24

Demand overview table

R290-20			
Logging Information			
Study type: **Energy study**	Topology: **1-ph with Neutral**	Cost: **803UGX/kWh, rcv; 0UGX/kWh, dlv**	
Start date: **20/10/2024 08:59:38**	End date: **20/10/2024 15:03:03**		
Duration: **6h 3m 25s**			
Demand interval: **5min**	Number of demand intervals: **74**	* ... series contained partial intervals that have been discarded.	
Cost of Energy			
Active energy, forward	**1.200 kWh**	Cost of Energy standard / advanced (standard selected) Total energy cost **UGX963.30**	
Active energy, reverse	**0.000 kWh**		
Total active energy	**1.200 kWh**		
Max. demand	**485.8* W** 20/10/2024 13:15:00		

Demand interval:

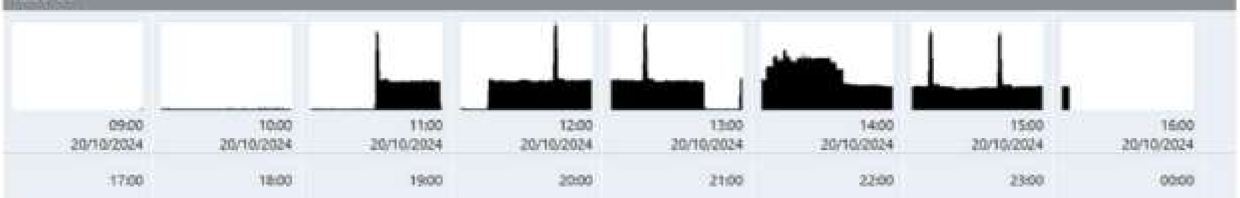
	Configured Interval length
R290-20	5min

Figure A 8: R-290 AC system demand overview table for 20th October 2024

20/03/2025 15:03:24

Calendar overview table

R290-20



Averaging interval:

	Configured Interval length
R290-20	5sec

Figure A 9: R-290 AC system calendar overview table for 20th October 2024

20/03/2025 15:05:31

FLUKE

RMS Power overview table

R290-21				
Logging Information				
Study type: **Energy study**	Topology: **1-ph with Neutral**			
Start date: **21/10/2024 08:59:32**	End date: **21/10/2024 15:01:31**			
Duration: **6h 1m 59s**				
Averaging interval: **5sec**	Number of averaging intervals: **4345**	* ... series contained invalid values that have been discarded for the		
Active Power [W]	A	B	C	Total
Max	**739.1 W** 21/10/2024 10:35:40			**739.1 W** 21/10/2024 10:35:40
linear Avg	**135.3 W**			**135.3 W**
Min	**8.3 W** 21/10/2024 12:24:45			**8.3 W** 21/10/2024 12:24:45
Apparent Power [VA]	A	B	C	Total
Max	**788.5 VA** 21/10/2024 09:18:20			**788.5 VA** 21/10/2024 09:18:20
linear Avg	**217.8 VA**			**217.8 VA**
Min	**58.9 VA** 21/10/2024 12:19:25			**58.9 VA** 21/10/2024 12:19:25
Non-Active Power [var]	A	B	C	Total
Max	**528.5 var** 21/10/2024 09:18:20			**528.5 var** 21/10/2024 09:18:20
linear Avg	**160.7 var**			**160.7 var**
Min	**58.0 var** 21/10/2024 12:19:25			**58.0 var** 21/10/2024 12:19:25
Power Factor [1]	A	B	C	Total
Max	**0.98* cap** 21/10/2024 10:34:50			**0.98* cap** 21/10/2024 10:34:50
linear Avg	**0.62**			**0.62**
Min	**0.40*** 21/10/2024 12:17:20			**0.40*** 21/10/2024 12:17:20

Averaging interval:

	Configured Interval length
R290-21	5sec

Figure A 10: R-290 AC system RMS power overview table for 21st October 2024

20/03/2025 15:05:31

FLUKE

Demand overview table

R290-21					
Logging Information					
Study type:	Energy study	Topology:	1-ph with Neutral	Cost:	803UGX/kWh, rcv; 0UGX/kWh, dlv
Start date:	21/10/2024 08:59:32	End date:	21/10/2024 15:01:31		
Duration:	6h 1m 59s				
Demand interval:	5min	Number of demand intervals:	74	* ... series contained partial intervals that have been discarded.	

Cost of Energy		
Active energy, forward	816.2 Wh	Cost of Energy standard / advanced Total energy cost UGX655.427f
Active energy, reverse	0.0 Wh	
Total active energy	816.2 Wh	
Max. demand	524.9* W 21/10/2024 09:20:00	

Demand interval:

	Configured Interval length
R290-21	5min

Figure A 11: R-290 AC system demand overview table for 21st October 2024

20/03/2025 15:05:31

FLUKE

Calendar overview table

R290-21

Averaging interval:

	Configured Interval length
R290-21	5sec

Figure A 12: R-290 AC system calendar overview table for 21st October 2024

20/03/2025 15:09:37

RMS Power overview table

ES.066				
Logging Information				
Study type: Energy study Start date: 22/10/2024 08:59:50 Duration: 6h 2m 0s Averaging interval: 5sec	Topology: 1-ph with Neutral End date: 22/10/2024 15:01:50 Number of averaging intervals: 4344		* ... series contained invalid values that have been discarded for the	
Active Power [W]	A	B	C	Total
Max	**760.2 W** 22/10/2024 10:27:35			**760.2 W** 22/10/2024 10:27:35
linear Avg	**109.4 W**			**109.4 W**
Min	**8.7 W** 22/10/2024 13:02:00			**8.7 W** 22/10/2024 13:02:00
Apparent Power [VA]	A	B	C	Total
Max	**778.9 VA** 22/10/2024 10:27:35			**778.9 VA** 22/10/2024 10:27:35
linear Avg	**174.2 VA**			**174.2 VA**
Min	**60.3 VA** 22/10/2024 11:12:20			**60.3 VA** 22/10/2024 11:12:20
Non-Active Power [var]	A	B	C	Total
Max	**519.4 var** 22/10/2024 09:04:00			**519.4 var** 22/10/2024 09:04:00
linear Avg	**119.4 var**			**119.4 var**
Min	**59.0 var** 22/10/2024 11:12:20			**59.0 var** 22/10/2024 11:12:20
Power Factor [1]	A	B	C	Total
Max	**0.98* cap** 22/10/2024 09:56:25			**0.98* cap** 22/10/2024 09:56:25
linear Avg	**0.63**			**0.63**
Min	**0.50* cap** 22/10/2024 11:02:45			**0.50* cap** 22/10/2024 11:02:45

Averaging interval:

	Configured Interval length
ES.066	5sec

Figure A 13: R-290 AC system RMS power overview table for 22nd October 2024

20/03/2025 15:09:37

FLUKE

Demand overview table

ES.066			
Logging Information			
Study type: Energy study	Topology: 1-ph with Neutral	Cost: 803UGX/kWh, rcv; 0UGX/kWh, dlv	
Start date: 22/10/2024 08:59:50	End date: 22/10/2024 15:01:50		
Duration: 6h 2m 0s			
Demand interval: 5min	Number of demand intervals: 74	* ... series contained partial intervals that have been discarded.	
Cost of Energy			
Active energy, forward	660.3 Wh	Cost of Energy standard / advanced Total energy cost UGX530.184ℓ	
Active energy, reverse	0.0 Wh		
Total active energy	660.3 Wh		
Max. demand	708.6* W 22/10/2024 09:10:00		

Demand interval:

	Configured Interval length
ES.066	5min

Figure A 14: R-290 AC system demand overview table for 22nd October 2024

20/03/2025 15:09:37

FLUKE

Calendar overview table

Averaging interval:

	Configured Interval length
ES.066	5sec

Figure A 15: R-290 AC system calendar overview table for 22nd October 2024

20/03/2025 15:11:44

FLUKE

RMS Power overview table

R290-23				
Logging Information				
Study type: Energy study	Topology: 1-ph with Neutral			
Start date: 23/10/2024 08:59:38	End date: 23/10/2024 15:01:36			
Duration: 6h 1m 58s				
Averaging interval: 5sec	Number of averaging intervals: 4345	* ... series contained invalid values that have been discarded for the		
Active Power [W]	A	B	C	Total
Max	**763.9 W** 23/10/2024 11:50:45			**763.9 W** 23/10/2024 11:50:45
linear Avg	**154.1 W**			**154.1 W**
Min	**10.5 W** 23/10/2024 09:00:25			**10.5 W** 23/10/2024 09:00:25
Apparent Power [VA]	A	B	C	Total
Max	**792.3 VA** 23/10/2024 11:50:15			**792.3 VA** 23/10/2024 11:50:15
linear Avg	**230.0 VA**			**230.0 VA**
Min	**51.7 VA** 23/10/2024 11:07:40			**51.7 VA** 23/10/2024 11:07:40
Non-Active Power [var]	A	B	C	Total
Max	**541.4 var** 23/10/2024 09:12:05			**541.4 var** 23/10/2024 09:12:05
linear Avg	**157.0 var**			**157.0 var**
Min	**49.4 var** 23/10/2024 11:07:40			**49.4 var** 23/10/2024 11:07:40
Power Factor [1]	A	B	C	Total
Max	**0.98* cap** 23/10/2024 11:51:05			**0.98* cap** 23/10/2024 11:51:05
linear Avg	**0.67**			**0.67**
Min	**0.38*** 23/10/2024 11:29:30			**0.38*** 23/10/2024 11:29:30

Averaging interval:

	Configured Interval length
R290-23	5sec

Figure A 16: R-290 AC system RMS power overview table for 23rd October 2024

20/03/2025 15:11:45

FLUKE

Demand overview table

R290-23			
Logging Information			
Study type: Energy study	Topology: 1-ph with Neutral	Cost: 803UGX/kWh, rcv; 0UGX/kWh, dlv	
Start date: 23/10/2024 08:59:38	End date: 23/10/2024 15:01:36		
Duration: 6h 1m 58s			
Demand interval: 5min	Number of demand intervals: 74	* ... series contained partial intervals that have been discarded.	
Cost of Energy			
Active energy, forward	929.9 Wh	Cost of Energy standard / advanced Total energy cost UGX746.733	
Active energy, reverse	0.0 Wh		
Total active energy	929.9 Wh		
Max. demand	685.4* W 23/10/2024 11:55:00		

Demand interval:

	Configured Interval length
R290-23	5min

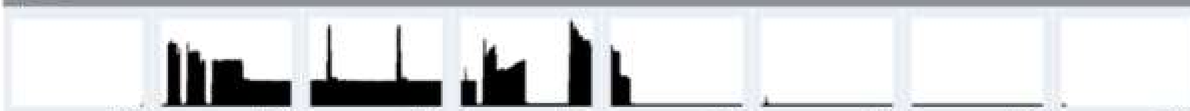
Figure A 17: R-290 AC system demand overview table for 23rd October 2024

20/03/2025 15:11:45

FLUKE

Calendar overview table

R290-23



09:00 23/10/2024	10:00 23/10/2024	11:00 23/10/2024	12:00 23/10/2024	13:00 23/10/2024	14:00 23/10/2024	15:00 23/10/2024	16:00 23/10/2024
17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00

Averaging interval:

	Configured Interval length
R290-23	5sec

Figure A 18: R-290 AC system calendar overview table for 23rd October 2024

20/03/2025 15:18:53

FLUKE ®

RMS Power overview table

R410-18				
Logging Information				
Study type: **Energy study**	Topology: **1-ph with Neutral**			
Start date: **18/10/2024 08:59:35**	End date: **18/10/2024 15:08:39**			
Duration: **6h 9m 4s**				
Averaging interval: **5sec**	Number of averaging intervals: **4429**	* ... series contained invalid values that have been discarded for the		
Active Power [kW]	A	B	C	Total
Max	**1.068 kW** 18/10/2024 10:25:40			**1.068 kW** 18/10/2024 10:25:40
linear Avg	**0.216 kW**			**0.216 kW**
Min	**0.0036 kW** 18/10/2024 08:59:50			**0.0036 kW** 18/10/2024 08:59:50
Apparent Power [kVA]	A	B	C	Total
Max	**1.077 kVA** 18/10/2024 10:25:40			**1.077 kVA** 18/10/2024 10:25:40
linear Avg	**0.318 kVA**			**0.318 kVA**
Min	**0.040 kVA** 18/10/2024 10:50:10			**0.040 kVA** 18/10/2024 10:50:10
Non-Active Power [kvar]	A	B	C	Total
Max	**0.668 kvar** 18/10/2024 12:05:50			**0.668 kvar** 18/10/2024 12:05:50
linear Avg	**0.229 kvar**			**0.229 kvar**
Min	**0.035 kvar** 18/10/2024 10:50:10			**0.035 kvar** 18/10/2024 10:50:10
Power Factor [1]	A	B	C	Total
Max	**0.99* cap** 18/10/2024 10:25:40			**0.99* cap** 18/10/2024 10:25:40
linear Avg	**0.68**			**0.68**
Min	**0.62* cap** 18/10/2024 12:05:45			**0.62* cap** 18/10/2024 12:05:45

Averaging interval:

	Configured Interval length
R410-18	5sec

Figure A 19: R-410A AC system RMS power overview table for 18th October 2024

20/03/2025 15:18:53

FLUKE

Demand overview table

R410-18			
Logging Information			
Study type: Energy study	Topology: 1-ph with Neutral	Cost: 803UGX/kWh, rcv; 0UGX/kWh, dlv	
Start date: 18/10/2024 08:59:35	End date: 18/10/2024 15:08:39		
Duration: 6h 9m 4s			
Demand interval: 5min	Number of demand intervals: 75	* ... series contained partial intervals that have been discarded.	
Cost of Energy			
Active energy, forward	1.327 kWh	Cost of Energy standard / advanced Total energy cost UGX1,065.722	
Active energy, reverse	0.000 kWh		
Total active energy	1.327 kWh		
Max. demand	452.7* W 18/10/2024 14:25:00		

Demand interval:

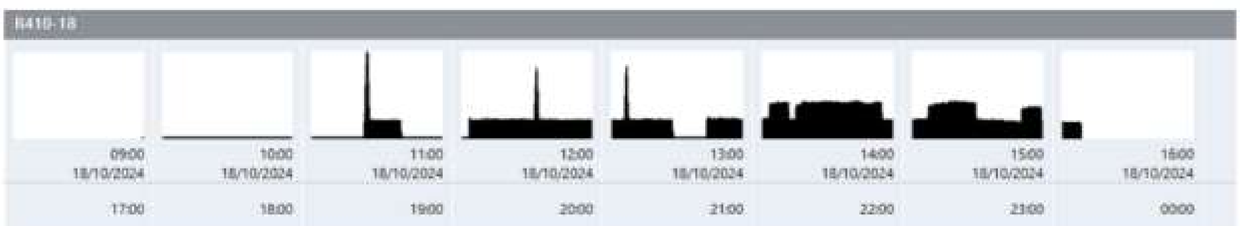
	Configured Interval length
R410-18	5min

Figure A 20: R-410A AC system demand overview table for 18th October 2024

20/03/2025 15:18:53

FLUKE

Calendar overview table



Averaging interval:

	Configured Interval length
R410-18	5sec

Figure A 21: R-410A AC system calendar overview table for 18th October 2024

20/03/2025 15:21:38

FLUKE ®

RMS Power overview table

R410A-19

Logging Information

Study type:	Energy study	Topology:	1-ph with Neutral
Start date:	19/10/2024 09:00:18	End date:	19/10/2024 14:50:41
Duration:	5h 50m 23s		
Averaging interval:	5sec	Number of averaging intervals:	4206

* ... series contained invalid values that have been discarded for the

Active Power [kW]	A	B	C	Total
Max	**1.072 kW** 19/10/2024 10:43:10			**1.072 kW** 19/10/2024 10:43:10
linear Avg	**0.191 kW**			**0.191 kW**
Min	**-0.0009 kW** 19/10/2024 12:31:45			**-0.0009 kW** 19/10/2024 12:31:45
Apparent Power [kVA]	A	B	C	Total
Max	**1.080 kVA** 19/10/2024 10:43:10			**1.080 kVA** 19/10/2024 10:43:10
linear Avg	**0.271 kVA**			**0.271 kVA**
Min	**0.0000 kVA** 19/10/2024 12:14:50			**0.0000 kVA** 19/10/2024 12:14:50
Non-Active Power [kvar]	A	B	C	Total
Max	**0.666 kvar** 19/10/2024 11:45:40			**0.666 kvar** 19/10/2024 11:45:40
linear Avg	**0.185 kvar**			**0.185 kvar**
Min	**0.0000 kvar** 19/10/2024 12:14:50			**0.0000 kvar** 19/10/2024 12:14:50
Power Factor [1]	A	B	C	Total
Max	**0.99* cap** 19/10/2024 10:43:10			**0.99* cap** 19/10/2024 10:43:10
linear Avg	**0.71**			**0.71**
Min	**0.63* cap** 19/10/2024 13:17:00			**0.63* cap** 19/10/2024 13:17:00

Averaging interval:

	Configured Interval length
R410A-19	5sec

Figure A 22: R-410A AC system RMS power overview table for 19th October 2024

20/03/2025 15:21:38

FLUKE

Demand overview table

R410A-19			
Logging Information			
Study type: Energy study Start date: 19/10/2024 09:00:18 Duration: 5h 50m 23s Demand interval: 5min	Topology: 1-ph with Neutral End date: 19/10/2024 14:50:41 Number of demand intervals: 71	Cost: 803UGX/kWh, rcv; 0UGX/kWh, dlv * ... series contained partial intervals that have been discarded.	
Cost of Energy			
Active energy, forward	1.116 kWh	Cost of Energy standard / advanced Total energy cost UGX896.446	
Active energy, reverse	0.000 kWh		
Total active energy	1.116 kWh		
Max. demand	628.9* W 19/10/2024 12:40:00		

Demand interval:

	Configured Interval length
R410A-19	5min

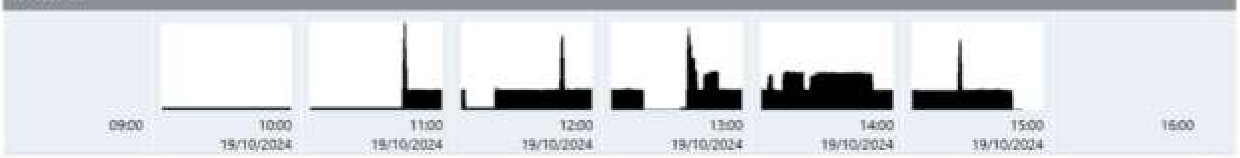
Figure A 23: R-410A system demand overview table for 19th October 2024

20/03/2025 15:21:38

FLUKE

Calendar overview table

R410A-19



Averaging interval:

	Configured Interval length
R410A-19	5sec

Figure A 24: R-410A AC system calendar overview table for 19th October 2024

20/03/2025 15:24:23

FLUKE ®

RMS Power overview table

R410A-20				
Logging Information				
Study type: **Energy study**	Topology: **1-ph with Neutral**			
Start date: **20/10/2024 08:59:04**	End date: **20/10/2024 15:02:31**			
Duration: **6h 3m 27s**				
Averaging interval: **5sec**	Number of averaging intervals: **4363**	* ... series contained invalid values that have been discarded for the		
Active Power [W]	A	B	C	Total
Max	**982.1 W** 20/10/2024 10:12:30			**982.1 W** 20/10/2024 10:12:30
linear Avg	**198.2 W**			**198.2 W**
Min	**4.0 W** 20/10/2024 08:59:20			**4.0 W** 20/10/2024 08:59:20
Apparent Power [VA]	A	B	C	Total
Max	**991.1 VA** 20/10/2024 10:12:30			**991.1 VA** 20/10/2024 10:12:30
linear Avg	**272.5 VA**			**272.5 VA**
Min	**42.8 VA** 20/10/2024 11:00:05			**42.8 VA** 20/10/2024 11:00:05
Non-Active Power [var]	A	B	C	Total
Max	**791.0 var** 20/10/2024 14:27:50			**791.0 var** 20/10/2024 14:27:50
linear Avg	**181.6 var**			**181.6 var**
Min	**36.6 var** 20/10/2024 10:11:00			**36.6 var** 20/10/2024 10:11:00
Power Factor [1]	A	B	C	Total
Max	**0.99* cap** 20/10/2024 10:12:35			**0.99* cap** 20/10/2024 10:12:35
linear Avg	**0.73**			**0.73**
Min	**0.62* cap** 20/10/2024 13:55:40			**0.62* cap** 20/10/2024 13:55:40

Averaging interval:

	Configured Interval length
R410A-20	5sec

Figure A 25: R-410A AC system RMS power overview table for 20th October 2024

20/03/2025 15:24:23

Demand overview table

R410A-20

Logging Information

Study type:	Energy study	Topology:	1-ph with Neutral	Cost:	803UGX/kWh, rcv; 0UGX/kWh, dlv
Start date:	20/10/2024 08:59:04	End date:	20/10/2024 15:02:31		
Duration:	6h 3m 27s				
Demand interval:	5min	Number of demand intervals:	74		* ... series contained partial intervals that have been discarded.

Cost of Energy

Active energy, forward	1.200 kWh	Cost of Energy: standard / advanced
Active energy, reverse	0.000 kWh	Total energy cost
Total active energy	1.200 kWh	UGX963.933
Max. demand	417.1* W 20/10/2024 13:20:00	

Demand interval:

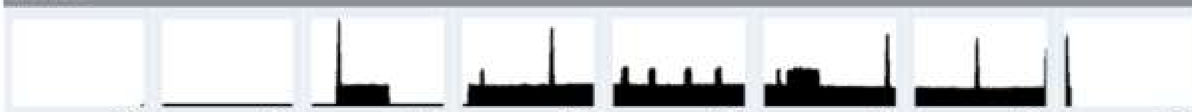
	Configured Interval length
R410A-20	5min

Figure A 26: R-410A AC system demand overview table for 20th October 2024

20/03/2025 15:24:23

Calendar overview table

R410A-20



09:00 20/10/2024	10:00 20/10/2024	11:00 20/10/2024	12:00 20/10/2024	13:00 20/10/2024	14:00 20/10/2024	15:00 20/10/2024	16:00 20/10/2024
17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00

Averaging interval:

	Configured Interval length
R410A-20	5sec

Figure A 27: R-410A AC system calendar overview table for 20th October 2024

20/03/2025 15:28:05

FLUKE

RMS Power overview table

R410A-21				
Logging Information				
Study type: **Energy study** Start date: **21/10/2024 08:58:58** Duration: **6h 2m 2s** Averaging interval: **5sec**	Topology: **1-ph with Neutral** End date: **21/10/2024 15:01:00** Number of averaging intervals: **4203**		* ... series contained invalid values that have been discarded for the	
Active Power [W]	A	B	C	Total
Max	**883.3* W** 21/10/2024 12:19:00			**883.3* W** 21/10/2024 12:19:00
linear Avg	**132.3* W**			**132.3* W**
Min	**9.0* W** 21/10/2024 08:59:15			**9.0* W** 21/10/2024 08:59:15
Apparent Power [VA]	A	B	C	Total
Max	**908.7* VA** 21/10/2024 09:02:40			**908.7* VA** 21/10/2024 09:02:40
linear Avg	**180.6* VA**			**180.6* VA**
Min	**45.1* VA** 21/10/2024 11:35:55			**45.1* VA** 21/10/2024 11:35:55
Non-Active Power [var]	A	B	C	Total
Max	**719.4* var** 21/10/2024 09:02:40			**719.4* var** 21/10/2024 09:02:40
linear Avg	**117.7* var**			**117.7* var**
Min	**35.5* var** 21/10/2024 09:02:00			**35.5* var** 21/10/2024 09:02:00
Power Factor [1]	A	B	C	Total
Max	**0.99* cap** 21/10/2024 12:18:55			**0.99* cap** 21/10/2024 12:18:55
linear Avg	**0.73***			**0.73***
Min	**0.63* cap** 21/10/2024 09:44:25			**0.63* cap** 21/10/2024 09:44:25

Averaging interval:

	Configured Interval length
R410A-21	5sec

Figure A 28: R-410A AC system RMS power overview table for 21st October 2024

20/03/2025 15:28:05

FLUKE

Demand overview table

R410A-21			
Logging Information			
Study type: Energy study	Topology: 1-ph with Neutral	Cost: 803UGX/kWh, rcv; 0UGX/kWh, dlv	
Start date: 21/10/2024 08:58:58	End date: 21/10/2024 15:01:00	* ... series contained invalid values that have been discarded for the shc	
Duration: 6h 2m 2s		* ... series contained partial intervals that have been discarded.	
Demand interval: 5min	Number of demand intervals: 72		
Cost of Energy			
Active energy, forward	761.8* Wh	Cost of Energy: standard / advanced	
Active energy, reverse	0.0* Wh	Total energy cost	
Total active energy	761.8* Wh	UGX611.71f	
Max. demand	417.0* W 21/10/2024 12:20:00		

Demand interval:

	Configured Interval length
R410A-21	5min

Figure A 29: R-410A AC system demand overview table for 21st October 2024

20/03/2025 15:28:05

FLUKE

Calendar overview table

R410A-21

Averaging interval:

	Configured Interval length
R410A-21	5sec

Figure A 30: R-410A AC system calendar overview table for 21st October 2024

20/03/2025 15:30:20

FLUKE ®

RMS Power overview table

ES.086				
Logging Information				
Study type: **Energy study** Start date: **22/10/2024 08:59:16** Duration: **6h 2m 0s** Averaging interval: **5sec**	Topology: **1-ph with Neutral** End date: **22/10/2024 15:01:16** Number of averaging intervals: **4345**	* ... series contained invalid values that have been discarded for the		
Active Power [W]	A	B	C	Total
Max	**868.0 W** 22/10/2024 10:20:55			**868.0 W** 22/10/2024 10:20:55
linear Avg	**123.4 W**			**123.4 W**
Min	**8.7 W** 22/10/2024 08:59:35			**8.7 W** 22/10/2024 08:59:35
Apparent Power [VA]	A	B	C	Total
Max	**886.4 VA** 22/10/2024 09:47:45			**886.4 VA** 22/10/2024 09:47:45
linear Avg	**166.5 VA**			**166.5 VA**
Min	**44.5 VA** 22/10/2024 11:11:50			**44.5 VA** 22/10/2024 11:11:50
Non-Active Power [var]	A	B	C	Total
Max	**699.3 var** 22/10/2024 09:47:45			**699.3 var** 22/10/2024 09:47:45
linear Avg	**104.2 var**			**104.2 var**
Min	**33.6 var** 22/10/2024 09:02:15			**33.6 var** 22/10/2024 09:02:15
Power Factor [1]	A	B	C	Total
Max	**0.99* cap** 22/10/2024 10:20:55			**0.99* cap** 22/10/2024 10:20:55
linear Avg	**0.74**			**0.74**
Min	**0.65* cap** 22/10/2024 10:51:50			**0.65* cap** 22/10/2024 10:51:50

Averaging interval:

	Configured Interval length
ES.086	5sec

Figure A 31: R-410A AC system RMS power overview table for 22nd October 2024

20/03/2025 15:30:20

FLUKE

Demand overview table

ES.086			
Logging information			
Study type: **Energy study**	Topology: **1-ph with Neutral**	Cost: **803UGX/kWh, rcv; 0UGX/kWh, dlv**	
Start date: **22/10/2024 08:59:16**	End date: **22/10/2024 15:01:16**		
Duration: **6h 2m 0s**			
Demand interval: **5min**	Number of demand intervals: **74**	* ... series contained partial intervals that have been discarded.	

Cost of Energy		
Active energy, forward	**744.6 Wh**	Cost of Energy standard / advanced Total energy cost **UGX597.874**
Active energy, reverse	**0.0 Wh**	
Total active energy	**744.6 Wh**	
Max. demand	**418.0* W** 22/10/2024 09:10:00	

Demand interval:

	Configured Interval length
ES.086	5min

Figure A 32: R-410A AC system demand overview table for 22nd October 2024

20/03/2025 15:30:20

FLUKE

Calendar overview table

Averaging interval:

	Configured Interval length
ES.086	5sec

Figure A 33: R-410A AC system demand overview table for 22nd October 2024

20/03/2025 15:32:18

FLUKE

RMS Power overview table

R410A-23				
Logging Information				
Study type: **Energy study** Start date: **23/10/2024 08:59:04** Duration: **6h 1m 58s** Averaging interval: **5sec**	Topology: **1-ph with Neutral** End date: **23/10/2024 15:01:02** Number of averaging intervals: **4345**	* ... series contained invalid values that have been discarded for the		
Active Power [W]	A	B	C	Total
Max	**790.8 W** 23/10/2024 09:46:10			**790.8 W** 23/10/2024 09:46:10
linear Avg	**106.8 W**			**106.8 W**
Min	**7.9 W** 23/10/2024 08:59:20			**7.9 W** 23/10/2024 08:59:20
Apparent Power [VA]	A	B	C	Total
Max	**869.2 VA** 23/10/2024 09:45:10			**869.2 VA** 23/10/2024 09:45:10
linear Avg	**146.3 VA**			**146.3 VA**
Min	**40.8 VA** 23/10/2024 11:14:40			**40.8 VA** 23/10/2024 11:14:40
Non-Active Power [var]	A	B	C	Total
Max	**680.7 var** 23/10/2024 09:45:10			**680.7 var** 23/10/2024 09:45:10
linear Avg	**95.1 var**			**95.1 var**
Min	**34.1 var** 23/10/2024 11:14:40			**34.1 var** 23/10/2024 11:14:40
Power Factor [1]	A	B	C	Total
Max	**0.99* cap** 23/10/2024 10:50:15			**0.99* cap** 23/10/2024 10:50:15
linear Avg				
Min	**0.64*** 23/10/2024 08:59:25			**0.64*** 23/10/2024 08:59:25

Averaging interval:

	Configured Interval length
R410A-23	5sec

Figure A 34: R-410A AC system RMS power overview table for 23rd October 2024

20/03/2025 15:32:18

FLUKE

Demand overview table

R410A-23

Logging Information

Study type:	Energy study	Topology:	1-ph with Neutral	Cost:	803UGX/kWh, rcv; 0UGX/kWh, dlv
Start date:	23/10/2024 08:59:04	End date:	23/10/2024 15:01:02		
Duration:	6h 1m 58s				
Demand interval:	5min	Number of demand intervals:	74		* ... series contained partial intervals that have been discarded.

Cost of Energy

Active energy, forward	644.2 Wh	Cost of Energy: standard (selected) / advanced
Active energy, reverse	0.0 Wh	
Total active energy	644.2 Wh	Total energy cost: UGX517.275†
Max. demand	464.2* W 23/10/2024 09:05:00	

Demand interval:

	Configured Interval length
R410A-23	5min

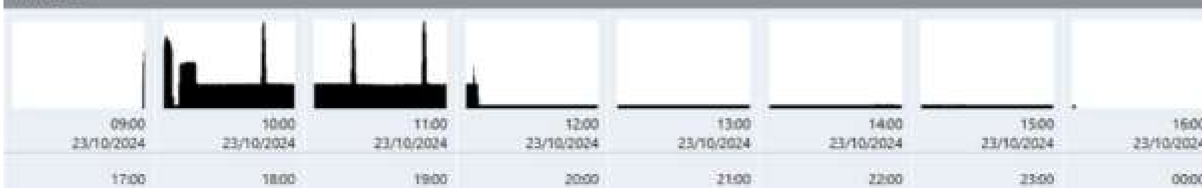
Figure A 35: R-410A AC system demand overview table for 23rd October 2024

20/03/2025 15:32:18

FLUKE

Calendar overview table

R410A-23



Averaging interval:

	Configured Interval length
R410A-23	5sec

Figure A 36: R-410A AC system calendar overview table for 23rd October 2024

APPENDIX B

Temperature Tracking of R-290 and R-410A Air Conditioner Systems

This appendix presents details of temperature logged across the duration of the experiment.

Table B 1: Temperature readings for R-290 and R-410A AC systems on 18th October 2024

Time (Hrs)	Outdoor Ambient Temperature(°C)	Room Temperature (R-290) (°C)	Room Temperature (R-410A) (°C)	Set Room Temperature (°C)
08:55	22.5	24.1	24.3	26
09:30	25.2	24.1	24.5	26
10:00	25.2	24.5	25	26
10:30	25.5	24.9	24.3	26
11:00	25.8	23.2	25.1	26
11:30	25.5	23.5	23.6	24
12:00	26.5	23	23.4	24
12:30	27.2	23.5	23.6	24
13:00	27.9	23.5	24.4	24
13:30	27.4	22.3	23.1	22
14:00	26.5	22.5	23.2	22
14:30	25.4	22.6	22.9	22
15:00	21	22.1	23	22

Table B 2: Temperature readings for R-290 and R-410A AC systems on 19th October 2024

Time (Hrs)	Outdoor Ambient Temperature(°C)	Room Temperature (R-290) (°C)	Room Temperature (R-410A) (°C)	Set Room Temperature (°C)
08:55	22.6	23.5	23.7	26
09:30	23.7	23.8	24.1	26
10:00	27.9	24.1	24.7	26
10:30	26.2	24.6	25.1	26
11:00	26.9	24.3	23.8	26
11:30	27.5	22.4	24	24
12:00	28	23.8	23.9	24
12:30	28.1	26.1	26.5	24
13:00	28.2	22.4	24.3	24
13:30	26.6	22.1	23.7	22
14:00	24.9	22.2	23.3	22
14:30	27.2	22.2	23.7	22
15:00	28.6	22.5	24.5	22

Table B 3: Temperature readings for R-290 and R-410A AC systems on 20th October 2024

Time (Hrs)	Outdoor Ambient Temperature (°C)	Room Temperature (R-290) (°C)	Room Temperature (R-410A) (°C)	Set Room Temperature (°C)
08:55	21.8	24.3	24.6	26
09:30	23	24.3	24.7	26
10:00	26.2	24.5	25.1	26
10:30	27.2	25	23.8	26
11:00	27.2	23.5	25.3	26
11:30	28.2	23.5	24.1	24
12:00	28.8	23.1	24.1	24
12:30	28.6	23	24	24
13:00	26.9	24.8	23.9	24
13:30	22.6	21.9	23.1	22
14:00	20	21.9	23.1	22
14:30	15.4	21.4	22.7	22
15:00	20	21.2	22.5	22

Table B 4: Temperature readings for R-290 and R-410A AC systems on 21st October 2024

Time (Hrs)	Outdoor Ambient Temperature (°C)	Room Temperature (R-290) (°C)	Room Temperature (R-410A) (°C)	Set Room Temperature (°C)
08:55	21.4	24	24.2	22
09:30	22.3	20.8	22	22
10:00	22.6	20.9	21.6	22
10:30	23.7	20.9	21.9	22
11:00	25	22.7	21.9	22
11:30	25.8	23.6	24.1	24
12:00	26.5	22.9	24.1	24
12:30	27.5	23.8	23.5	24
13:00	26.1	23.1	24.1	24
13:30	27.5	24.7	25.2	26
14:00	27.2	24.7	25.9	26
14:30	23.4	25.8	26.3	26
15:00	24	23.9	26.3	26

Table B 5: Temperature readings for R-290 and R-410A AC systems on 22nd October 2024

Time (Hrs)	Outdoor Ambient Temperature (°C)	Room Temperature (R-290) (°C)	Room Temperature (R-410A) (°C)	Set Room Temperature (°C)
08:55	23	24.1	24.5	22
09:30	24.1	21.1	22.2	22
10:00	25.5	21.2	22.1	22
10:30	26.5	21.2	22.3	22
11:00	28.1	22.5	22.3	22
11:30	28.4	24.5	24.9	24
12:00	27.5	25.2	25.8	24
12:30	26.5	25.8	26.2	24
13:00	27.7	26	26.1	24
13:30	25.3	26.2	26.1	26
14:00	28.2	26.3	26.6	26
14:30	29.4	26.7	27.1	26
15:00	28.3	27.1	27.4	26

Table B 6: Temperature readings for R-290 and R-410A AC systems on 23rd October 2024

Time (Hrs)	Outdoor Ambient Temperature (°C)	Room Temperature (R-290) (°C)	Room Temperature (R-410A) (°C)	Set Room Temperature (°C)
08:55	21.4	24.6	24.8	22
09:30	21	22.4	22.4	22
10:00	22.6	21.6	22.1	22
10:30	22.4	21.3	21.9	22
11:00	23	21.2	21.8	22
11:30	25.5	26.4	23.7	24
12:00	26.6	22.3	24.6	24
12:30	26.5	24.2	25.3	24
13:00	27.5	25.1	25.8	24
13:30	26.9	25.7	26.2	26
14:00	28.7	26	26.5	26
14:30	27.3	26.3	26.9	26
15:00	27.5	26.5	27.2	26