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Air Conditioning Technologies and Applications

Edited by Muhammad Sultan, Zhaoli Zhang, Muhammad Wakil Shahzad, Muhammad Farooq and Uzair Sajjad

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Meet the editors

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Dr. Uzair Sajjad is a postdoctoral fellow at the Interdisciplinary Research Center of Sustainable Energy Systems at King Fahd University of Petroleum and Minerals. Previously, he worked as a Research Assistant Professor at the Department of Energy and Refrigerating Air-Conditioning Engineering at the National Taipei University of Technology in Taiwan for two and a half years. He completed his Ph.D. at National Chiao Tung University Taiwan and, for his research excellence, was awarded two science and technology awards by CTCI Taiwan. He is investigating different topics of heat transfer, energy, machine learning and artificial intelligence applications, surface engineering, heat pump and vacuum freeze-drying, and additive manufacturing. He has won 3.5 million NTD grants from the National Science and Technology Council (NSTC) in Taiwan, China. He has published over 80 SCI articles and book chapters in these areas. Besides, he has served as a reviewer and guest editor for many well-reputed journals.

Contents

Preface

Air conditioning has evolved from a mere luxury to a necessity, playing an indispensable role in enhancing the quality of life and supporting modern lifestyles. As the global community faces mounting challenges posed by climate change, energy scarcity, and environmental degradation, air conditioning technologies must rise to the occasion with sustainable, efficient, and innovative solutions. This book, *Air Conditioning Technologies and Applications*, endeavours to capture the essence of these advancements, showcasing the potential of cutting-edge research and applications to redefine the future of climate control.

The compilation of chapters reflects the diverse yet interconnected dimensions of contemporary air conditioning research. The contributions in this volume provide fresh perspectives and actionable insights into key technological and material innovations, sustainable practices, and energy-efficient solutions. Dedicated researchers have authored each chapter in their respective fields, ensuring a blend of academic rigour and practical relevance.

The book opens with "Study on Evaporative Cooling Assisted Temperature and Humidity Control Systems for Greenhouse Farming in Pakistan". This chapter sheds light on the adaptation of air conditioning technologies for agricultural applications, particularly in the context of greenhouse farming. Addressing the unique climatic challenges of Pakistan demonstrates how innovative evaporative cooling techniques can promote sustainable farming practices.

In the chapter on "Sea Water Air Conditioning (SWAC) Technology: Performance and Worldwide Potential", readers are introduced to an exciting, eco-friendly alternative for cooling systems. This chapter explores the mechanics and benefits of leveraging oceanic resources to meet cooling demands and discusses the global potential of SWAC as a sustainable air conditioning solution.

The chapter on "Advancements in Materials Used in Air Conditioning Technologies" comprehensively reviews the material innovations driving air conditioning systems forward. From advanced refrigerants to novel thermal insulators, this chapter emphasizes the pivotal role of materials in enhancing system performance, energy efficiency, and environmental compatibility.

The concept of localized cooling takes centre stage in the chapter "Localized Air Conditioning Can Enable Zero-Energy Buildings in South Asia". This chapter examines the feasibility and benefits of integrating targeted air conditioning systems into building designs, offering a pathway toward energy self-sufficiency and sustainability in one of the world's most populous regions.

In the chapter on "Heat Pipe Heat Exchangers for Air-Conditioning Applications", readers gain insights into the potential of heat pipe technology to optimize air conditioning systems. This chapter delves into the principles, design considerations, and applications of heat pipe heat exchangers, demonstrating their ability to improve thermal efficiency and reduce energy consumption.

The final chapter, "Comparative Exergetic Assessment for the Modernization of Synthetic Fluids by Natural Refrigerants Used in Residential and Commercial Cooling and Air Conditioning Applications", critically evaluates the transition from synthetic to natural refrigerants. It highlights the environmental and thermodynamic advantages of natural refrigerants, offering a clear roadmap for modernizing air conditioning systems in both residential and commercial contexts.

Through these six chapters, this book, *Air Conditioning Technologies and Applications*, aims to serve as a valuable resource for academics, researchers, and industry professionals striving to address the pressing challenges of our time. By showcasing innovative strategies, sustainable practices, and emerging technologies, this book contributes to the ongoing dialogue on how air conditioning can evolve into a greener, smarter, and more efficient domain.

As the editors of this book, we express our deepest gratitude to the authors for their insightful contributions, the reviewers for their constructive feedback, and the publishing team for their dedication to bringing this vision to life. We hope this volume inspires readers to push the boundaries of innovation and sustainability in air conditioning technologies and applications.

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Chapter 1

Study on Evaporative Cooling Assisted Temperature and Humidity Control Systems for Greenhouse Farming in Pakistan

Nadia Riaz, Muhammad Sultan, Hadeed Ashraf, Muhammad Hamid Mahmood, Fiaz Ahmad, Muhammad Usman Khan, Muhammad Farooq, Uzair Sajjad, Muhammad Wakil Shahzad and Zhaoli Zhang

Abstract

Evaporative cooling systems have evolved as highly effective greenhouse-control solutions, particularly in hot and dry places such as Multan, Pakistan. This chapter evaluates the performance of direct (DEC) and indirect evaporative cooling systems (IEC) for an asymmetric greenhouse using TRNSYS software. The performance of the systems was assessed in terms of simulated ideal vapor pressure deficit (VPD), temperature, and humidity for tomato cultivation. According to the results, the DEC system effectively reduced the temperature, while the IEC system effectively managed the humidity. The DEC system showed maximum energy saving of up to 40% in hot and dry months. The combination of both DEC and IEC systems produced the optimum level of temperature and humidity for increased tomato output, energy savings, and water usage efficiency. A higher (up to 0.35 kg/h) evapotranspiration mass flow rate was observed in the middle of the year in the case of the second and fourth system configurations. Findings from this study highlight the need for sustainable, energy-efficient cooling methods for greenhouse agriculture.

Keywords: evaporative cooling, asymmetric design, energy efficiency, TRNSYS, greenhouse simulation

1. Introduction

Pakistan's environmental issues have led to the rise of greenhouse agriculture as a key solution, especially in areas like Multan where high summertime temperatures significantly limit agricultural productivity. About 42.3% of the labor force is employed in Pakistan's agriculture sector, which generates 18.9% of the country's Gross Domestic Product (GDP) [1]. Nevertheless, the country's semi-arid and dry areas have extended hot weather and insufficient rainfall, which causes conventional open-field farming to be incredibly ineffective. To guarantee year-round crop growth and better yields, farmers in these areas can manage the temperature, humidity, and light in greenhouses [2].

The agricultural sector in Pakistan has been influenced by the introduction of greenhouse agriculture, especially for high-value crops like tomatoes, cucumbers, and peppers. By reducing the impact of extraneous environmental stresses, greenhouses provide longer growing seasons, higher crop yields, and better-quality crops. Nevertheless, it costs money to keep greenhouses at optimal inside temperatures, particularly in places like Multan where summertime highs may reach 45°C. While typical air conditioning systems are effective, they are expensive to operate and unfeasible for small- to medium-sized farms due to the significant energy required to maintain interior cooling [3].

Figure 1 shows that the agricultural industry is Punjab's third-largest user of electricity, emphasizing the high energy demands of greenhouse activities in the province. The high energy cost impedes the widespread adoption of greenhouses, particularly in rural regions where electricity rates are rapidly increasing.

Given these constraints, using energy-efficient cooling technology is vital to guaranteeing the long-term viability of greenhouse agriculture in Pakistan. Evaporative cooling systems, notably direct evaporative cooling (DEC) and indirect evaporative cooling (IEC), present a viable approach for lowering energy usage while preserving ideal growth conditions [4–6].

1.1 Energy consumption for greenhouse cooling systems

Maintaining the confined environment of a greenhouse is critical for crop development, especially in areas where exterior temperatures often reach 40°C during the summer months. Cooling is required to reduce heat stress and promote crop growth, yet the energy consumption associated with cooling is one of the major expenses for greenhouse operators. Traditional air conditioning systems use vapor-compression refrigeration cycles, which demand power to keep the correct interior temperature

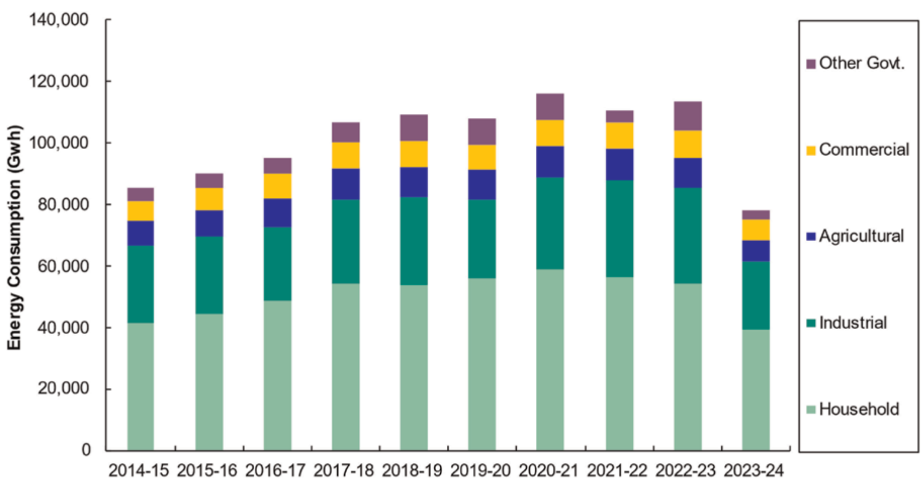

Figure 1.
Sector-wise electricity consumption in Pakistan. Data are obtained from the Pakistan Economic Survey, available online at https://finance.gov.pk/survey_2024.html.

Types	Performance	Advantages	Locations	Limitation	Ref.
Indirect–direct evaporative cooling (IDEC) unit using groundwater	Higher cooling efficiency as compared to the direct evaporative cooler	Water saving	Iraq	Dependent on the groundwater availability	[10]
Fan and Pad systems	Decrease in water temperature of 3°C, and increase in the RH to 100%	Energy saving and freshwater production	Oman	N/A	[11]
	Decrease in temperature to 27–29°C	Energy saving and easily adjustable	Shanghai	Not sufficient in humid climates, and it is necessary to add shading	[12]
Fan and pad evaporative cooling system	Cooling efficiency up to 90%	Low energy consumption	Sudan	The short life cycle of the pads	[13]

Table 1.
Performance comparison of different evaporative cooling systems.

and humidity levels [3]. This is especially true in dry areas like Multan, where outside temperatures are high, and the cooling load is substantial.

Direct evaporative cooling (DEC) systems work on the principle of allowing hot air to pass through the water-saturated pads, which in return cools the air as the water evaporates. Similarly, the greenhouse's interior temperature is decreased by passing the cooled air around, which eliminates the need for energy-intensive compressors or refrigerants. Because of the increased evaporation and resulting in cooling in dry conditions with low relative humidity, this system performs best there [7]. In contrast, systems that use indirect evaporative cooling (IEC) employ a heat exchanger to chill the air without introducing more moisture. IEC is therefore better suited for areas with greater relative humidity as it keeps too much moisture out of the greenhouse environment [8]. Both DEC and IEC systems have been extensively utilized in greenhouse operations across the globe as part of strategies for reducing operating cooling costs. Nevertheless, the efficiency of these systems is primarily dependent on the ambient temperature, greenhouse design, and crop cooling needs [9]. A performance comparison of different evaporative cooling systems is given in **Table 1**.

In view of the literature, there exists a gap in localized studies on temperature and humidity management of asymmetric greenhouses for regionalized crops such as tomatoes. Tomatoes perish quickly during cultivation as well as post-harvest stage if the temperature and humidity are not maintained. Therefore, this chapter investigates the performance of direct and indirect evaporative cooling systems and their combinations for asymmetric greenhouse air conditioning, focusing on the tomato crop. The study was conducted under climatic conditions of Multan, Pakistan.

2. Evaporative cooling systems

As climate change keeps altering weather patterns throughout, the need for sustainable agriculture techniques becomes increasingly important. In arid and semi-arid regions such as Pakistan, where water is scarce and temperatures are rising,

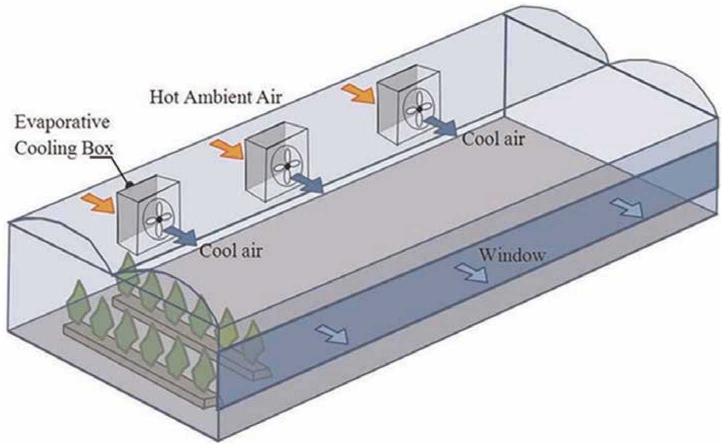

Figure 2.
A schematic representation of the conventional direct evaporative cooling system in the greenhouse [3].

greenhouses equipped with energy-efficient cooling technology are critical to guaranteeing food security. Evaporative cooling systems (as shown in **Figure 2**), notably DEC and IEC, provide a sustainable alternative to typical air conditioning systems by reducing energy consumption while maintaining ideal interior conditions for crop development [3, 14].

The deployment of direct and indirect evaporative cooling systems in an asymmetric greenhouse in Multan is the primary focus of this chapter. The efficacy of these cooling systems will be assessed in terms of energy consumption, cooling efficiency, and effect on crop yield using TRNSYS, a simulation program that simulates the thermal dynamics of buildings and structures.

3. Materials and methods

3.1 Greenhouse location and climate

The dynamic simulation in this study was performed for a greenhouse in Multan, Pakistan (30.2609°N, 71.5121°E). According to the Köppen-Geiger classification, this region has a BWh climate characterized by tropical and subtropical desert conditions. Multan, located in the southern part of Pakistan's Punjab region, has an arid setting with sweltering summers and winters. The location receives little rainfall all year, resulting in a deserted environment [15]. **Figure 3** presents the schematics of greenhouse under study with evaporative cooling systems and tomato crops, modeled in SketchUp.

Multan has 25.6°C average annual temperature and 175 mm of yearly rainfall. Daily weather data for the following parameters were utilized to model actual conditions at this location: relative humidity, humidity ratio, enthalpy, dry bulb temperature, wet bulb temperature, and dew point temperature. The data was essential for simulating the greenhouse's thermal activity and assessing the cooling systems' effectiveness in common climatic conditions.

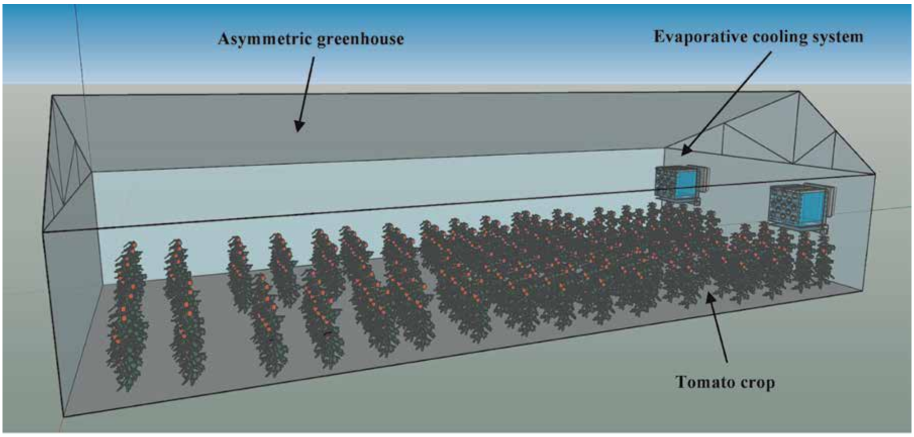

Figure 3.
The schematics of the greenhouse under study with evaporative cooling systems and tomato, modeled in SketchUp.

3.2 Modeling for building energy simulation (BES)

The tomato crop was grown in the greenhouse utilized for this study, and it was designed as a single-span structure with a total floor area of 300 m^2. TRNSYS 18 [16, 17] was utilized for the implementation of simulation and modeling owing to its modular and adaptable building construction. By linking a series of default "*Types*" from its library within the Simulation Studio interface, this software facilitates dynamic simulations.

Using the run simulation command, the simulation begins once all required connections are made. **Figure 4** presents a flow chart offers an understanding of the steps that follow modeling and calculating. Considering the simulation's output based on hourly calculations, the greenhouse's thermal behavior could be accurately represented daily.

3.3 Greenhouse 3D model and design

As the model was produced, it was imported into TRNBuild [16, 17], where different parameters were established, such as the orientation of the greenhouse and the envelope's thermophysical characteristics.

The walls, windows, and structural components of the greenhouse were specified in this chapter using real-world characteristics. The dimensions and material properties of the model are presented in **Table 2**. These metrics comprised wall layers, the materials' optical qualities, and their thermal characteristics were applied to create the greenhouse. TRNFlow software [16, 17] was used to estimate the air-mass exchanges within the greenhouse, allowing for natural ventilation and vents. The air node temperatures, which were obtained by building a thermal network in TRNBuild, were used by TRNFlow to calculate air flow exchanges.

3.4 Heat transfer and solar radiation

The internal environmental conditions and variations in the external climate have a significant impact on the thermodynamic characteristics of the greenhouse. The solar radiation that penetrates the greenhouse through its glass walls constitutes

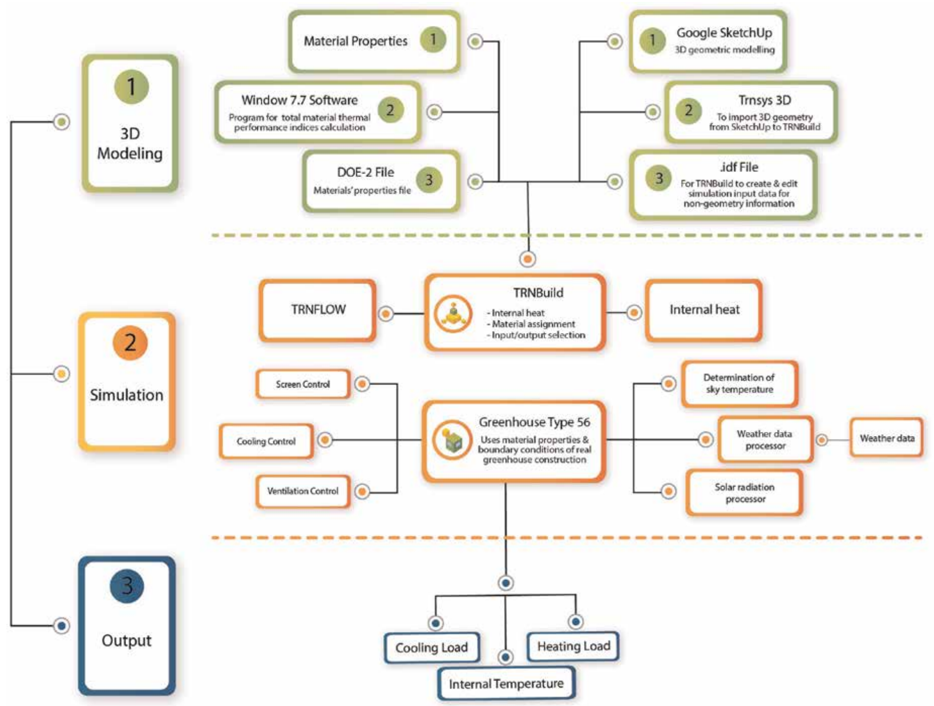

Figure 4.
The TRNSYS modeling and simulation approaches are depicted.

Material	Component	Density (kg/m^3)	Thermal capacity (kJ/kg K)	Resistance (h m^2 K/kJ)	Thermal conductivity (kJ/ h m^2 K)
Vegetation	Ground floor	N/A	N/A	2.348	N/A
Glaze 1001	External window	2900	0.75	N/A	1.2
Steel	External wall	7800	1.8	N/A	54
Ground	Ground floor	1210	1.3075	N/A	0.972

Table 2.
The greenhouse model's geometric dimensions and material characteristics.

variables determining its interior climate. Internal temperatures are significantly influenced by solar radiation, which was considered while modeling the impact using data on both diffused and direct radiation. Hourly observations were used to thoroughly investigate these data to recreate realistic interactions between solar radiation and the greenhouse's environment.

The dynamics of natural ventilation and convective heat transfer coefficients were modeled with time-varying parameters that accounted for the large variations in interior temperature caused by solar radiation. In addition, heat stratification resulted from the greenhouse's large interior volume, which was represented both horizontally and vertically. Evapotranspiration, or the release of water vapor from plants and soil that results in the emission of latent energy, was also modeled in the study.

3.5 Model specifications and TRNSYS software integration

Following the specification of the geometric and thermal characteristics, the TRNSYS program was used to dynamically simulate the greenhouse model. The airflow network produced by TRNFlow, which made it possible to calculate the air flow exchanges through the greenhouse's apertures, was one of the important factors considered. The developed simulation mechanism used thermal nodes, airflow, and thermal networks to iteratively solve the numerical simulation at every time step. **Figure 5** shows the connections among the components and types in the TRNSYS simulation studio.

The internal temperature variations were significantly impacted by the realistic simulation of thermal stratification made possible by the 3D geometric modeling technique. The penetration and ventilation rates via the windows and doors were taken into consideration while modeling the greenhouse's natural ventilation using TRNFlow.

3.6 Window design and heat transfer coefficients

Windows play a crucial role in the thermal performance of the greenhouse. Their size, positioning, and shading systems have a significant impact on the overall energy

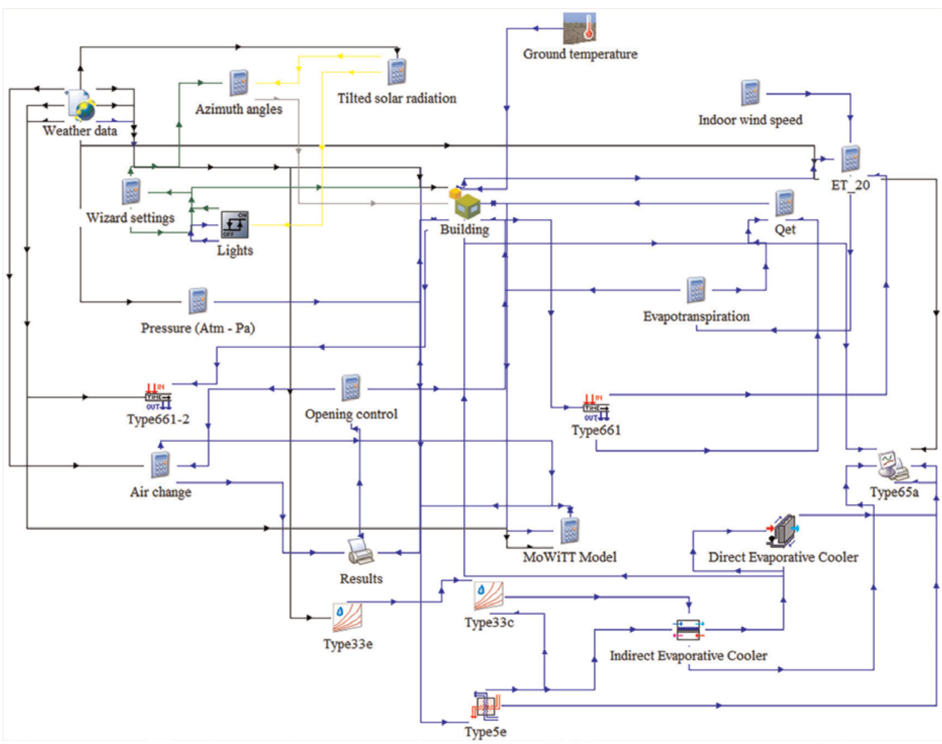

Figure 5.
Greenhouse scheme in TRNSYS simulation studio.

efficiency of the structure. In this simulation, SketchUp Pro 2021 was used to create the geometric model of the greenhouse, with TRNBuild being used to specify the material and thermophysical properties of the windows.

The inclination and orientation of the surface served as the basis for calculating the convective heat transfer coefficients for both the interior and exterior surfaces. Applying the MoWiTT approach, which takes wind speed and temperature variations in the outside surface and air into consideration, the convective heat transfer coefficient (h_{ce}) for external walls was determined [18]. Heat losses through the glass surfaces of the greenhouse were calculated using this model, which was incorporated into the TRNSYS environment.

3.7 Material properties of the greenhouse

Steel was used for the greenhouse's exterior walls, while glass was used for the covering envelope. As indicated in **Table 2**, the selection of these materials was based on their thermal conductivity, density, and thermal capacity. The thermophysical characteristics of the materials used in greenhouses are listed in detail in **Table 3**.

3.8 Internal heat gains and evapotranspiration

Models of internal heat gains from illumination and evapotranspiration were created using empirical techniques that have been refined over the past few decades. In this work, the FAO Penman-Monteith equation was employed to determine the evapotranspiration rate within the greenhouse [19, 20].

3.9 Cooling system configuration

The greenhouse's cooling system was comprised of two types of evaporative coolers: direct and indirect. Together, these systems prepped the outside hot air for admittance through the greenhouse. The entering air was pre-cooled by the cooling coil, lowering the wet and dry bulb temperature of the air. The ASHRAE standards were utilized to assess the cooling system's effectiveness. These criteria gauge how evaporative cooling devices reduce air temperatures and maintain subsequent humidity levels [21]. The following Eqs. (1) and (2) were used to determine the cooling system's wet-bulb efficiency (ε_{wb}).

$$\varepsilon_{wb} = \frac{t_{p,DBT,i} - t_{p.DBT,o}}{t_{p,DBT,i} - t_{p.WBT,i}} \tag{1}$$

$$Q_T = c_p m_p \left(t_{p,DBT,i} - t_{p,DBT,o}\right) \tag{2}$$

The IDEC's coefficient of performance is given by Eq. (3) [22, 23].

$$COP = \frac{Q_T}{W_{in}} \tag{3}$$

The calculation of the outlet dry bulb temperature of air for the direct evaporative cooling is performed as shown in Eq. 4 [22, 23].

$$T_{DBT,o} = T_{DBT,i} - \varepsilon_{wb}(T_{DBT,i} - T_{WBT,i}) \tag{4}$$

Component	Type	Description
Weather data processor	15	This module regularly extracts information from an external meteorological data file and interpolates it, including solar radiation estimates for tilted surfaces, at intervals of less than 1 hour. These data is then available to other TRNSYS components.
Soil temperature profile	77	This program simulates ground vertical temperature distribution using different input parameters.
Multi-zone building	56	This module models multi-zone building thermal dynamics. The model receives its attributes and layout from a building description file. The preprocessor TRNBuild created this file.
On/off differential controller	2	The on/off differential controller generates a one or zero control function. A comparison of the temperature differential (T_h - T_l) and two predefined dead band temperature differences determines this control signal's value.
Delayed output device	661	This component replicates a "sticky" controller using inputs from a former time step.
Online graphical plotter with output file	65	The online graphics component displays system variables in real time throughout the simulation.
Print-on-demand printer	535	The triggered event printer outputs system variables. This component generates output when the first input exceeds one instead of time-based intervals.
Psychrometrics	33c & 33e	This component takes dry bulb temperature and moist air humidity ratio inputs. After that, it calculates using TRNSYS Psychrometrics.
		This component takes dry bulb temperature and moist air relative humidity. It then utilizes TRNSYS Psychrometrics for the computation.
Heat exchanger	5	Different arrangements of zero capacitance sensible heat exchangers are calculated and modeled.
Indirect evaporative cooler	757	Type757 is an evaporative cooling system that requires inputs for main and secondary air stream intake air characteristics and efficacy.
Evaporative cooling device	506	An evaporative cooling device cools incoming air by directing it over or through a wet surface. Air temperature drops when water evaporates from the surface.

Table 3.
Thermophysical characteristics of the materials used to construct the greenhouse.

To lessen the cooling load, the air that flows from the system's exhaust is supplied into the greenhouse. The performance of the indirect evaporative cooling system is assessed using the ASHRAE guidelines [23, 24].

4. Results and discussion

4.1 Cooling performance of DEC and IEC systems

TRNSYS modeling software assessed the cooling efficiency of the DEC and IEC systems throughout a full growing season. The principal aim was to sustain the greenhouse's interior temperature between 20 and 25°C, which is the ideal range for tomato development, while also guaranteeing that the relative humidity stayed between 60 and 70%. These systems' performance was evaluated in a range of external climate conditions, from the normal June heatwave and dryness to the more humid August conditions.

The DEC system showed high cooling efficiency, especially in May and June when outside temperatures often rose over 45°C. The interior temperature remained well within the ideal range for tomato growing during these months attributable to the DEC system's ability to lower it by up to 15°C [25, 26]. The low outside humidity, which increased the rate at which water evaporated from the cooling pads, is primarily responsible for this performance. During these dry months, the DEC system continuously reduced temperatures faster than the IEC system. **Figure 6** illustrates the working principles of DEC and IEC. This resulted in a steady interior climate favorable to optimal crop development.

The rapid evaporation rate, maximized under dry circumstances, is responsible for the DEC system's efficiency. The water-saturated cooling pads extract a substantial quantity of heat from the air to swiftly cool the hot, dry air entering the greenhouse. The temperature inside the greenhouse is then maintained by circulating the cooled air in space. However, according to the findings presented in **Figures 7** and **8**, due to the less chance of evaporation during the humid months, the DEC system's cooling effectiveness marginally declined [7].

Considering the DEC system's dependence on wet-bulb effectiveness, which may reach values of 0.9 under certain circumstances, it functions ideally under dry conditions [8]. Nevertheless, due to the decreased evaporation potential caused by the high moisture content of the outside air during the wet months, its cooling efficiency decreased. During these months, the temperature inside the greenhouse reached 30°C at peak hours.

Even though the IEC system showed a satisfactory performance, it was more appropriate for the humid months of July and August when the relative humidity

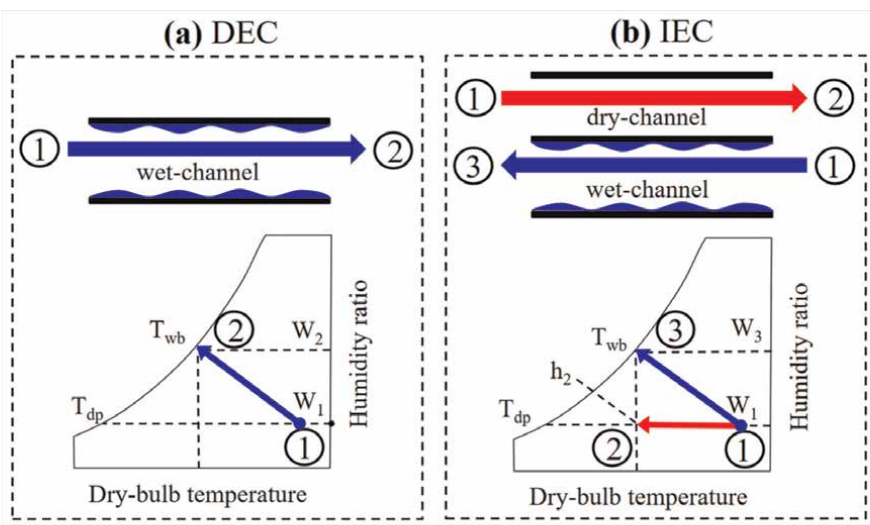

Figure 6.
Schematics of evaporative cooling systems (a) direct evaporative cooling system, (b) indirect evaporative cooling system [27].

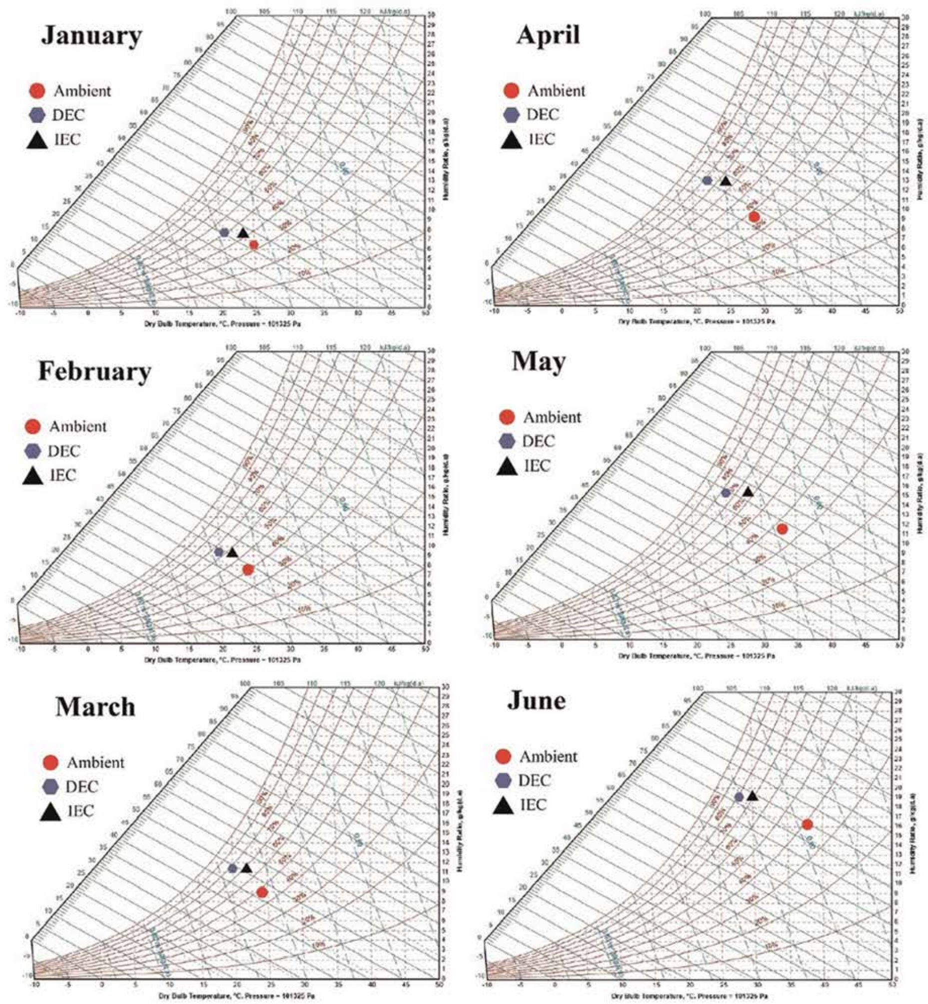

Figure 7.
Psychrometric representation of performance (Tdb, RH, and enthalpy) of DEC, and IEC systems for greenhouse air conditioning for the climatic conditions of Multan (Pakistan) for January–June.

outside rose. The IEC system cools the air without adding moisture, unlike the DEC system, which does the opposite. This makes it more suitable for conditions where excessive humidity may normally promote the growth of mold or fungi that infect crops. Throughout these months, the IEC system kept the inside temperature constant at about 22°C, protecting the crops from excessive moisture [3].

In general, the IEC system performed better in humid months while the DEC system offered improved cooling during dry months. This suggests that combining the two systems might be advantageous for year-round temperature management in greenhouses.

4.2 Energy efficiency of cooling systems

This research imposed a strong emphasis on energy efficiency, with both cooling systems displaying different amounts of energy use depending on the external

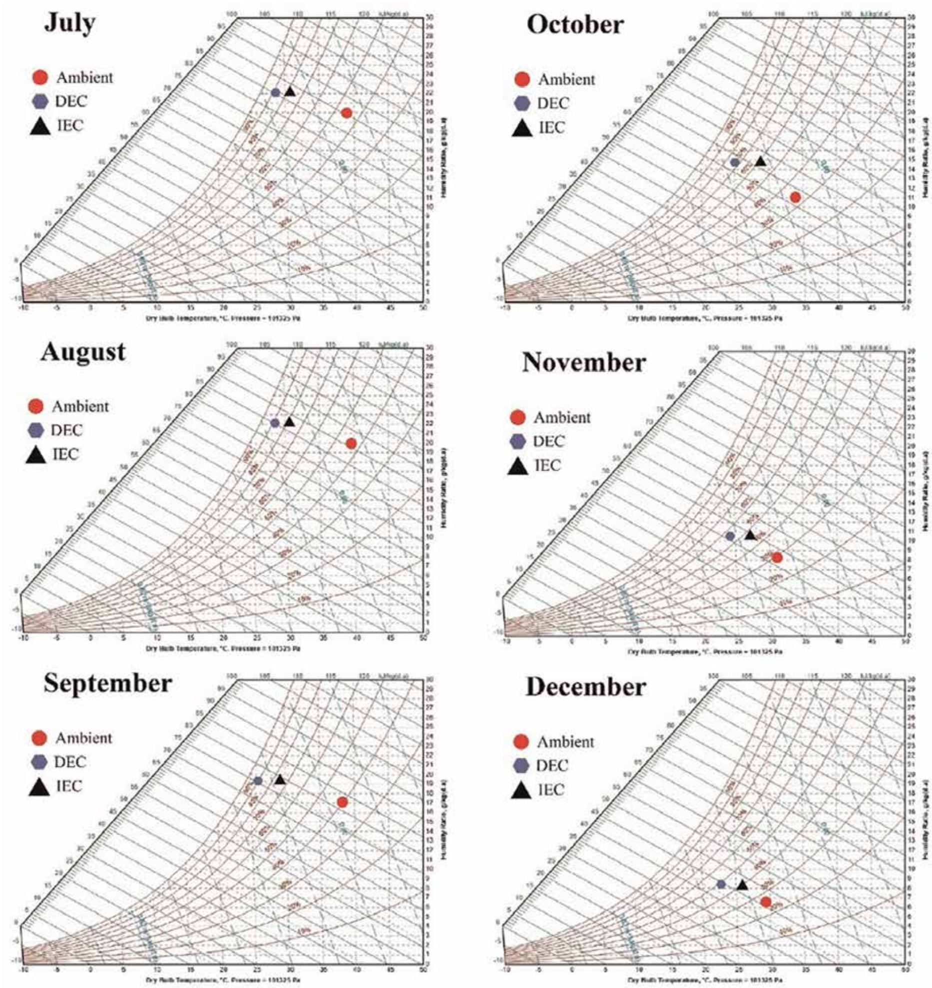

Figure 8.
Psychrometric representation of performance (Tdb, RH, and enthalpy) of DEC, and IEC systems for greenhouse air conditioning for the climatic conditions of Multan (Pakistan) for July–December.

temperature. When compared to conventional air conditioning systems as shown in **Figure 9**, the DEC system showed notable energy savings, especially in the dry months of May and June, when energy usage was as much as 40% lower [28]. This was explained by the dry season's high evaporation rate, which made it possible for the DEC system to maintain ideal cooling with minimal power input.

Nevertheless, the DEC system's energy efficiency decreased in the humid months of July and August since the system had to use more energy to maintain the appropriate temperature due to the reduced evaporation potential in such environments. During these months, the energy efficiency ratio (EER) decreased to 17.8, which was lower than 37.32 in the dry months [7].

On the other hand, the IEC system used less energy during the humid months since it did not add extra moisture to the greenhouse, which reduced the requirement for energy-intensive dehumidification. In addition to this, the IEC system was able to operate consistently with minimal energy consumption, particularly during the

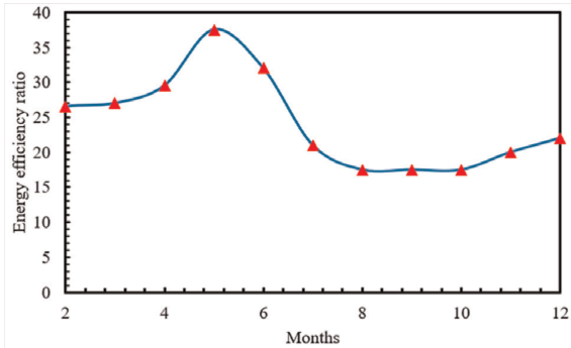

Figure 9.
Graphical representation of energy efficiency ratio of DEC and IEC systems.

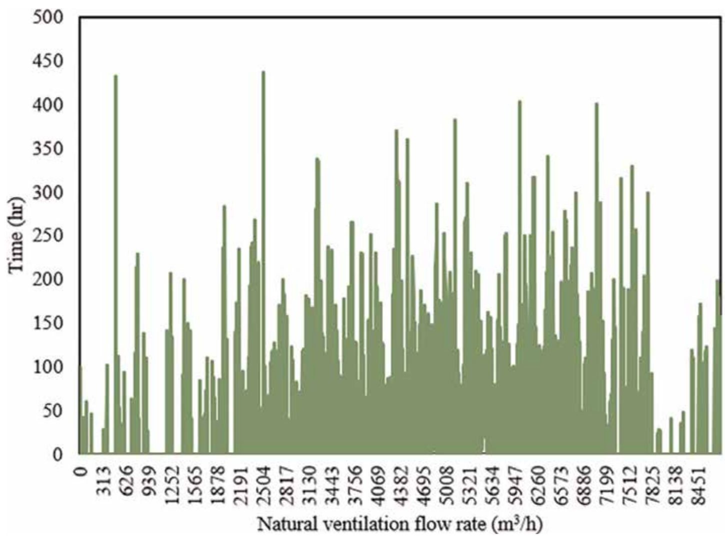

Figure 10.
The natural ventilation flow rate on a yearly basis.

monsoon season when ambient humidity was high [3]. The IEC system's ability to regulate interior climate with limited energy usage has been demonstrated by the energy savings it offers during the humid months.

4.3 Impact of ventilation on cooling efficiency

Figure 10 presents the natural ventilation flow rate on a yearly basis. In addition, **Figure 11** presents an overview of the impact of glazing material, infiltration rate and nighttime heat loss in greenhouse farming. In addition, the costs of heat distribution and supplementary lighting are the primary factors that contribute to lower greenhouse energy utilization. Improving the cooling efficiency of DEC and IEC systems depends heavily on ventilation. Ridge vents and sidewall vents, two natural ventilation elements included in the greenhouse's design, permit air movement around the structure. By allowing hot air to escape via the vents and cooler air to penetrate

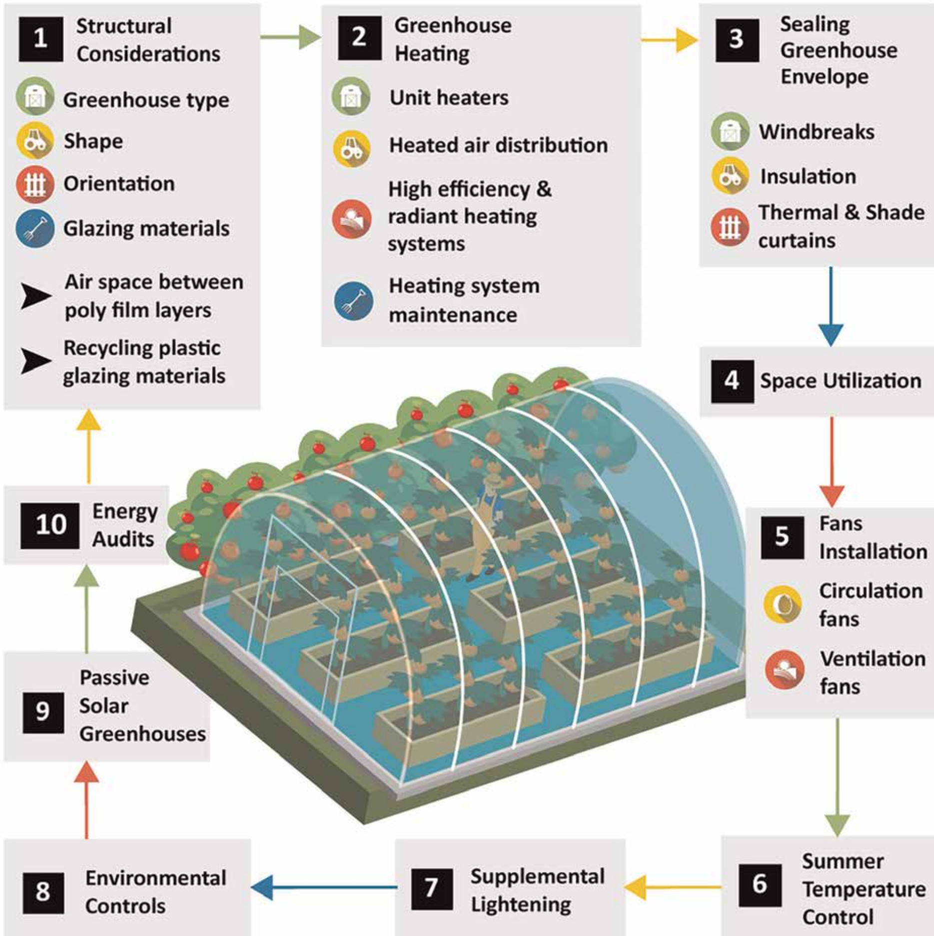

Figure 11.
The impacts of glazing materials, a decrease in infiltration and nighttime heating losses, the impact of heat distribution on heating costs, and the use of supplementary lighting to lower energy requirements are the primary factors that contribute to lowering greenhouse energy use.

through the sidewalls, natural ventilation lowered the interior temperature and eliminated the need for mechanical cooling systems [2].

The temperature differential between both indoor and outdoor environments, together with the external wind speeds, was used to determine the convective heat transfer coefficients. The natural ventilation system contributed to a further layer of passive cooling by assisting in lowering the inside temperature during the summer months when outside temperatures were high. Nevertheless, in winter, when solar radiation was low and interior temperature fluctuations were more pronounced, natural ventilation proved less effective [7].

4.4 Microclimate management and evapotranspiration

The natural phenomenon of evapotranspiration and the cooling systems had a significant impact on the microclimate of the greenhouse. Evapotranspiration is the term used to describe the combined process of water evaporation from the soil and transpiration from the plants. The process is important for controlling the greenhouse's internal temperature and humidity. **Figure 12** summarizes the effects of combination of the systems on the evapotranspiration and the control of greenhouse temperature and humidity.

The evapotranspiration rates inside the greenhouse were modeled using the FAO Penman-Monteith equation, which enabled the simulation to take into consideration the latent heat exchange that resulted from plant transpiration [19]. This model demonstrated how evapotranspiration may lessen the greenhouse's cooling demand since the plants' latent heat absorption aided with internal cooling. Lower energy consumption and stable interior temperatures were the results of evapotranspiration and convective heat transfer combined [3]. The evapotranspiration power, calculated

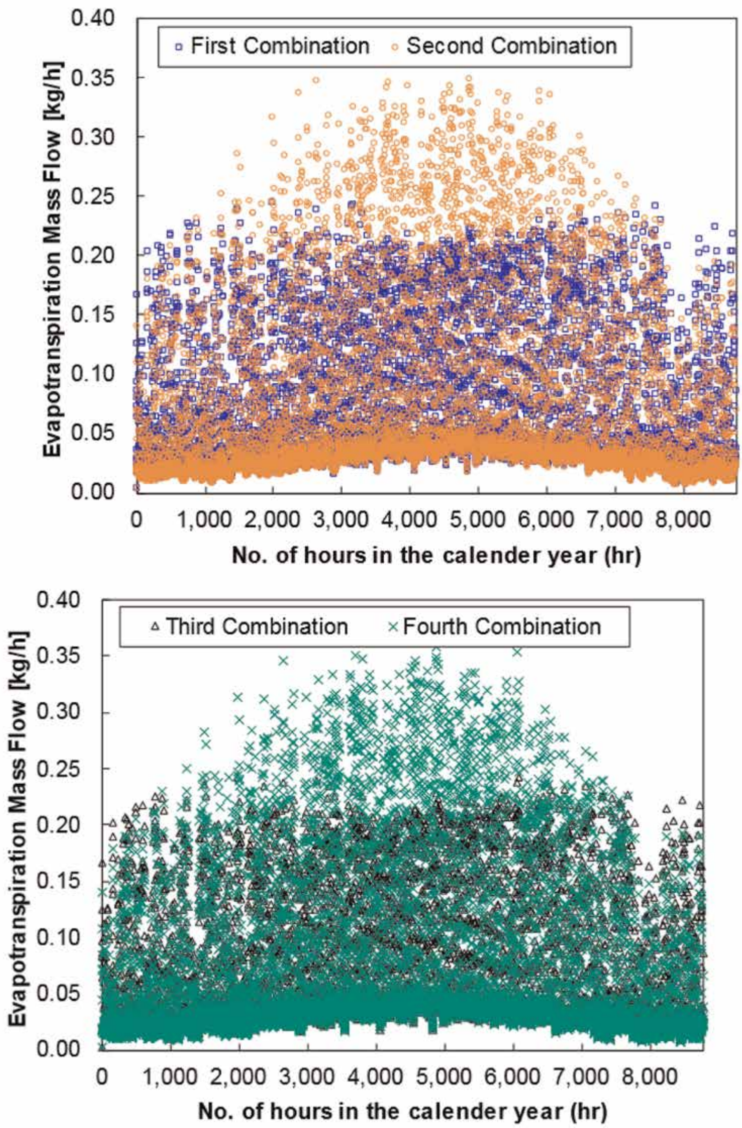

Figure 12.
The summarized effects of evapotranspiration on the control of greenhouse temperature and humidity.

with the Penman-Monteith model, is directly influenced by the internal air temperature and solar radiation inside the greenhouse and ranges between 2 and 174 W.

5. Conclusions

The present study investigates the thermodynamic performance of direct (DEC) and indirect evaporative cooling (IEC) systems for tomato production in an asymmetric greenhouse in Multan, Pakistan. According to the simulated results, both systems were able to successfully control internal temperatures. Key findings of the study are given below.

- The systems maintained a temperature range of 20–25°C.
- In dry months like May and June, when the outside temperature reached 45°C, the DEC system successfully lowered inside temperatures by a significant 15°C.
- Owing particularly to the effectiveness of the evaporation process under low humidity circumstances, the DEC system showed energy savings of up to 40% during these periods.
- However, during humid months like July, it performed worse, with an energy efficiency ratio (EER) of 17.8 in contrast to 37.3 in dry months.
- On the other hand, during the hot and humid months, the IEC system consistently controlled humidity and temperature, limiting internal moisture accumulation that may lead to fungal diseases in tomato crops.

The results also showed the importance of natural ventilation (using ridge vents and sidewall vents) in lowering interior temperatures, which improved the energy efficiency of both cooling systems. Finally, for greenhouse climate management in areas with significant temperature fluctuations, combining DEC and IEC systems provides a year-round solution. To further optimize energy consumption and promote the sustainability of agricultural operations in dry regions, future research should investigate the integration of solar energy.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Government of Pakistan. Pakistan Economic Survey 2023–24. Islamabad, Pakistan: Economic Adviser's Wing, Finance Division; 2024

[2] Golzar F, Heeren N, Hellweg S, Roshandel R. A novel integrated framework to evaluate greenhouse energy demand and crop yield production. Renewable and Sustainable Energy Reviews. 2018;**96**:487-501. DOI: 10.1016/j.rser.2018.06.046

[3] Franco A, Valera DL, Peña A. Energy efficiency in greenhouse evaporative cooling techniques: Cooling boxes versus cellulose pads. Energies. 2014;**7**(3): 1427-1447. DOI: 10.3390/en7031427

[4] Agrebi S, Chargui R, Tashtoush B, Guizani A. Comparative performance analysis of a solar assisted heat pump for greenhouse heating in Tunisia. International Journal of Refrigeration. 2021;**131**:547-558. DOI: 10.1016/j. ijrefrig.2021.06.004

[5] Noor S, Ashraf H, Sultan M, Khan ZM. Evaporative cooling options for building air-conditioning: A comprehensive study for climatic conditions of Multan (Pakistan). Energies. 2020;**13**(12):3061. DOI: 10.3390/en13123061

[6] Noor S, Ashraf H, Hussain G, Sultan M, Miyazaki T, Shakoor A, et al. Spatiotemporal investigation of evaporative cooling options for greenhouse air-conditioning application in Pakistan. Fresenius Environmental Bulletin. 2021;**30**(03):13

[7] Jain D. Development and testing of two-stage evaporative cooler. Building and Environment. 2007;**42**(7): 2549-2554. DOI: 10.1016/j. buildenv.2006.07.034

[8] Montero JI, Antón A, Torrellas M, Ruijs MNA, Vermeulen PCM. Environmental and Economic Profile of Present Greenhouse Production Systems in Europe. Annex. Brussels, Belgium: European Commission; 2011. p. 53

[9] Soussi M, Chaibi MT, Buchholz M, Saghrouni Z. Comprehensive review on climate control and cooling systems in greenhouses under hot and arid conditions. Agronomy. 2022; **12**(3):626. DOI: 10.3390/agronomy 12030626

[10] Aljubury IMA, Ridha HDa. Enhancement of evaporative cooling system in a greenhouse using geothermal energy. Renewable Energy. 2017;**111**: 321-331. DOI: 10.1016/j. renene.2017.03.080

[11] Perret JS, Al-Ismaili AM, Sablani SS. Development of a humidification–dehumidification system in a Quonset greenhouse for sustainable crop production in arid regions. Biosystems Engineering. 2005;**91**(3):349-359. DOI: 10.1016/j.biosystemseng.2005. 04.009

[12] Xu J, Li Y, Wang RZ, Liu W, Zhou P. Experimental performance of evaporative cooling pad systems in greenhouses in humid subtropical climates. Applied Energy. 2015;**138**: 291-301. DOI: 10.1016/j. apenergy.2014.10.061

[13] Ahmed EM, Abaas O, Ahmed M, Ismail MR. Performance evaluation of three different types of local evaporative cooling pads in greenhouses in Sudan. Saudi Journal of Biological Sciences. 2011;**18**(1):45-51. DOI: 10.1016/j. sjbs.2010.09.005

[14] Noor S, Ashraf H, Sultan M, Miyazaki T, Mahmood MH, Khan ZM. Investigation of direct and indirect evaporative cooling options for greenhouse air conditioning in Multan (Pakistan). In: 6th International Exchange and Innovation Conference on Engineering and Sciences (IEICES-2020); Fukuoka, Japan; 2020. DOI: 10.5109/4102474

[15] Merlone A, Al-Dashti H, Faisal N, Cerveny RS, AlSarmi S, Bessemoulin P, et al. Temperature extreme records: World Meteorological Organization metrological and meteorological evaluation of the 54.0°C observations in Mitribah, Kuwait and Turbat, Pakistan in 2016/2017. International Journal of Climatology. 2019;**39**(13):5154-5169. DOI: 10.1002/joc.6132

[16] Klein SA. TRNSYS-A Transient System Simulation Program. Madison, United States of America: Solar Energy Laboratory, University of Wisconsin; 1978. p. 536

[17] University of Wisconsin - Madison. Solar Energy L. TRNSYS, A Transient Simulation Program. Madison, Wis: The Laboratory; 1975

[18] Yazdanian M, Klems JH. Measurement of the exterior convective film coefficient for windows in low-rise buildings. ASHRAE Transactions. 1993; **9**(1):932-944

[19] Allen RG, Pereira LS, Raes D, Smith M. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. Rome, Italy: Food and Agriculture Organization (FAO) of the United Nations; 1998. 300 p

[20] Ashraf H, Qamar S, Riaz N, Shamshiri RR, Sultan M, Khalid B, et al. Spatiotemporal estimation of reference evapotranspiration for agricultural applications in Punjab, Pakistan. Agriculture. 2023;**13**(7):1388. DOI: 10.3390/agriculture13071388

[21] Caliskan H, Hepbasli A, Dincer I, Maisotsenko V. Thermodynamic performance assessment of a novel air cooling cycle: Maisotsenko cycle. International Journal of Refrigeration. 2011;**34**(4):980-990. DOI: 10.1016/j.ijrefrig.2011.02.001

[22] Cuce PM, Riffat S. A state of the art review of evaporative cooling systems for building applications. Renewable and Sustainable Energy Reviews. 2016;**54**: 1240-1249. DOI: 10.1016/j.rser.2015.10.066

[23] Duan Z, Zhan C, Zhang X, Mustafa M, Zhao X, Alimohammadisagvand B, et al. Indirect evaporative cooling: Past, present and future potentials. Renewable and Sustainable Energy Reviews. 2012;**16**(9): 6823-6850. DOI: 10.1016/j.rser.2012.07.007

[24] Ahmad A, Rehman S, Al-Hadhrami LM. Performance evaluation of an indirect evaporative cooler under controlled environmental conditions. Energy and Buildings. 2013;**62**:278-285. DOI: 10.1016/j.enbuild.2013.03.013

[25] Ashraf H, Sultan M, Shamshiri RR, Abbas F, Farooq M, Sajjad U, et al. Dynamic evaluation of desiccant dehumidification evaporative cooling options for greenhouse air-conditioning application in Multan (Pakistan). Energies. 2021;**14**(4):1097. DOI: 10.3390/en14041097

[26] Sultan M, Ashraf H, Miyazaki T, Shamshiri RR, Hameed IA. Temperature and humidity control for the next generation greenhouses: Overview of desiccant and evaporative cooling systems. In: Redmond RS, editor. Next-Generation Greenhouses for Food

Security. Rijeka: IntechOpen; 2021. DOI: 10.5772/intechopen.97273

[27] Mahmood MH, Sultan M, Miyazaki T, Koyama S, Maisotsenko VS. Overview of the Maisotsenko cycle – A way towards dew point evaporative cooling. Renewable and Sustainable Energy Reviews. 2016;**66**:537-555. DOI: 10.1016/j.rser.2016.08.022

[28] Abdel-Ghany AM, Kozai T. Dynamic modeling of the environment in a naturally ventilated, fog-cooled greenhouse. Renewable Energy. 2006; **31**(10):1521-1539. DOI: 10.1016/j.renene.2005.07.013

Chapter 2

Sea Water Air Conditioning (SWAC) Technology: Performance and Worldwide Potential

Franck Lucas and Kanhan Sanjivy

Abstract

By drawing seawater from great depths (over 900 m), sea water air conditioning (SWAC) systems directly cool buildings without the need for supplementary backup systems, ensuring precise indoor temperature regulation. With a coefficient of performance values ranging from 25 to 150, depending on the distribution loop's length, this technology presents remarkable energy efficiencies. When applicable, it serves as a credible alternative to compression vapor cycle air conditioning. This chapter offers a comprehensive overview of SWAC technology, evaluating energy performances through the analysis of operational data collected from installations in operation for several years. The assessment includes a comparative analysis between SWAC and conventional air conditioning systems. Additionally, potential avenues for enhancing the technology are explored, emphasizing associated energy benefits, and discussing prospects for its widespread adoption globally. An additional paragraph will present the state of the art in research on this technology.

Keywords: sea water air conditioning (SWAC), marine thermal energy, district cooling, efficient active cooling, deep ocean water (DOW)

1. Introduction

The need for building cooling has been constantly increasing for many years. According to the International Energy Agency's study "The Future of Cooling," published in 2018, energy consumption related to air conditioning tripled between 1990 and 2016. It is expected to triple again between 2020 and 2050. This trend could worsen if we consider climate change, which is expected to increase the occurrence of heatwaves. Indeed, more intense, more frequent, and longer heatwaves are expected by 2050 and 2100 [1]. The worsening of heatwaves will be even more pronounced for regions with hot climates, such as zones 0, 1, and 2 of the ASHRAE Standard 169-2013 classification [2]. For example, in hot climates like Singapore (zone 0A) and São Paulo (zone 2A), the number of heatwaves observed in 2010 was 7 per year. This number is expected to increase to 58 per year for Singapore and 87 per year for São Paulo by 2050, and to 136 per year for Singapore and 172 per year for São Paulo by 2100. The increase in frequency will be accompanied by more intense heatwaves with higher temperatures and longer durations. Under these conditions, passive cooling solutions based on natural ventilation will not be sufficient to ensure acceptable indoor comfort conditions. The development of highly energy-efficient air conditioning solutions is therefore a major challenge for the coming years.

Recent studies comparing air conditioning methods based on solar energy (using PV panels or thermal collectors) have shown that the difference from conventional air conditioning is not significant. Noro demonstrated that for the city of Milan, PV Solar technology coupled with a vapor compression chiller was not much more interesting than a system combining an absorption machine with solar thermal panels [3]. Eicker [4] found that the technologies are quite similar in energy performance, but economic performances vary greatly depending on operational costs. He presented a study of vapor compression air conditioning systems powered by PV panels for different cities and different panel surface areas. It appears that the primary energy ratio (PER), calculated as the ratio of cooling production to total primary energy demand, varies between 1.5 and 4.9. The study assumes a primary energy-to-electricity conversion ratio of 2, leading to energy efficiency ratio (EER) values between 3 and 9.8 for this technology. This value is to be compared to the value of a vapor compression system operating under the same conditions, which would vary between 3.6 and 5.6, according to this study.

As will be presented later, the sea water air conditioning (SWAC) technology, which involves drawing cold water from the ocean at great depths, offers much higher energy performances. This technology allows the active cooling of large buildings or neighborhoods located near the coasts. Coastal areas worldwide are expected to host over 1.3 billion people by 2060 (compared to 0.6 billion people in the year 2000) [5]. These elements suggest that SWAC technology could be an efficient cooling solution for buildings in many application sites in the future. This chapter will present the technical aspects of "direct SWAC" technology based on currently operational installations. It will provide a state-of-the-art review of research and an evaluation of energy performances based on experimental measurements of operating installations. The possibilities for improvement and potential gains will then be discussed, as well as the potential for deploying the technology worldwide.

2. Presentation of the technology

2.1 General principles

The SWAC technology involves pumping naturally cold water from deep ocean or lakes via a pipeline laid on the seabed. This water, if sufficiently cold, can be used directly for air conditioning buildings. The extracted water temperature should be around 5°C to match the temperature regimes typically used for centralized chilled water air conditioning systems, which operate between 7 and 12°C. To achieve such temperatures in the oceans of hot regions, depths close to 1000 m must be reached. This technology, which allows direct cooling without additional devices to lower the water temperature, can be called "direct SWAC" or "deep SWAC." If the deep-water temperature is not cold enough, a supplementary system is required to lower the distributed water temperature to the usual 7°C used in buildings. This is referred to as "SWAC assisted" by a chiller.

Unlike conventional cooling production processes, direct SWAC does not rely on a thermodynamic cycle—the vapor compression cycle is typically used in refrigeration and air conditioning. Thus, it avoids the physical limit set by Carnot efficiency, which limits the transfer of heat from a cold source to a hot source. The SWAC technology simply involves transporting a cold liquid from the extraction point to its point of use. The process is therefore extremely simple, with the main components being pumps. However, if the deep water is salty seawater, a heat exchanger is necessary to prevent corrosion in the cold distribution circuit within buildings. Three installations are currently operational in Polynesia (**Table 1**). They operate on the "direct SWAC" principle to air condition two hotels and a hospital.

Figure 1 presents the two types of installations implemented in Polynesia: those with a secondary distribution loop that allows for direct cold distribution into buildings (Thalasso – Bora Bora and The Brando) and those using an intermediate loop that supplies the building through a distribution substation (CHPF – Taone Hospital).

The SW loop (Sea Water Loop), also known as the "primary loop," includes an intake pipeline descending to approximately 1000 m in depth and a discharge pipeline. The seawater is about 5–6°C at the intake and is discharged at a temperature between 11 and 13°C. The discharge point is defined as releasing the seawater at a temperature close to the surrounding environment to avoid impacting the local marine flora and fauna; however, this discharge temperature is not subject to specific regulations. The intake and discharge pipelines are constructed from high-density polyethylene and buried in a trench between the technical room and the sea to cross the lagoon. The pipeline is then anchored to vibro-driven piles in the seabed down to a depth of approximately 55 m, and from this point, it is secured by concrete weights.

The CW loop (chilled water loop), also known as the secondary loop, delivers cold water directly into buildings from the heat exchangers located in the technical room. For installations with an intermediate loop, this loop ensures the connection between the heat exchangers and a substation located in or near the building. In this case, the

Name	Location	Year	Building type	Drawing depth	Drawing pipeline length	Drawing pipeline diameter	Cooling power
Thalasso Bora Bora	Bora Bora	2006	Hotel	−915 m	2300 m	400 mm	1.6 MW
The Brando	Tetiaroa	2011	Hotel	−960 m	2618 m	368/383 mm	2.4 MW
CHPF-Taone	Tahiti	2021	Hospital	−900 m	3800 m	710 mm	6 MW

Table 1.
Characteristics of installations operating in French Polynesia.

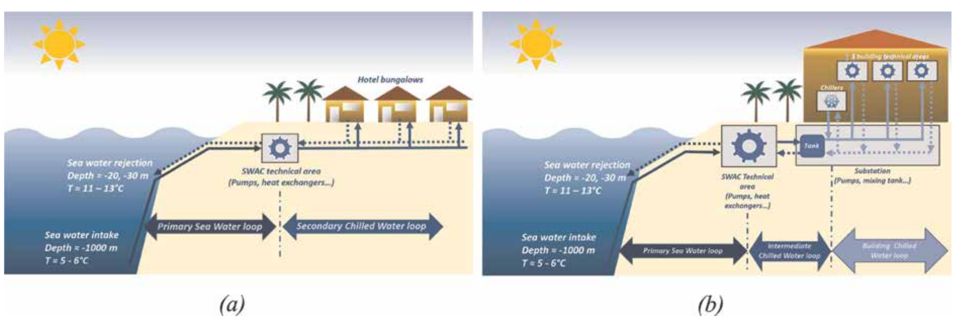

Figure 1.
Diagram of the operating principle of the direct SWAC system without an intermediate circuit (Thalasso-Bora Bora and The Brando) (a) and with an intermediate distribution loop (CHPF-Taone) (b).

intermediate loop supplies the various technical rooms of the building from a mixing tank. The chilled secondary water loop (district cooling) of The Brando is around 3.8 km long (**Figure 2**, left) and supplies the entire hotel, including staff quarters and technical buildings. The hotel has 30 single-bedroom villas, four two-bedroom villas, and one three-bedroom villa, making a total of 35 villas distributed around the coastline.

The distribution network for the CHPF includes an intermediate secondary loop 660 m long (**Figure 2**, right) that connects the SWAC technical room to the main building. In this building, the mixing tank located in the substation distributes the chilled water flow to three technical rooms to supply three internal distribution loop. It should also be noted that this installation operated for 10 years (from 2012 to 2022) with chillers before the SWAC system was commissioned. The chillers are still in place and retained as a backup in case of a SWAC system failure. For maintenance reasons, the chillers are regularly operated according to the manufacturer's instructions.

Regardless of the type of distribution, the technical room includes three pumps for each of the two loops, as well as three heat exchangers to transfer the cold from the SW loop to the CW loop or to the intermediate loop. The heat exchangers are titanium plate counterflow types and operate in parallel. In both the primary and secondary or intermediate circuits, the pumps are arranged in parallel. To avoid corrosion issues, the pump body and impeller are made of 316 L stainless steel, and the bearing body is made of cast iron. Depending on the needs, one or two pumps are in operation, and the third is kept on standby (**Figure 3**).

2.2 State of the art

Two thermal processes utilizing seawater for energy production can be distinguished. The OTEC (Ocean Thermal Energy Conversion) technology produces electricity using a

Figure 2.
Plan and aerial view of the water loops of The Brando (left) and the CHPF – Taone Hospital (right).

Figure 3.
Plate heat exchanger, primary pump, and secondary pump for Tetiaroa (a) and Tahiti (b).

thermodynamic cycle, usually an organic Rankine cycle, powered by cold deep water at the condenser and warm surface water at the evaporator. The second process is the SWAC (sea water air conditioning) process, which produces cooling energy for air conditioning buildings using seawater. When seawater is drawn from shallow depths, its temperature needs to be lowered with a chiller or a heat pump if the building requires heating. This is referred to as a "Sea Water Heat Pump" (SWHP) or SWAC assisted by a chiller (assisted SWAC). While there are several installations operating on the SWHP principle, "direct SWAC" installations are much rarer. Andres [6] identified six installations qualified as "SWAC" in 2016. Among these, two commercial installations are located in temperate climates (Toronto and Amsterdam) but use freshwater from lakes or rivers. The "Fraîcheur de Paris" installation uses a similar system, using water from the river La Seine and incorporating heat pumps to adjust the distribution temperature. Similarly, in France, the Thassalia installed air-conditioned buildings in Marseille by drawing seawater from a depth of 6 m in the port. In Korea, Japan, and Hawaii, identified installations primarily serve research on OTEC cycles and the derived use of deep water (aquaculture, pharmacology, cosmetology). Ultimately, the only industrial "direct SWAC" installations operating in hot climates are located in Polynesia. However, many "direct SWAC" projects are currently under study worldwide, notably on Reunion Island (3 projects under study), in Mauritius (1 project), several projects throughout the Caribbean, and one project in Polynesia on the island of Bora Bora.

A number of studies on "direct SWAC" technology aim to establish the potential of this process for various locations based on theoretical analyzes [7–9]. The global potential for implementing direct SWAC or assisted SWAC installations is precisely evaluated by Sanjivy [10]. For the case of a hotel in a tropical climate, Dinesh Surroop offers a theoretical comparison between conventional air conditioning technology, direct SWAC, and SWAC assisted by a chiller [11]. He concludes that direct SWAC allows for an 88% energy savings and assisted SWAC with a 47% energy savings compared to conventional air conditioning. Only one publication provides a performance evaluation of the process based on experimental data [12]. The EUROSWAC project explored the feasibility of a flexible intake pipeline to reduce the investment costs of the technology [13]. Other research focuses on improving SWAC technology, including a high-speed SWAC variant with energy storage [14] or the use of an ammonia distribution loop [15]. Ilse María Hernandez-Romero proposes a method for sizing installations [16].

It should also be noted that there is a large number of scientific articles on district cooling systems [17–21]. The different generations of district cooling have led to considering combined cooling and heating needs and envisioning multiple distribution networks at various temperature levels. Fourth-generation networks have been mentioned [22], followed by fifth-generation networks [23–25]. Young has shown that for cooling production, it is more efficient to use a water-cooled system rather than an air-cooled system [26]. Following this logic, it becomes relevant to study the possibility of a district cooling or heating system assisted by a seawater source. For cooling production, the chiller's condenser is then cooled by a seawater circuit, and for heating buildings, the evaporator is heated by seawater. This technology has also been studied by many authors [27, 28]. Yik proposes a study on improving chiller performance when cooled by a seawater circuit drawn from Hong Kong harbor compared to air-cooled chillers [29]. For the warmest months of the year, this study shows that chiller efficiency increases from 3 to 5 for water-cooled systems. The average annual electricity consumption ratio drops from 217 to 168 kWh/m^2 with water condensation.

Overall, the bibliography shows that district cooling offers several advantages. Notably, very high-power chillers generally have better energy performance than low-power chillers. The size of the district cooling distribution network also allows for optimization strategies in terms of sizing and control. However, it should be kept in mind that overly long water distribution networks require high-power, energy-intensive pumps. Thus, there is a limit to the size of district cooling beyond which energy performance declines. SWAC appears to be an active building cooling technology offering significant energy performance, which will be presented below.

3. Performances assessment

3.1 Methodology

Deep seawater provides a relatively stable source of cooling throughout the year. The fluctuations observed in **Figure 4** are due to thermal exchanges affected by the daily and seasonal variations in the flow rates of the primary loop. Buildings experience highly transient operations due to many internal factors (occupancy, internal sensible, and latent thermal loads) and external factors (weather conditions and air

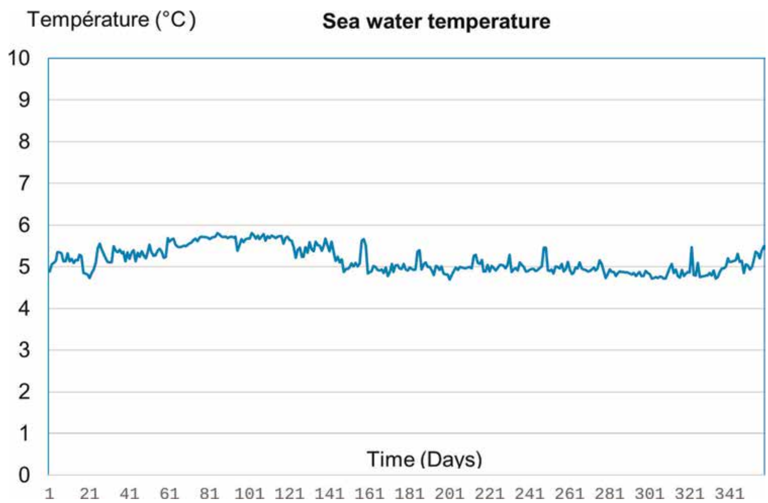

Figure 4.
Seawater temperature measured at the heat exchanger inlet.

transfer). Therefore, characterizing the performance of SWAC must be done through an experimental approach on an installation operating under real conditions. It is thus essential to have an operational and instrumented SWAC installation.

There are two instrumented SWAC installations in French Polynesia: The Brando and the CHPF. These two installations are implemented following the same principle with three heat exchangers in parallel and three pumps in parallel on both the seawater and chilled water loops. Both installations have been instrumented according to the plan proposed in **Figure 5**, and the measurement results will be presented below. In this chapter, when these two installations provide similar results, only the results of one installation will be presented.

All measurements are collected by an automation system to track the evolution of operating parameters and calculate Key Performance Indicators (KPIs) of the installation. In accordance with the work of Annex 80 of the International Energy Agency

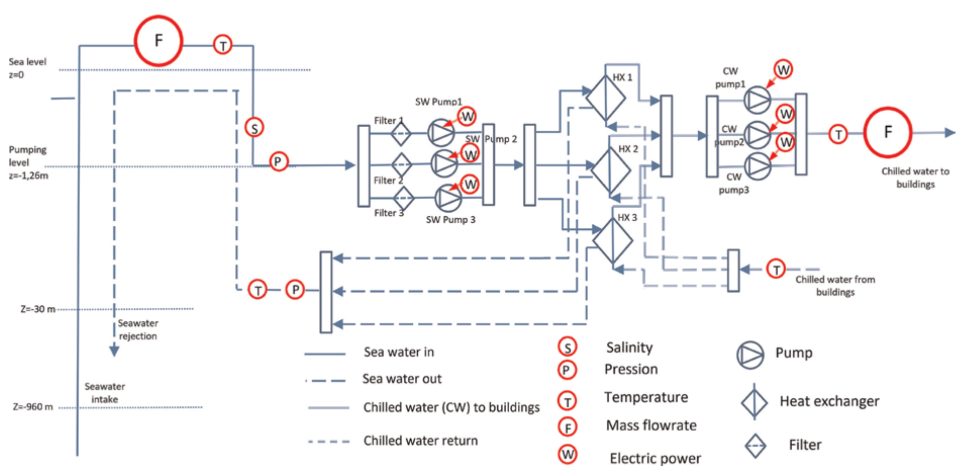

Figure 5.
Instrumentation plan for SWAC installations enabling the evaluation of energy performance.

(IEA), several KPIs are important for qualifying the performance of active cooling installations [30]. The following annual values are proposed:

- Annual Cooling Site Energy Use per Conditioned Floor Area.
- Annual CO_2 Emission per Conditioned Floor Area.
- Annual HVAC System Total Primary Energy Use per Conditioned Floor Area.
- Degree Hours or Degree Days.
- Reduction in Peak Site Power Demand Intensity.
- Seasonal Energy Efficiency Ratio (SEER).

The SEER is an important value which is common to all cooling systems and is calculated based on the energy efficiency ratio (EER). The EER provides an instantaneous estimate of the energy performance of cooling installations, which can vary significantly over time. It is expressed as:

$$EER(t) = \frac{Cooling\ capacity\ (t)\ [W]}{Electric\ power\ for\ cooling\ (t)\ [W]} \tag{1}$$

$$SEER = \int_0^S EER\ dt \tag{2}$$

S: is the duration of the season, typically taken as 1 year for climates requiring year-round cooling.

The electrical power required for cooling depends on the type of technology studied. For an air-cooled vapor compression system such as chillers, the electrical power used to produce cold is needed to power the compressor and the condenser fan. According to the IEA study [31], the energy efficiency ratio (EER) values for chillers range from 3 to 11.5 depending on the cooling type (air or water), compressor technology, and operating conditions. Recent models of air conditioners currently available on the market have an average EER of 6.1. For SWAC, the power used to produce cold is that of the primary pumps. The pumps in the secondary circuit serve to transport the cold to the building (s). This network is the same for both "chiller" technology and SWAC technology if we assume the chiller is located in the same room as the SWAC. For SWAC, we can therefore define an EER value corresponding to cold production, denoted as EER_{prim} and an overall energy performance value corresponding to cold production and cold transport to the building, denoted as EER_{global}.

$$EER_{SWAC\ cold\ production}(t) = EER_{prim}(t) = \frac{Cooling\ capacity\ (t)\ [W]}{Electric\ power\ of\ pumps\ of\ primary\ loop\ (t)\ [W]} \tag{3}$$

$$EER_{global}(t) = \frac{Cooling\ capacity\ (t)\ [W]}{Electric\ power\ of\ pumps\ of\ primary\ and\ secondary\ loop\ (t)\ [W]} \tag{4}$$

The values of $SEER_{prim}$ and $SEER_{global}$ are obtained by integrating EER_{prim} and EER_{global} over the operational period of the air conditioning system. If SWAC is to be compared to centralized air conditioning technologies such as chillers, where an internal distribution network within buildings is necessary, similar to SWAC, the electrical consumption of this network can be neglected. Therefore, it is sufficient to compare the EER values of the chiller to the cold production EER of SWAC, i.e., EER_{prim}. Unitary air conditioning systems such as split systems deliver cold through direct expansion directly into buildings without using a chilled water distribution network. In this case, one should compare the EER of a split system to the overall EER of SWAC, considering the secondary distribution loop. The EER values for split systems available on the market are typically around 3.5. However, it should be noted that many installed systems often perform significantly below the values claimed by manufacturers. Continuous measurements allow for the assessment of the dynamic behavior of the installation and the actual operation of the control and command system. The following paragraphs provide an analysis of the temporal evolution of the main energy variables of the CHPF installation.

3.2 Operating variables analysis

The temporal evolution of seawater (SW) and chilled water (CW) loop temperatures for CHPF is shown in **Figure 6** over the period from August 10, 2022, to September 30, 2022, after the SWAC was commissioned. The seawater inlet temperature to the heat exchanger remains relatively stable, ranging between 4.5 and 5.6°C with an average of 5°C. The seawater outlet temperature from the heat exchanger fluctuates between 8.6 and 10°C with an average of 9.1°C. On the chilled water loop, the average temperature at the heat exchanger inlet is 7°C, and the return temperature varies between 8.2 and 11.2°C. The inlet temperatures of seawater and chilled water in the heat exchanger are slightly below the nominal values, which is advantageous for system operation. However, the outlet temperatures from the seawater and chilled water heat exchangers are significantly lower than the nominal values. Consequently, the average temperature difference across the seawater loop is 4.1°C and only 2.9°C across the chilled water network.

We observe relatively small temperature differentials in both seawater and chilled water, which can be explained by the high volumetric flow rates in these loops. For seawater, the average volumetric flow rate measured is 657 m^3/h, whereas the nominal

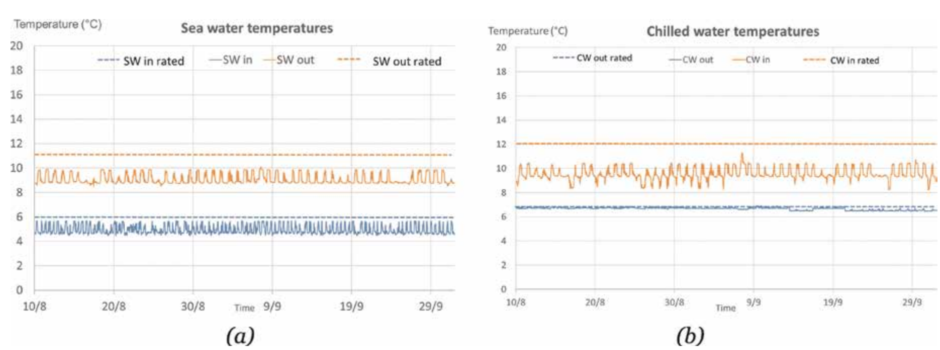

Figure 6.
Evolution of temperatures for CHPF for the primary seawater loop (SW) before the heat exchangers (a) and the secondary chilled water loop (CW) after the heat exchangers (b). Dashed lines indicate the nominal value for each temperature. SW in and CW in represent the temperatures at the inlet of the heat exchanger. SW out and CW out are the temperatures at the outlet. The measurement period shown is from August 10, 22, to September 30, 2022.

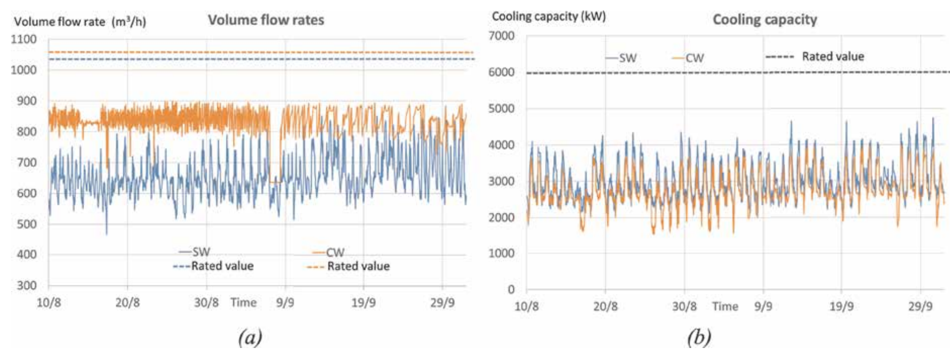

Figure 7.
Evolution of volumetric flow rates (a) and exchanged cooling capacities (b) for CHPF.

value at full capacity is 1052 m^3/h. In the chilled water loop, the average flow rate is 832 m^3/h compared to a nominal value of 1032 m^3/h. The corresponding refrigeration capacities measured on the seawater and chilled water loops are shown in **Figure 7** on the right. Both values are quite close to each other and fluctuate around 3000 kW. However, they are well below the nominal capacity of the installation intended to deliver 6000 kW. The capacity factor of this installation is therefore quite low, around 45.8%. This indicates that the installation is never operated at its maximum power and that the loop regulation does not adjust flow rates to the appropriate values. Therefore, there is potential to reduce the electrical consumption of the installation if the flow rates can be reduced to maintain temperature differentials of at least 5°C in both loops.

The electrical powers shown in **Figure 8** demonstrate the savings brought by SWAC technology. These powers do not include the pumps of the internal chilled water distribution network in the building, as these pumps operate continuously, alongside the chillers and SWAC. Before the SWAC was commissioned, the average power drawn by the chillers for cooling the hospital was 1025 kW. This power was reduced to 106 kW upon commissioning of the SWAC, resulting in a tenfold reduction in electricity consumption. The SWAC consumption is primarily due to the pumps of the intermediate secondary circuit, which account for 80% of the consumption.

Figure 8.
Electrical power of the chillers before the commissioning of SWAC (period from May 12, 2022, to June 28, 2022) (a) and electrical powers of the SWAC pumps (primary, secondary, and total) (period from August 10, 2022, to September 30, 2022) (b).

3.3 Energy performance analysis

The energy performance of the installation with SWAC and chillers can be evaluated by the instantaneous value of the energy efficiency ratio (EER) and a seasonal value of this ratio, the SEER, as presented earlier. **Figure 9a** shows the evolution of the primary and global energy efficiency ratio values after the SWAC was commissioned in mid-2022. The global EER values (including the consumption of the primary loop and the secondary loop pumps) vary between 15 and 40, while the primary EER varies between 75 and 180. These values are much higher than conventional air conditioning EER values. However, despite the resource temperature being very stable, these values vary significantly. These variations are mainly due to fluctuations in the building's cooling demand that the system struggles to accommodate. As shown in **Figure 9b**, the global EER decreases significantly when the cooling demand is low. The explanation is that the control system, based on a setpoint for the flow pressure of the secondary loop pumps (**Figure 7**), does not finely adjust the cooling production to match the building's actual needs.

The annual trends of EER values for CHPF and The Brando, as shown in **Figure 10**, confirm the very good performance of SWAC technology over long operating periods. Despite slightly different configurations (with an intermediate secondary loop for CHPF and direct distribution within buildings for The Brando), their energy performances remain very similar. As discussed earlier, the performances are generally better during the hot period from December to March.

Table 2 presents a summary of the main measurements from the studied installations, showing that both installations are significantly underutilized with capacity factors below 0.5. The decrease in hotel occupancy during the post-COVID period partly explains the capacity factor for The Brando.

3.4 Economic aspect

The feedback from The Brando SWAC installation allows us to experimentally and precisely assess the energy performance of the system over a long period. This analysis can be complemented by economic and environmental elements. To compare the average cost of cooling production with other systems, we will calculate the Levelized Cost of Energy (LCOE) for The Brando SWAC defined by the following formula:

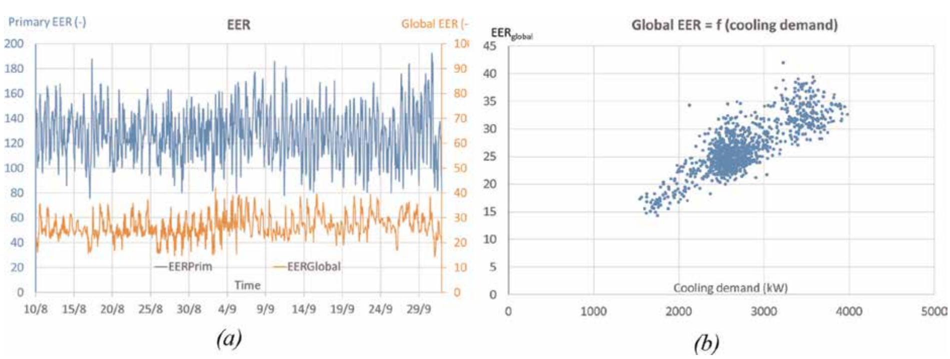

Figure 9.
Evolution of the primary and global EERs for CHPF from August 10, 2022, to September 30, 2022 (a), and evolution of the global EER based on the building's cooling demand (b).

	SW temperature		CW temperature		Volume flow rate		Cooling capacity	Rated cooling capacity	Capacity factor
	in	**out**	**in**	**out**	**SW**	**CW**			
	°C	°C	°C	°C	m^3/h	m^3/h	kW	kW	%
Brando	5,8	9,1	11,1	7,4	187,8	154,2	684	2400	28.5
CHPF SWAC	4.9	9.1	9.5	6.7	657.5	833.0	2752	6000	45.8
CHPF chiller	—	—	10.5	7.5	—	863.8	2961	8250	35.9

Table 2.
Comparison of average operating variables for The Brando installation and for the CHPF installation operating with SWAC and with conventional AC (chillers).

$$LCOE = \frac{\sum_{t=0}^{T} \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{E_t}{(1+r)^t}} \quad (5)$$

where I_t, O_t, F_t are, respectively, for each year t, the initial investment, operating and maintenance costs, and fuel costs. The LCOE also depends on the project duration in years T, the energy produced E_t, and the discount rate r. The costs associated with The Brando SWAC are summarized in the **Table 3** below.

The lifespan of the SWAC installation is estimated to be 50 years. The LCOE will be calculated over this period using the average annual cooling production and electricity consumption measured. Fuel costs will be determined based on the electricity cost, estimated by the supplier "Énergie de Tetiaroa" at \$0.78/kWh. The discount rate r will be set at 2%. The resulting LCOE value is \$0.15/kWh. However, this value is highly dependent on local costs, especially for equipment and electricity, which remain very high in Polynesia.

3.5 Comparison of SWAC with conventional AC

The measurements clearly highlight the advantages of SWAC compared to conventional chiller-based air conditioning, as summarized in **Table 4**. SWAC indeed

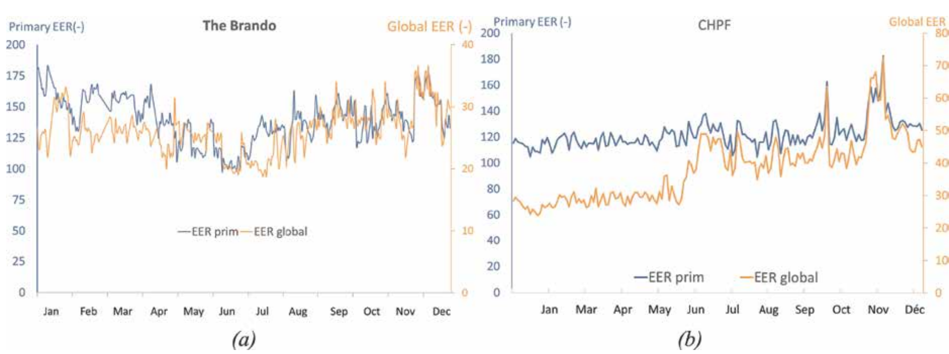

Figure 10.
Evolution of EER over 1 year for The Brando installation (a) and CHPF (b).

Cost	Description	Amount (USD)
CAPEX (I_t)	Maritime works	13,87 M$
	Heat exchanger	749,6 k$
	SWAC technical room	828,7 k$
	Chilled water distribution loop	2,047 M$
OPEX (O_t)	Maintenance	129 k$/year
	Inspection of the intake pipe	120 k$/year

Table 3.
Tetiaroa SWAC associated costs.

	SEER		Mean electric power			Electric peak power	LCOE	Savings over lifespan
	Primary	**Global**	**SW**	**CW**	**Total**			
	(–)	(–)	(kW)	(kW)	(kW)	(kW)	$US/ kWh cooling	M$US
SWAC Brando [i]	***127***	***25.6***	***5.4***	***21.3***	***26.7***	***60.3***	***0.15***	***VS Chillers: 18.48 VS Spilt: 36.96***
Brando with Chillers [ii]	6	—	—	—	113.9	257.3	0.21	—
Brando with spilt systems [ii]	—	3.6	—	—	189.9	926.2	0.27	—
SWAC CHPF [i]	***127.5***	***26.6***	***22.9***	***83.1***	***106.0***	***140.0***	***0.06***	***Chiller: 118.13***
Chiller CHPF [i]	—	***2.97***	—	***1025***	***1025***	***1367.6***	***0.16***	—

[i]*values calculated from measurements.*[ii]*values estimated.*
Bold and italic characters are used for values obtained directly from measurements on the studied installations.

Table 4.
Comparison of the energy and economic performance of SWAC versus conventional AC. Bold and italic characters are used for values obtained directly from measurements on the studied installations.

allows for a significant reduction in electrical consumption for cooling and also reduces the peak electrical demand on the grid. For instance, in the case of CHPF, the average electrical power was 1025 kW with chillers, which decreased to 106 kW once SWAC was commissioned. This represents nearly a tenfold reduction in electricity consumption for air conditioning. The EER measured with chillers was 3, whereas, with SWAC, it increased to 26.6. This value is corroborated by measurements at The Brando, where the global EER is 25.5. The reduction in peak electrical demand on the grid is also substantial, decreasing from 1367.6 kW to only 140 kW with SWAC, significantly easing the electrical load on the building and the surrounding area. For CHPF, air conditioning with chillers accounted for 17% of the average power delivered by the electrical substation supplying the neighborhood of the hospital. This share decreased to only 1.4% when SWAC was commissioned.

SWAC also presents significant economic advantages. The LCOE values calculated from measurements taken on the installations give LCOE values of 0.15 for The Brando and only 0.06 for the CHPF. These values should be compared to those obtained for conventional air conditioning. In the case of The Brando, two systems can be considered: a centralized installation using chillers located in a technical room or individual split systems for each bungalow. For the CHPF, the SWAC is compared to chiller-based air conditioning, which is the only feasible alternative for this building, based on measurements taken when the chillers were operational. The LCOE values were evaluated following the method presented in the previous paragraph. The LCOE value for the SWAC at The Brando being twice as high as that for the CHPF is explained by the electricity cost of $0.78/kWh in Tetiaroa versus $0.32/kWh in Tahiti for the CHPF. These LCOE values remain well below those for conventional air conditioning by chillers or split systems, generating significant savings over the equipment's lifespan. For The Brando, the SWAC ensures savings of 18.48 million USD compared to chillers and 39.96 million USD compared to split systems. For the CHPF, the savings over the lifespan amount to 118.13 million USD compared to the chiller solution.

4. Possible improvements

Although the performance of SWAC technology is particularly impressive based on the results from currently operating installations, there are still possibilities for improvement. These improvements concern either the design or the control of the installations. This article proposes an analysis of the potential gains related to modifying the chilled water distribution regime within the building and improving flow control in the secondary loop. These analyzes are conducted using a numerical model of SWAC installations presented below.

4.1 Methodology

To evaluate opportunities for modifying the design of existing SWAC installations, a numerical model of SWAC coupled with a building was developed. This model consists of a building model created in the EnergyPlus environment [32], coupled with Python plugins that perform calculations for the primary and secondary loop components specific to the SWAC process, which are not available in EnergyPlus (**Figure 11**).

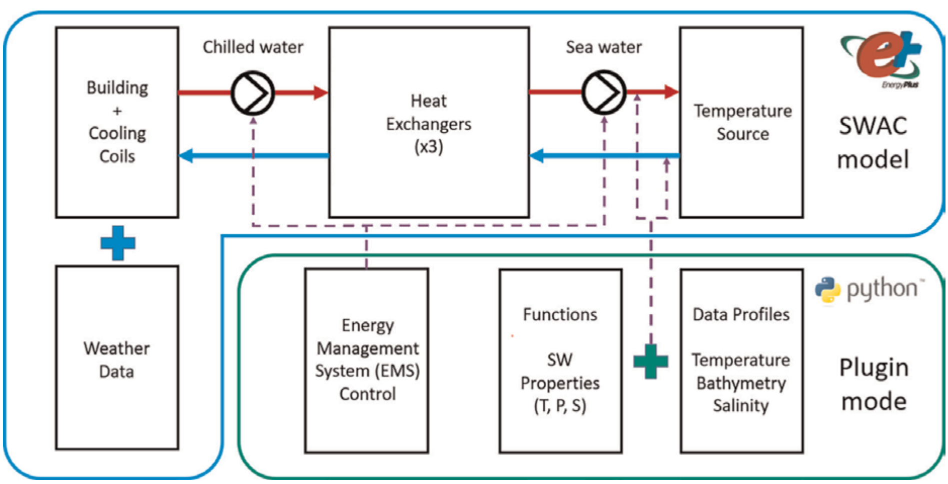

Figure 11.
Block diagram of the SWAC model created with EnergyPlus and the Python plugin.

The plugins enable the calculation of the electrical power of the pumps in the primary loop, considering the thermo-physical and chemical characteristics of seawater, bathymetry, pipe characteristics (diameter, thickness, roughness, length per section), and the flow regulation modes of the loop. Thermal losses in the primary loop are estimated for both the buried section and the submerged section of the pipeline. The calculation takes into account the seawater temperature profile according to depth. The model has been validated by comparing it with measurements taken from The Brando installation. The power of the primary and secondary loop pumps, as well as the flow rates, are predicted with good accuracy. The residual, defined as the difference between the model and the measurement, is centered on zero and is less than the measurement accuracy (**Figure 12**).

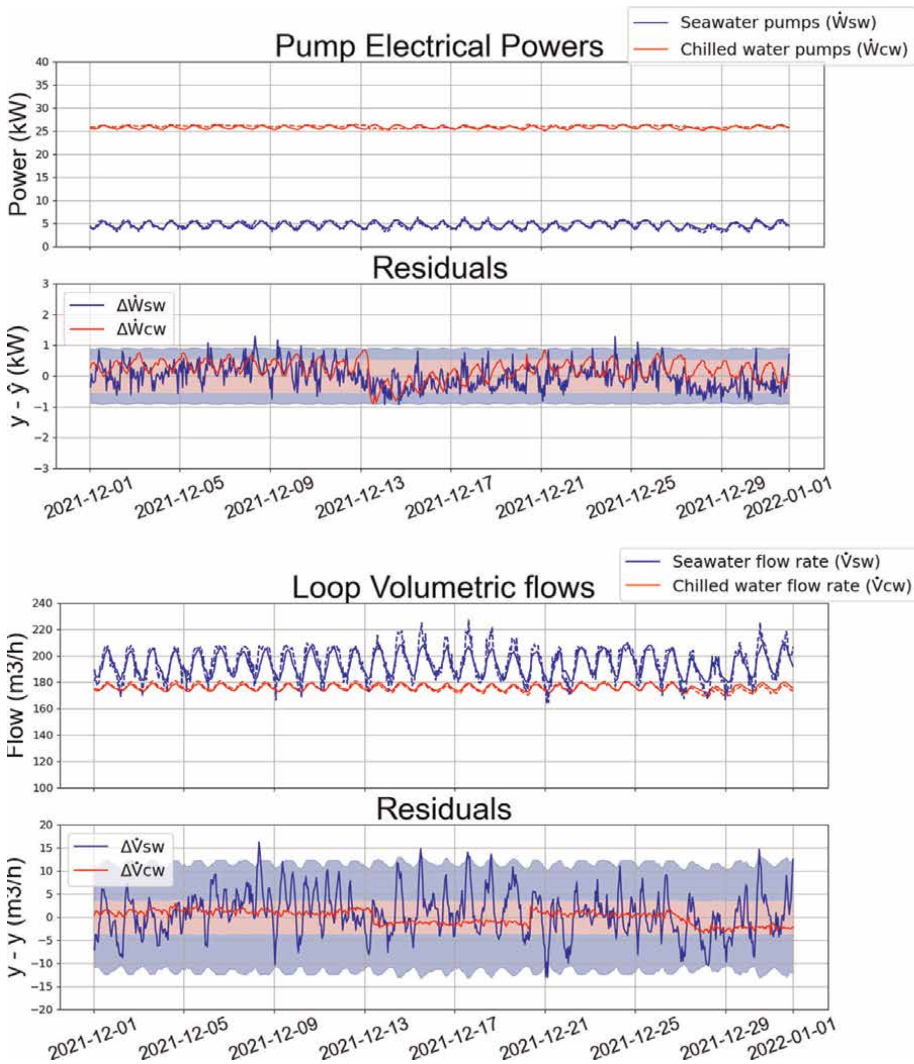

Figure 12.
Validation of the SWAC model through experimental comparison with estimation of the residual (model-measurement difference) for pump electrical power (above) and loop volumetric flowrate (below); Simulation results is represented by solid lines; Measured data is represented by dashed lines; Measurement uncertainty is represented by the colored area.

With the model validation confirmed, it can be used to assess the benefits of modifying the design and control of existing installations, as presented below.

4.2 District cooling temperature regime adjustment

The temperature regime of chilled water networks is generally 7/12°C. This means that chilled water is produced at 7°C to be sent to the building and returns at 12°C to the cooling production unit. This regime was inherited from older vapor compression cooling systems that ensured evaporation temperatures around 5°C. The replacements of refrigerants due to regulatory environmental changes were made while maintaining the same temperature regimes to adapt to existing distribution networks. However, it is now apparent that higher temperature regimes are possible and have been studied for conventional air conditioning systems [33, 34]. These studies show that chilled water temperatures of 15°C led to energy savings while maintaining comfort conditions in buildings. For the SWAC system, raising the temperature regime of the chilled water distribution loop presents particularly interesting advantages. To achieve a distribution temperature of 7°C, it is necessary to draw water at approximately 5°C, requiring depths of 900–1000 m. By increasing the chilled water temperature, the length of the primary loop can be reduced, significantly lowering capital expenditures (CAPEX) and operational expenditures (OPEX) by decreasing pressure losses. Therefore, it is important to evaluate the potential gains from raising the temperature regime.

The temperature regime modification will be studied using the numerical model representing The Brando installation presented earlier. The baseline configuration of this installation corresponds to a distribution regime of 7/12°C with a drawing temperature of 5°C. It is evident that changing the temperature regime necessitates resizing the chilled water distribution network by increasing the heat exchange surfaces of the building's fan-coils. Additionally, it is crucial to resize the heat exchangers between the two loops. **Figure 13** shows the evolution of the primary and global EER for different drawing temperatures of 5°C, 6°C, 7°C, 8°C, 9°C, 10°C, 11°C, resulting in chilled water distribution regimes of 7/12°C, 8/13°C, 9/14°C, 10/15°C, 11/16°C, 12/17°C, and 13/18°C, respectively. Resizing the exchanger results in a modification of the UA value of the exchanger, obtained by the product of the Overall Heat Transfer Coefficient and the heat exchanger's surface area. The UA values studied are 100,000, 200,000, 300,000, and 400,000 W/K. Changing the temperature regime reduces the

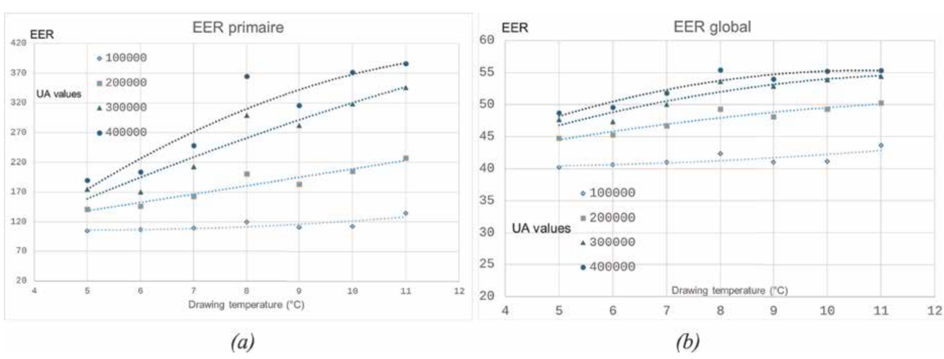

Figure 13.
Evolution of primary and global EERs based on draw temperature for different values of the heat exchanger coefficient (UA).

length of the drawing pipeline and improves the primary EER. This improvement is less pronounced on the global EER because the secondary pumps' consumption is more significant than the primary pumps. It should be noted that the performance gain from increasing the temperature regime is strongly linked to the UA value. The higher the UA, the greater the performance increases with the temperature regime rise. The design of future installations should therefore target higher temperature regimes, but this must be accompanied by resizing the loop heat exchangers.

4.3 District cooling flow rate control upgrade

The consumption of the secondary loop accounts for approximately 80% of the electrical consumption for both studied installations. The flow control regulation in district cooling loops is typically based on pressure control [35]. This approach is favored because the length and circulation time of chilled water in the loop make temperature-based control challenging. However, based on measurements, it appears that flow control operates inadequately, leading to excessively low return loop temperatures and a very small temperature difference across the loop (often referred to as "low delta T syndrome"). Recent research focuses on advanced flow control techniques for district cooling systems [36, 37]. For the studied SWAC installations, the network configuration remains relatively straightforward as it is single-source heat. However, in the case of The Brando installation, unusually high return temperatures and very small temperature differentials between supply and return are observed. For both installations, the average temperature difference in the primary loop is 4.1°C, whereas in the secondary loop, it is only 2.8°C. Typically, such loops maintain a temperature differential of at least 5°C (**Figure 14**).

The temperature differentials observed on the secondary loops of both installations indicate that the flow rates could be halved, leading to a significant reduction in the electrical consumption of the pumps. An 'ideal' regulation would maintain a temperature differential of 5°C consistently across the loops. Using the numerical model of the SWAC installation presented earlier, a precise estimation of the annual gains can be provided. **Figure 15** compares the electrical powers for the secondary loop of The Brando between an ideal regulation maintaining a constant temperature differential of 5°C and the current regulation. The energy savings achieved with ideal control are estimated at 147.2 MWh per year, with the average power consumed by the pump over the year decreasing from 25.44 to 8.7 kW.

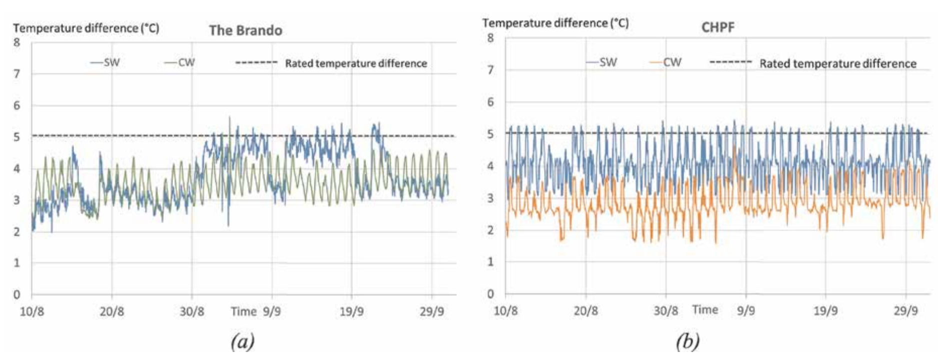

Figure 14.
Evolution of temperature differentials on the primary and secondary loops for The Brando (a) and CHPF (b).

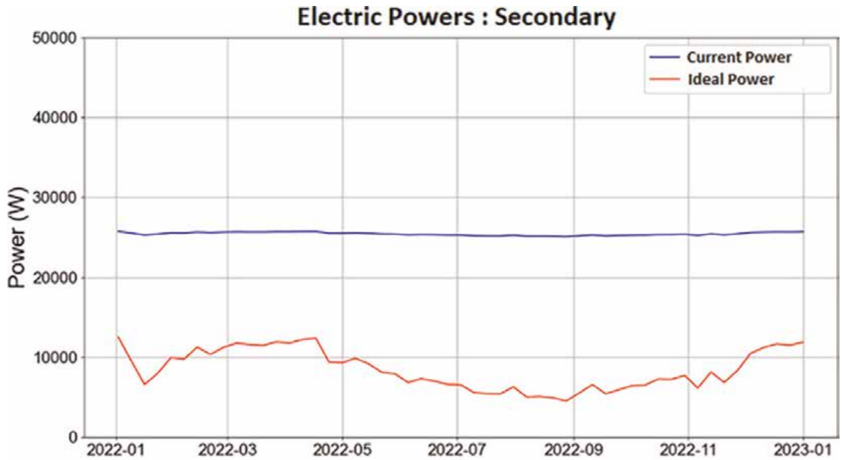

Figure 15.
Simulation of the electrical power consumed by the secondary loop of The Brando installation under ideal flow rate regulation.

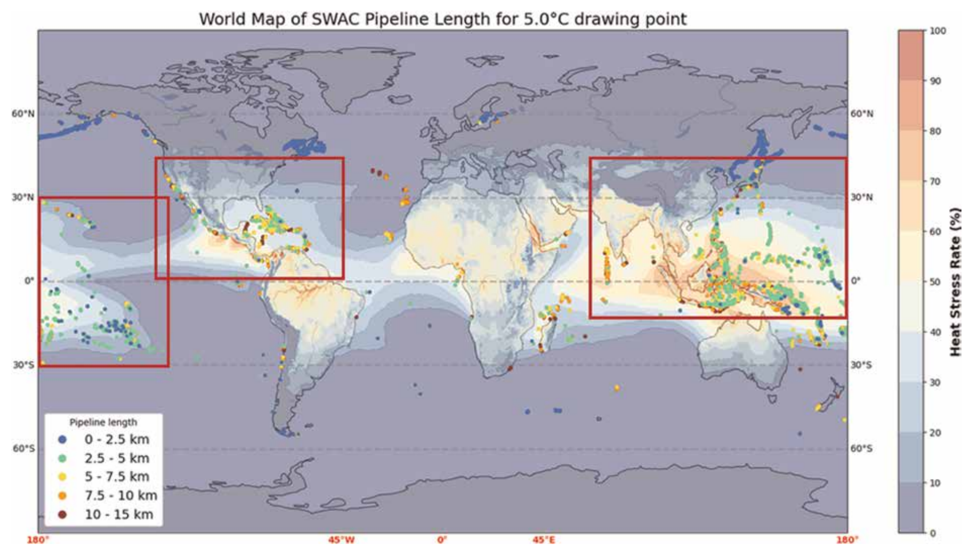

Figure 16.
Global mapping of SWAC potential for a drawing point of 5°C ensuring a chilled water loop temperature regime of 7/12°C; The red rectangles outline the areas of interest selected.

5. Worldwide potential of the technology

To study the development and dissemination of SWAC technology, it is important to define areas worldwide with favorable bathymetry for SWAC and assess the air conditioning needs in these areas.

A global mapping of sites favorable for this technology was established based on the design of a typical SWAC installation (operating with a temperature regime of 7/12°C) and also considering the potential for higher temperature regimes. Three datasets were used to identify feasible SWAC zones:

- The General Bathymetric Chart of the Oceans (GEBCO) 2021 [38] provides global elevation information in meters on a 30 arc-second grid, approximately 930 m near the equator.

- Global Ocean Reanalysis (GLORYS) [39], with a horizontal resolution of 1/12° (about 9.3 km near the equator) and 50 standard depth levels.

- ERA5-Heat data [40] is used to highlight areas with air conditioning demand. It has a horizontal resolution of 0.25° (about 28 km near the equator) and temporal coverage from January 1940 to present, with hourly intervals. This dataset provides the Universal Thermal Climate Index (UTCI), describing human physiological response to thermal environment combining temperature, humidity, wind speed, and thermal radiation.

The global potential for SWAC using the classical temperature regime of 7/12°C with a drawing temperature of 5°C is depicted in **Figure 16**, showing points near coastlines under thermal stress. Three geographically significant zones are highlighted by a red rectangle due to their high concentration of points: Central America, Asia, and Pacific Islands. Blue points indicate sites where the depth corresponding to a seawater temperature of 5°C is accessible within 2.5 km from the coast, while green points indicate distances between 2.5 and 5 km. These zones experience high thermal stress with exposure rates exceeding 30%. The Pacific Islands exhibit numerous blue points, indicating accessibility to greater depths near the coast, which facilitated the development of installations in Polynesia and justified the initial operational sites being located there.

Following the considerations discussed in the paragraph "district cooling temperature adjustment," it is important to assess the impact of changing the withdrawal depth on the deployment of the technology. **Figure 17** provides the mapping for a withdrawal point at 11°C and a chilled water distribution regime of 13/18°C.

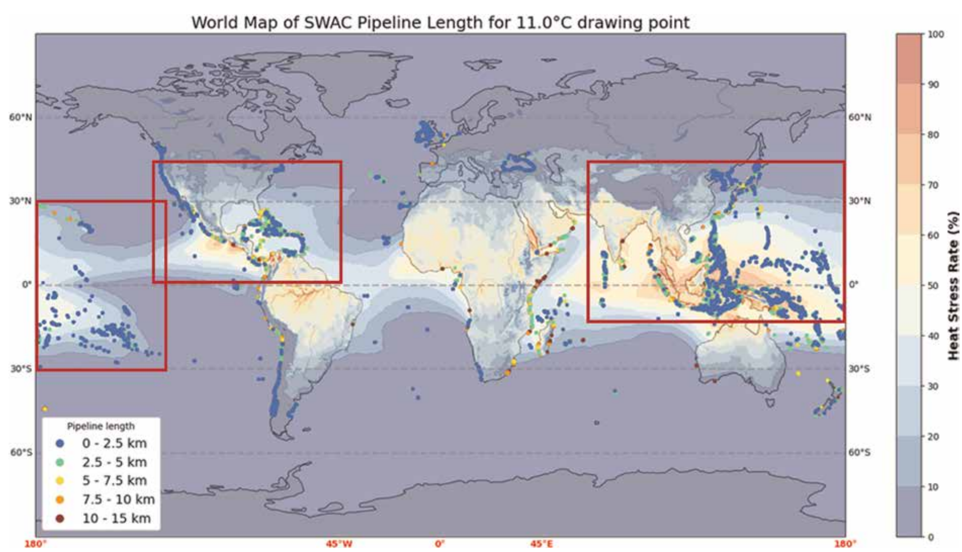

Figure 17.
Global mapping of SWAC potential for a drawing point of 11°C, ensuring a chilled water loop temperature regime of 13/18°C. The red frames outline the areas of interest selected.

		Central America	Asia	Pacific Islands
Drawing temperature 5°C Regime 5/12°C	Number of blue points (0–2,5 km)	376	12,913	193
	Number of green points (2,5–5 km)	1922	14,952	11,953
Drawing temperature 11°C Regime 13/18°C	Number of blue points (0–2,5 km)	29,779	76,478	11,204
	Number of green points (2,5–5 km)	26,522	104,280	29,428

Table 5.
Evolution of the implementation potential of SWAC technology for withdrawal temperatures of 5 and 11°C in the three geographic zones of interest.

For a drawing temperature of 11°C, the implementation potential of the technology worldwide is significantly increased, with a substantial increase in the number of blue and green points for the geographical areas of interest, as presented in **Table 5**. The number of potential sites increases by 332.2% when increasing the withdrawal temperature from 5 to 11°C for the Americas, by 225.7% for Asia, and by 124.3% for the Pacific. It can be noted that worldwide, outside the three areas of interest, the trend in the number of points favorable to SWAC is similar.

The use of higher temperature regimes in the chilled water distribution loop can thus improve energy performance (increased EER) and financial viability (reduced CAPEX) of installations, while also potentially enabling a much broader adoption of the technology worldwide. However, it will be necessary to verify that these temperature regimes are compatible with comfort conditions, especially in humid climates, ensuring proper indoor air dehumidification. Moreover, the temporal and spatial variability of the SWAC drawing temperature, in the context of climate change, is unknown because there are very few studies on the evolution of seawater temperatures at great depths (greater than 500 m), as the state-of-the-art focuses on surface temperature changes.

6. Conclusions

SWAC technology is an active cooling method for buildings that provides the same service as conventional air conditioning but with higher energy efficiency. The operating principle is straightforward: it involves transporting cold liquid-phase fluid from the sea to a large building or district. This process is not subject to the Carnot efficiency limit, offering numerous advantages:

- The energy efficiency ratio ranges from 25 to 125, depending on the length of the loops.
- In a specific example of an existing building, experimental data show that energy consumption, electrical power demand, and CO_2 emissions from air conditioning were reduced by a factor of 10 with SWAC.
- No refrigerants are required for operation.

- The resource remains at a stable temperature throughout the year and is minimally affected by climate change.
- The energy performance of the process is independent of external conditions.
- The process does not generate heat discharge near the building or in the air-conditioned area, thus limiting urban heat island effects.

The scope of direct SWAC is currently limited to coastal areas with water at approximately 5°C. The maximum distance from the coast to access these temperatures seems to be 10 km. Beyond that, performance drops, and costs skyrocket. However, if the water temperature is not favorable for direct SWAC, a chiller-assisted SWAC solution remains feasible. This solution can be particularly applicable to lakes or rivers. The main limitation to the exploitation of SWAC is the high investment costs, primarily due to maritime works. Solutions are currently being studied to develop direct SWAC systems using less cold seawater available at shallower depths, thus broadening the scope of SWAC application and reducing investment costs.

6.1 Recommendation and future work

Moreover, there is room for further process improvements. Future research should aim to:

- Further enhance performance (improving flow control, modifying distribution temperature regimes, integrating cold storage or supplementation).
- Expand the technology's application potential globally, including areas with shallower depths, while ensuring indoor comfort conditions and maintaining dehumidification in humid climates.
- Explore resource sharing with other industrial activities to enhance economic viability, such as electricity production through OTEC cycles, aquaculture, and agriculture utilizing seawater effluents.
- Evaluate the environmental benefits of the process in combating surface water warming.
- Investigate opportunities for combining the technology with soft cooling solutions (passive cooling techniques, adaptive comfort).

SWAC technology offers significant advantages, although its applicability is site-specific. Nonetheless, it emerges as a resilient solution for actively cooling buildings in the face of climate change, especially in regions experiencing more severe heatwaves. Therefore, it should be considered for future large building and district projects near coastal areas.

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References

[1] Machard A, Salvati A, Tootkaboni PM, et al. Typical and extreme weather datasets for studying the resilience of buildings to climate change and heatwaves. Scientific Data. 2024;**11**:531. DOI: 10.1038/s41597-024-03319-8

[2] ANSI/ASHRAE, 2013 Standard 169-2013. Climatic Data for Building Design Standards, 8400. 2013. p. 104

[3] Noro M, Lazzarin RM. Solar cooling between thermal and photovoltaic: An energy and economic comparative study in the Mediterranean conditions. Energy. 2014;**73**:453e464

[4] Eicker U, Pietruschka D, Schmitt A. Maximilian Haag comparison of photovoltaic and solar thermal cooling systems for office buildings in different climates. Solar Energy. 2015;**118**: 243-255

[5] Allan H, Levin N, Kark S. Quantifying and mapping the human footprint across Earth's coastal areas. Ocean & Coastal Management. 2023;**236**:106476. ISSN 0964-5691. DOI: 10.1016/j.ocecoaman.2023.106476

[6] Osorio AF, Arias-Gaviria J, Devis-Morales A, Acevedo D, Velasquez HI, Arango-Aramburo S. Beyond electricity: The potential of ocean thermal energy and ocean technology ecoparks in small tropical islands. Energy Policy. 2016;**98**: 713-724

[7] Hunt JD, Byers E, Sánchez AS. Technical potential and cost estimates for seawater air conditioning. Energy. 2019;**166**:979-988

[8] Hernández-Romero IM, Nápoles-Rivera F, Mukherjee R, et al. Optimal design of air-conditioning systems using deep seawater. Clean Technologies and Environmental Policy. 2018;**20**:639-654. DOI: 10.1007/s10098-018-1493-7

[9] Arias-Gaviria J, Osorio AF, Arango-Aramburo S. Estimating the practical potential for deep ocean water extraction in the Caribbean. Renewable Energy. 2020;**150**:307-319

[10] Sanjivy K, Hopuare M, Jamelot A, Ferrucci F, Marc O, Lucas F. Exploring global accessibility of deep ocean water for sea water air conditioning (SWAC) process: Identifying feasibility areas depending on temperature source. Sustainable Energy Technologies and Assessments. 2024;**61**:103601

[11] Surroop D, Abhishekanand A. Technical and economic assessment of seawater air conditioning in hotels. International Journal of Chemical Engineering and Applications. 2013;**4**(6):382-388

[12] Sanjivy K, Marc O, Davies N, Lucas F. Energy performance assessment of sea water air conditioning (SWAC) as a solution toward net zero carbon emissions: A case study in French Polynesia. Energy Reports. 2023;**9**: 437-446

[13] Euro SWAC. Available from: https://euroswac.fr/

[14] Hunt JD, Zakeri B, Nascimento A, Garnier B, Pereira MG, Bellezoni RA, et al. High velocity seawater air-conditioning with thermal energy storage and its operation with intermittent renewable energies. Energy Efficiency. 2020;**13**:1825-1840. DOI: 10.1007/s12053-020-09905-0

[15] Hunt JD, Nascimento A, Zakeri B, Barbosa PSF, Costalonga L. Seawater air-

conditioning and ammonia district cooling: A solution for warm coastal regions. Energy. 2022;**254**:124359

[16] Hernandez-Romero IM, Fuentes-Cortes LF, Mukherjee R, El-Halwagi MM, Serna-Gonzalez M, Napoles-Rivera F. Multi-scenario model for optimal design of seawater air-conditioning systems under demand uncertainty. Journal of Cleaner Production. 2019;**238**: 117863

[17] Inayata A, Razab M. District cooling system via renewable energy sources: A review. Renewable and Sustainable Energy Reviews. 2019;**107**:360-373

[18] Broadstock DC, Wang X. District cooling services: A bibliometric review and topic classification of existing research. Renewable and Sustainable Energy Reviews. 2024;**190**:113893

[19] Werner S. District heating and cooling in Sweden. Energy. 2017;**126**: 419-429

[20] Chow TT, Au WH, Yau R, Cheng V, Chan A, Fong KF. Applying district-cooling technology in Hong Kong. Applied Energy. 2004;**79**:275-289

[21] Sameti M. Optimization approaches in district heating and cooling thermal network. Energy and Buildings. 2017; **140**:121-130

[22] Lund H, Duic N, Østergaard PA, Mathiesen BV. Future district heating systems and technologies: On the role of smart energy systems and 4th generation district heating. Energy. 2018;**165**(Part A):614-619

[23] Wirtz M, Kivilip L, Remmen P, Müller D. 5th generation district heating: A novel design approach based on mathematical optimization. Applied Energy. 2020;**260**:114158

[24] Bünninga F, Wettera M, Fuchsb M, Müller D. Bidirectional low temperature district energy systems with agent-based control: Performance comparison and operation optimization. Applied Energy. 2018;**209**:502-515

[25] The European Comission. Fifth Generation, Low Temperature, High Exergy District Heating and Cooling Networks. 2015. Available from: http://cordis.europa.eu/project/rcn/

[26] Youn YJ, Im YH. Assessment of the feasibility for hybrid seawater district cooling model under variable seawater temperature condition: Case study in South Korea. Renewable Energy. 2023; **218**:119311

[27] Zhen L, Lina DM, Shua HW, Jianga S, Zhub YX. District cooling and heating with seawater as heat source and sink in Dalian, China. Renewable Energy. 2007;**32**:2603-2616

[28] Hiawena S, Tingyua W, Xina J, Zhiyonga R, Haiyang Y, Lin D. Energy efficiency enhancement potential of the heat pump unit in a seawater source heat pump district heating system. Procedia Engineering. 2016;**146**:134-138

[29] Yik FWH, Burnett J, Prescott I. Predicting air-conditioning energy consumption of a group of buildings using different heat rejection methods. Energy and Buildings. 2001;**33**:151-166

[30] International Energy Agency. Resilient Cooling of Buildings; Key Performance Indicators Report (Annex 80); Energy in Buildings and Communities. Technology Collaboration Programme; 2024. Available from: https://www.building-research.at/wp-content/uploads/2024/06/International-Energy-Agency-Resilient-Cooling-of-Buildings-Key-Performance-Indicators-Report-Annex-80.pdf

[31] International Energy Agency (IEA). The Future of Cooling - Opportunities for Energy Efficient Air Conditioning. Paris, France: AIE; 2018

[32] EnergyPlus. Computer Software. Vers. 00. USDOE Office of Energy Efficiency and Renewable Energy (EERE), Energy Efficiency Office. Building Technologies Office. 2017. Available from: https://www.osti.gov//servlets/purl/1395882

[33] Wulfinghoff DR. Measure 2.2.1: Keep the chilled water supply temperature as high as possible. In: Energy Efficiency Manual. London, United Kingdom: Energy Institute Press; 2004. pp. 264-266

[34] Kyere EB, Jen T-C, Tartibu L. Analysis of the influence of chilled water temperature setpoint on thermal comfort and energy consumption. Arabian Journal for Science and Engineering. 2024;**49**:10409-10429 DOI: 10.1007/s13369-023-08350-2

[35] Calderoni M, Babu Sreekumar B, Dourlens-Quaranta S, Lennard Z, Rämä M, Klobut K, et al. Sustainable District Cooling; Guidelines. IEA DHC/CHP Report; 2019

[36] Zhang W, Jin X, Zhang L, Hong W. A novel method of variable flow operation in district cooling system: A case study. Case Studies in Thermal Engineering. 2023;**43**:102820

[37] Jangsten M, Lindholm T, Dalenback J-O. District cooling substation design and control to achieve high return temperatures. Energy. 2022; **251**:123913

[38] GEBCO Bathymetric Compilation Group 2021. The GEBCO_2021 Grid - a continuous terrain model of the global oceans and land. United Kingdom: NERC EDS British Oceanographic Data Centre NOC. 2021. DOI: 10.5285/c6612cbe-50b3-0cff-e053-6c86abc09f8f

[39] E.U. Copernicus Marine Service Information. Global Ocean Physics Reanalysis. n.d. Brussel, Belgium: CMEMS; DOI: 10.48670/moi-00021

[40] Bröde P, Fiala D, Błażejczyk K, Holmér I, Jendritzky G, Kampmann B, et al. Deriving the operational procedure for the universal thermal climate index (UTCI). International Journal of Biometeorology. 2012;**56**:481-494. DOI: 10.1007/s00484-011-0454-1

Chapter 3

Advancements in Materials Used in Air Conditioning Technologies

Ghalia A. Gaber and Lamiaa Z. Mohamed

Abstract

This chapter explores recent advancements in materials driving innovation within air conditioning technologies. Traditional materials face limitations in efficiency and sustainability, prompting a shift toward novel solutions. Nanostructured materials, with their enhanced heat transfer properties, are gaining prominence, alongside advanced heat exchanger materials offering superior performance and durability. Sustainability is prioritized through the adoption of eco-friendly materials and smart technologies. Shape memory alloys and smart materials enable adaptive systems for optimized comfort and energy efficiency. While challenges persist in cost and scalability, interdisciplinary efforts are propelling the field toward a future of greener, more efficient air conditioning solutions.

Keywords: air conditioning, sustainable technologies, advanced technologies, solar-powered air conditioning, advanced materials

1. Introduction

The energy demand has significantly increased due to the world's population growth and rising standards of living. Heating, ventilation, and air conditioning (HVAC) systems consume a considerable amount of energy among building services as shown in **Figure 1**. Energy demand roughly 10–20% of the total energy consumption in industrialized countries and 50% of the total energy consumption in buildings in developed countries [1]. The development of efficient energy systems for heating and cooling that use free energy sources is increasing quickly to lower the amount of nonrenewable energy used by HVAC systems. As such, the cooling demands in buildings could be met by utilizing a variety of energy sources (e.g., solar, biomass, waste, geothermal, etc.) or by hybridizing different cooling systems.

One energy-efficient cooling technique that can handle waste heat at low temperatures is adsorption cooling. A lot of work has gone into increasing the cooling capabilities and overall performance of adsorption systems. A summary of the development of silica gel-water adsorption cooling systems may be found in [2]. To lessen the high vacuum need dictated by water vapor, the researchers recommended employing mixed refrigerant. The development of hybrid systems, according to the authors in [3], is an effective strategy that lowers the cost of adsorption technology when compared to alternative cooling systems.

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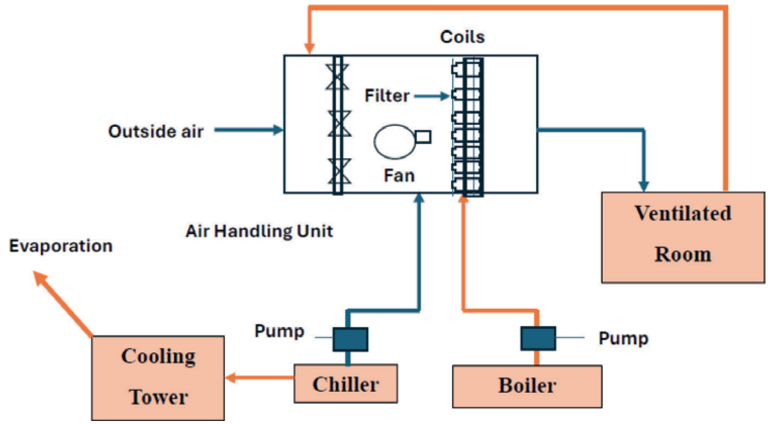

Figure 1.
Basic components of HVAC system.

According to Yin et al. [4], there have been advancements in the use of solar energy in these systems and the dehumidification of liquid desiccant. When combining a vapor compression machine with a hybrid liquid desiccant, Mohammad et al. [5] highlighted the significance of the vapor compression chiller's sizing and operating temperatures. The director in direct evaporative hybrid liquid desiccant systems produced a COP gain of more than 20% as compared to standalone evaporative coolers [6]. Traditional building cooling and heating systems need a lot of energy that comes from burning fossil fuels. This leads to the massive emissions of greenhouse gases into the atmosphere, which has adverse effects on human health like asthma as well as environmental harm like acid rain and global warming. However, for more than 60 years, typical air conditioning systems have been using chlorofluorocarbons (CFCs) as operating fluids. However, these refrigerants are known to weaken the ozone layer, which in turn causes global warming [7]. Research to find new technologies to offer an alternative to traditional vapor compression systems has been spurred by environmental concerns about CFCs, HCFCs, and some of their substitutes [8].

In the realm of air conditioning technologies, the materials utilized play a crucial role in determining efficiency, durability, and environmental impact. This chapter explores the latest advancements in materials that have revolutionized the field of air conditioning, enabling enhanced performance and sustainability. In addition to being made for people's comfort, air conditioning is necessary for enhancing processes and materials. The longevity and effectiveness of wrinkles in lower temperatures. Air cooling is also necessary for the effective operation of computer and microprocessor-based systems [9–12].

The following are common components used to create thermal insulation for air conditioning systems or building envelopes [13]:

- Fibrous materials, including cane, wood, glass, mineral wool, and other vegetal fibers.
- Materials with cells, like polystyrene, cellular glass, foam rubber, and polyurethane.
- Metallic reflective membranes. Open cells, or fibrous materials that are permeable by air, or closed cells, or airtight cellular materials, make up most insulating materials' airspaces [13].

An insulating material's thermal conductivity, a crucial physical characteristic, shows how quickly heat is transferred through the material *via* radiation, convection, and gas and solid conduction. An insulating material's physical structure (such as the diameter and shape of its cells), temperature, density, and the kind and quantity of binders and additives it contains all affect how thermally conductive it is [13]. Changes in density do not affect the thermal conductivity of many cellular insulating materials produced from polymers, such as polyurethane and extruded polystyrene. The density of other insulators is such that the thermal conductivity is negligible [13]. There are various refrigeration systems available for both building air conditioning and refrigeration. Based on the total energy required to run them, these systems can be divided into three primary groups: hybrid, thermal, and electrical systems. In the first category, electricity serves as the system's input energy (high-grade energy); in the second, any type of thermal energy can serve as the system's driving force (low-grade energy). The third one is made up of multiple energy types that work in concert to improve system performance and balance the energy supply [8].

More and more research as well as the commercial market are showing interest in the second group (thermal systems) lately. This is mostly because, compared to electrically run refrigeration plants, thermal systems have a lower potential to deplete the ozone layer and contribute less to greenhouse impacts. After all, they employ synthetic refrigerants. There are also fewer CO_2 emissions because they run on heat rather than electricity. In a conventional fossil fuel-powered power plant, producing electricity requires converting energy from chemical to thermal, mechanical, and then electrical forms in multiple steps. Higher CO_2 emissions to the environment are a result of losses related to each conversion step, the grid connection, and the transportation of electricity [14].

2. Traditional materials and their limitations

To maintain a suitable indoor climate, conventional mechanical air conditioning equipment uses a significant amount of fossil fuels [15, 16]. Pollution from the energy-generating system and greenhouse gasses from chemical-based refrigerants are the two main forms of pollution produced by a typical air conditioner [17]. Elevating the proportion of clean and renewable energy consumption and enhancing the energy efficiency of large-scale structures are imperative in mitigating the related risks of global warming and environmental degradation.

Traditional materials used in air conditioning systems are shown in **Figure 2** including metals like copper and aluminum, plastics, and various types of insulation. Copper is highly favored for refrigerant tubing, heat exchangers, and wiring because of its excellent thermal conductivity, corrosion resistance, and ease of fabrication. However, its higher cost and weight compared to alternative materials can be limiting in some applications. Aluminum, recognized for its lightweight nature and good thermal conductivity, is often used in heat exchangers (fins and coils). Plastics are used for components such as fan blades, housings, ducts, and insulation. Nonetheless, they may lack the strength and durability of metals, particularly at high temperatures, and generally have poorer thermal conductivity, limiting their use in heat transfer components. Additionally, improper recycling or disposal of certain plastics can raise environmental concerns [18]. The similar materials or alloys used as heat exchangers and inhibitory efficiencies are shown in **Table 1**.

Figure 2.
The traditional materials for air conditioning technologies.

Metal/alloy	Corrosion inhibitor	Efficiency %	References
Cu-Ni alloy	Chitosan-Sodium Pyruvate	65.0	[19]
Cu–Zn alloy	Expired Bepotastine-B	94.4	[20]
Cu-Zn alloy	Roselle (*Hibiscus sabdariffa*)	94.8	[21]
Al-Si-Cu-Mg	GO/ZrO_2	65.4	[22]
Cu-30 Ni alloy	Green tea aqueous extract	93.9	[23]

Table 1.
Contrasts the heat exchanger materials' inhibitory efficacy.

Insulation materials used in air conditioning systems include fiberglass and foam insulations such as polyurethane and polystyrene. Fiberglass is commonly employed for ductwork insulation due to its effective thermal resistance and sound absorption properties. However, it can cause skin irritation and respiratory issues during installation and is prone to moisture absorption, which can reduce its insulating effectiveness and encourage mold growth. Foam insulation materials like polyurethane and polystyrene are widely used for thermal insulation throughout air conditioning systems. Nevertheless, some foam types may pose flammability risks or emit toxic gases when burned, and they can degrade over time, especially when exposed to UV light or certain chemicals. Refrigerants such as CFCs, hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) have also been used in air conditioning systems. CFCs and HCFCs were historically favored for their excellent thermal properties but are now being phased out due to their contribution to ozone layer depletion and high global warming potential (GWP), as regulated under international agreements like the Montreal Protocol. HFCs have replaced CFCs and HCFCs in modern systems, but they still pose environmental concerns due to their significant GWP, leading to stricter regulations and the search for alternative refrigerants [24].

3. Nanostructured materials

Nanostructured materials are increasingly being studied for their potential applications in air conditioning systems, offering unique properties that could address the limitations of traditional materials. These include nanostructured coatings and nanocomposite materials. Anticorrosion coatings, such as those made from titanium

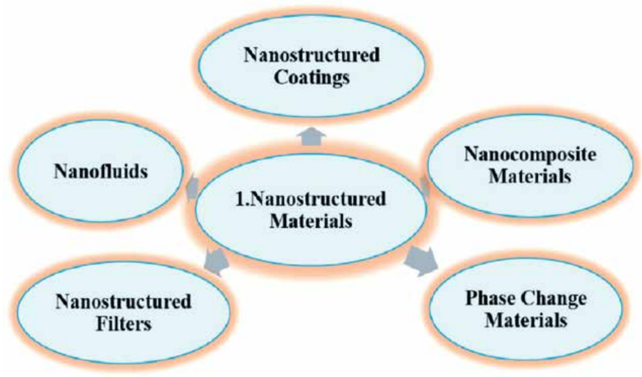

Figure 3.
The nanostructured materials for air conditioning technologies.

dioxide (TiO_2) or zinc oxide (ZnO), enhance corrosion resistance, prolong the component lifespan, and reduce maintenance costs [25]. Hydrophobic coatings, utilizing nanoparticles of silica or fluoropolymers, improve water resistance on heat exchangers, thereby enhancing efficiency and reducing corrosion risk. Nanocomposite materials also show promise in air conditioning applications. The nanostructured materials for air conditioning technologies are shown in **Figure 3**. For example, nanocomposite heat exchanger materials, which combine metals like aluminum or copper with carbon nanotubes (CNTs) or graphene, enhance thermal conductivity, improve heat transfer efficiency, and potentially reduce weight. Insulation materials, such as aerogels reinforced with nanoparticles, exhibit superior thermal insulation properties with minimal thermal conductivity, reducing energy loss and enhancing overall system efficiency [26, 27].

Nanofluids are being explored as refrigerants and heat transfer fluids due to their enhanced properties. Refrigerants blended with nanoparticles such as alumina (Al_2O_3), TiO_2, or copper oxide (CuO) increase thermal conductivity and heat transfer efficiency, potentially improving system performance and reducing energy consumption. Heat transfer fluids, consisting of nanoparticle suspensions in conventional fluids like water or ethylene glycol, enhance heat transfer coefficients and thermal conductivity, leading to more effective heat exchange processes. Nanostructured phase change materials (PCMs) are another innovative development. Embedding PCMs with nanoparticles enhances their thermal properties, improving heat storage and release capabilities. This is beneficial for thermal energy storage systems, thereby boosting the overall efficiency of air conditioning systems. Additionally, nanostructured filters are particularly effective for air filtration purposes. Nanofiber mats made from polymers such as polyvinyl alcohol (PVA) or polyacrylonitrile (PAN), often coated with antimicrobial nanoparticles like silver (Ag) or copper (Cu), enhance filtration efficiency. This improves the capture of fine particles and pathogens, thereby improving air quality and potentially extending the lifespan of the filters [28–30].

4. Advanced heat exchanger materials

Advanced heat exchanger materials for air conditioning systems are designed to improve efficiency, durability, and overall performance (**Figure 4**). This includes

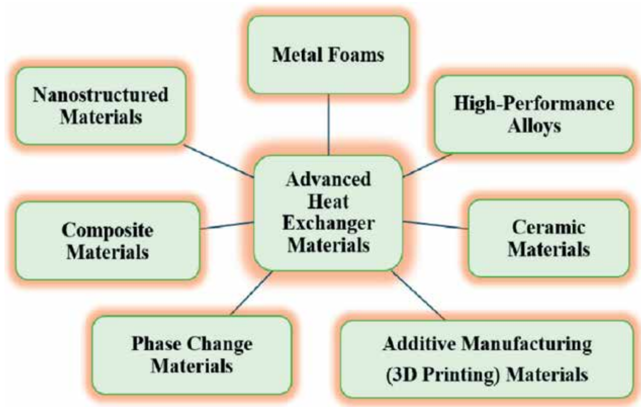

Figure 4.
The advanced heat exchanger materials for air conditioning technologies.

nanostructured materials such as graphene and CNTs. Graphene, known for its exceptional thermal conductivity, high mechanical strength, and lightweight properties, enhances heat transfer efficiency and reduces the weight of heat exchangers, leading to more compact and efficient designs. The CNTs also offer high thermal conductivity and strength, further improving thermal performance and potentially reducing the size and weight of heat exchangers. Composite materials, including metal matrix composites (MMCs) and polymer matrix composites (PMCs), are also utilized. MMCs combine metals like aluminum or copper with ceramic or carbon-based reinforcements, enhancing thermal conductivity, mechanical properties, and resistance to corrosion and wear. PMCs, on the other hand, are polymers reinforced with fibers such as carbon or glass, providing lightweight construction, corrosion resistance, and good thermal performance. Additionally, incorporating PCMs that can store and release large amounts of heat during phase transitions significantly enhances thermal energy storage capabilities. This improves overall thermal management and facilitates smoother temperature control in air conditioning systems [31–33].

Metal foams, such as aluminum and copper foams, are characterized by a high surface area-to-volume ratio, excellent thermal conductivity, and lightweight properties. These foams improve heat transfer efficiency, reduce weight, and enhance performance in compact heat exchanger designs. High-performance alloys, including nickel-based superalloys and titanium alloys, also play a crucial role. Nickel-based superalloys offer exceptional thermal stability, high strength, and resistance to oxidation and corrosion, making them suitable for high-temperature applications and challenging environments. This results in longer-lasting and more reliable heat exchangers. Titanium alloys, known for their high strength-to-weight ratio, excellent corrosion resistance, and good thermal conductivity, are ideal for lightweight and durable applications, particularly in marine or corrosive environments [34, 35].

Advanced ceramic materials such as silicon carbide (SiC), aluminum nitride (AlN), and boron nitride (BN) exhibit high thermal conductivity, excellent mechanical strength, and resistance to high temperatures and corrosion. These properties make them highly suitable for demanding heat exchanger applications. Additive manufacturing (3D printing) materials, including customized alloys and composites, offer precise control over material composition and structure. This enables the tailoring of thermal and mechanical properties. Additive manufacturing also provides design flexibility, the ability to create complex geometries, and optimized heat exchanger designs for enhanced performance [36].

5. Sustainable materials

A paradigm change in the development of eco-friendly and energy-efficient technology has become necessary due to the ongoing rise in the world's electricity demand and the depletion of fossil fuel resources. Summer air conditioning is still a difficult issue since it greatly raises the peak electricity consumption and lowers the cost of keeping a steady supply of electricity. Using renewable energy sources is one way to find solutions; solar energy is particularly promising because it is widely available and environmentally sustainable. Consequently, businesses and academics are becoming more interested in solar-assisted cooling systems that use solar thermal panels as heat sources [37–43].

For cooling applications, solar air conditioning systems are an environmentally friendly and economical choice. These solar-powered systems have many benefits. Solar-powered air conditioning systems support environmentally friendly cooling techniques and energy conservation. In places where access to electricity is scarce, they provide a chance to become energy-independent. Nonetheless, a few challenges prevent these systems from being widely used. These include installation expenses, reduced efficiency when compared to conventional systems, the necessity for efficient energy storage options, the space needed for solar panels, the effect of temperature variations, the intricacy of the system when integrating it with the current HVAC infrastructure, and public awareness. Despite obstacles, continuous research and development endeavors tackle these problems, stimulating creativity and clearing the path for the extensive integration of solar air conditioning systems [44].

Sustainable materials for air conditioning systems are designed to minimize environmental impact through enhanced energy efficiency, recyclability, and reduced carbon footprints (**Figure 5**). These materials include natural and recycled options like bamboo and metals. Bamboo is used in structural components, casings, and ductwork due to its renewability, biodegradability, and lower carbon footprint compared to metals and plastics. Recycled metals such as aluminum and copper help reduce the need for virgin material extraction, thereby lowering energy consumption and environmental impact. Bio-based plastics like polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are utilized in ductwork, housing, and insulation. These materials are derived from renewable resources such as corn starch or sugarcane, are biodegradable, and emit fewer carbon emissions than traditional plastics. Advanced insulation materials such as aerogels and natural fiber insulation offer significant benefits. Aerogels provide exceptionally low thermal conductivity and are lightweight, enhancing thermal insulation and reducing energy consumption. Some aerogels can be manufactured from silica, an abundant and environmentally friendly material. Natural fiber insulation materials like hemp, cotton, or sheep wool are renewable, biodegradable, and have minimal environmental impact during production [45, 46].

Bio-based PCMs, derived from plant oils or animal fats, are nontoxic, renewable, and enhance thermal energy storage, thereby improving the efficiency of air conditioning systems. Nanomaterials such as nanocellulose and silica nanoparticles play significant roles. Nanocellulose, derived from plant matter, is biodegradable, renewable, and offers excellent mechanical and thermal properties, used as reinforcement

Figure 5.
Sustainable materials for air conditioning technologies.

in composite materials and insulation. Silica nanoparticles are abundant, nontoxic, and enhance thermal insulation and durability in applications such as insulation and coatings. Environmentally friendly refrigerants, including natural options like ammonia (NH_3), carbon dioxide (CO_2), and hydrocarbons such as propane and isobutane, have low GWP and no ozone depletion potential (ODP). These alternatives are eco-friendly compared to traditional synthetic refrigerants. Recyclable and reusable components, including modular designs for easy disassembly and recycling, are employed. This approach facilitates recycling, reduces waste, and extends the lifespan of parts through reuse. Thermally conductive polymers, such as graphene-enhanced polymers used for heat exchangers and housings, offer high thermal conductivity and lightweight properties and can be produced with lower environmental impact compared to metals. Green manufacturing processes aim at low-emission production methods to minimize greenhouse gas emissions and energy use, thereby reducing the overall carbon footprint of air conditioning systems [47, 48].

6. Shape memory alloys and smart materials

Shape memory alloys (SMAs) and smart materials are increasingly integrated into air conditioning systems for their unique properties that enhance system efficiency, adaptability, and control (**Figure 6**). SMAs typically consist of alloys such as nickel-titanium (NiTi), copper-aluminum-nickel, or copper-zinc-aluminum. They exhibit the shape memory effect, allowing them to revert to their original shape after deformation when exposed to specific temperature changes. In air conditioning applications, SMAs are utilized in adaptive louvers and vents to automatically adjust airflow direction based on temperature changes. This capability improves airflow control, enhances energy efficiency, and boosts comfort levels by directing

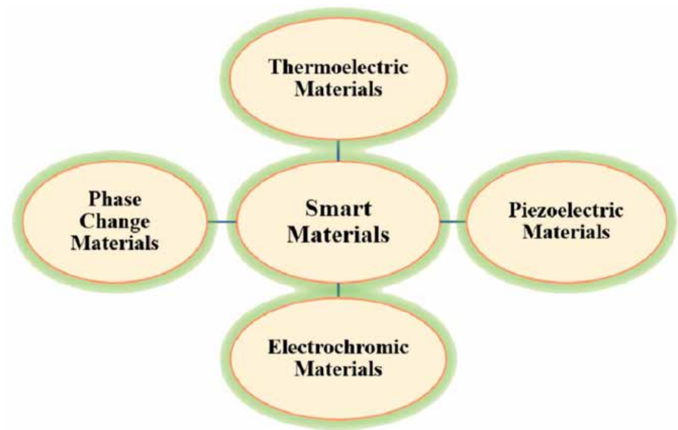

Figure 6.
Smart materials for air conditioning technologies.

air dynamically where it is most needed. SMAs also act as temperature-responsive actuators for controlling valves, dampers, and other components that require precise temperature-based adjustments. This enhances temperature regulation precision and reduces energy consumption by optimizing system performance. Moreover, SMAs are employed as heat exchanger enhancements, integrated into heat exchangers to improve heat transfer efficiency through dynamic changes in surface area. This enhancement improves thermal performance and potentially reduces the size and weight of heat exchangers [49, 50].

Smart materials like thermoelectric materials, piezoelectric materials, PCMs, and electrochromic materials are increasingly prominent in air conditioning systems due to their unique capabilities. Thermoelectric materials convert temperature differences directly into electrical voltage and vice versa, enabling active cooling and heating by converting waste heat into usable energy or creating temperature gradients for heat management. They enhance system efficiency through energy harvesting and waste heat recovery. Piezoelectric materials generate electrical charge in response to mechanical stress and can deform when an electrical field is applied. They are utilized in sensors and actuators to precisely control air conditioning components, thereby improving system responsiveness and energy management for enhanced comfort. The PCMs absorb and release significant amounts of latent heat during phase transitions (solid-liquid). Integrated into heat exchangers and thermal storage units, PCMs stabilize temperature fluctuations and store thermal energy, enhancing thermal management and energy efficiency for consistent indoor comfort. Electrochromic materials adjust color or opacity in response to electrical voltage, regulating the amount of heat and light passing through. They are employed in smart windows that automatically adjust the tint to manage solar heat gain, thereby reducing cooling demand and energy consumption while improving indoor comfort [51].

7. Future perspectives and challenges

The future of air conditioning materials is centered on enhancing efficiency, sustainability, and functionality while addressing environmental and economic challenges (**Figure 7**). Key areas of advancement include nanotechnology and

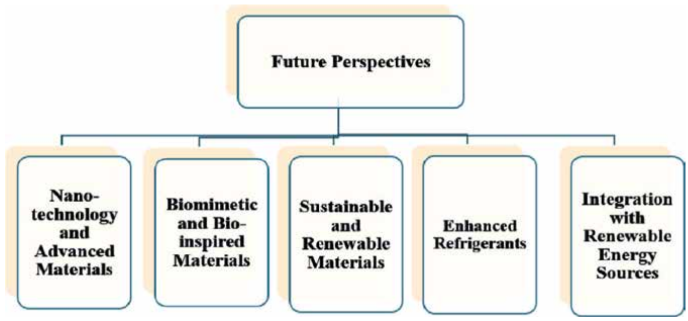

Figure 7.
Future perspectives for air conditioning technologies.

advanced materials, biomimetic coatings and structures, sustainable and renewable materials, enhanced refrigerants, and integration with renewable energy sources. Nanotechnology and advanced materials such as graphene and CNTs are enhancing heat exchangers, filters, and sensors due to their superior thermal conductivity, lightweight properties, and potential to reduce component size and weight. Aerogels are also being utilized as advanced insulation materials for their exceptionally low thermal conductivity, which improves energy efficiency. Smart materials like shape memory alloys, piezoelectric materials, and phase change materials offer enhanced responsiveness and adaptability in air conditioning systems. These materials optimize performance, conserve energy, and improve system efficiency. Biomimetic coatings and structures, inspired by natural systems, enhance efficiency and effectiveness in heat exchangers and airflow control devices by applying optimized biological designs. This approach aims to maximize energy efficiency and sustainability in air conditioning technology [52, 53].

Sustainable and renewable materials, including bio-based polymers and recycled/recyclable materials, are increasingly utilized in ductwork, insulation, and housing to diminish environmental impact and reduce reliance on fossil fuels. These materials contribute to sustainability efforts by enhancing durability and efficiency in air conditioning systems. Enhanced refrigerants, such as natural and low GWP options, are replacing traditional refrigerants to mitigate environmental harm. This transition aims to lower the overall impact of global warming while maintaining efficient cooling performance. Magnetocaloric and thermoelectric materials are under exploration for alternative cooling technologies, offering potentially more efficient and environmentally friendly cooling solutions. These materials leverage magnetic fields or temperature differentials to achieve cooling without harmful greenhouse gas emissions. Integration with renewable energy sources, such as solar-powered air conditioning and advanced energy storage systems, further promotes sustainability in air conditioning technology. Solar-powered air conditioning systems integrate photovoltaic systems with air conditioning units to reduce dependence on grid electricity, lower operational costs, and enhance overall sustainability. Advanced batteries and thermal storage systems are also pivotal in improving energy management and efficiency in air conditioning applications. These technologies enable better utilization of renewable energy sources, supporting sustainable practices in cooling solutions [54].

Air conditioning materials face several challenges including cost and scalability, environmental impact, technical integration, and regulatory and market acceptance (**Figure 8**). High initial costs and scalability issues are particularly notable, especially

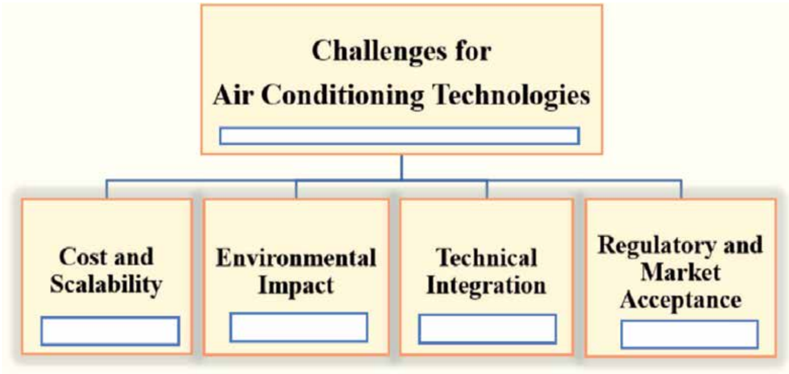

Figure 8.
Challenges for air conditioning technologies.

for advanced materials like graphene, CNTs, and aerogels, which are expensive to produce and scale up while maintaining cost-effectiveness. Ensuring economic feasibility is crucial for these materials and technologies to achieve widespread adoption in both consumer and industrial markets. Environmental impact is another significant concern, necessitating thorough lifecycle analysis of new materials from production through disposal. It is essential to ensure these materials are genuinely sustainable and do not introduce new environmental issues. Effective end-of-life management strategies are also critical to responsibly recycle or dispose of advanced materials without causing harm to the environment. Technical integration presents challenges in effectively incorporating new materials and technologies into existing air conditioning systems without compromising performance or reliability. Ensuring compatibility and optimizing system designs are essential steps in overcoming these integration hurdles. Regulatory requirements and market acceptance further influence the adoption of these innovations. Compliance with standards and demonstrating clear benefits in terms of efficiency, sustainability, and performance are necessary to gain industry and consumer confidence. Addressing these challenges requires collaborative efforts across research, industry, and regulatory bodies to advance air conditioning technologies sustainably and effectively [55].

Technical integration in air conditioning systems encompasses two critical aspects: compatibility and performance validation. Compatibility involves ensuring that new materials can seamlessly integrate into existing air conditioning systems and infrastructure without encountering significant compatibility issues with current technologies. This process addresses potential challenges that may arise when introducing novel materials into established systems, ensuring smooth operation and functionality. Performance validation is equally crucial, involving rigorous testing to assess and confirm the performance and reliability of new materials under real-world operating conditions. This step is essential to demonstrate that the materials can deliver the expected benefits in terms of efficiency, durability, and overall effectiveness in air conditioning applications. It ensures that the materials meet industry standards and user expectations, providing confidence in their suitability for widespread adoption [56].

Regulatory approval and market acceptance present additional challenges in the adoption of new air conditioning materials and technologies.

Obtaining regulatory approval involves navigating complex frameworks to meet environmental, safety, and other relevant standards. It requires demonstrating that new materials and technologies comply with regulations to ensure their safe and lawful use. This process involves thorough testing, documentation, and compliance efforts to address regulatory requirements effectively. Consumer and industry adoption is crucial for the widespread uptake of innovative materials. Educating consumers and industry stakeholders about the advantages and benefits of these materials is essential for overcoming resistance to change and fostering acceptance. Highlighting how these materials can improve energy efficiency, reduce environmental impact, and enhance overall performance compared to traditional solutions is key. This education helps build confidence in the reliability and effectiveness of new materials, encouraging their integration into mainstream air conditioning systems. Addressing these challenges requires collaboration among researchers, manufacturers, regulatory bodies, and stakeholders to streamline approval processes, enhance awareness, and promote the adoption of sustainable and efficient air conditioning technologies.

8. Conclusions

Advancements in air conditioning materials hold great promise for enhancing energy efficiency, sustainability, and comfort in response to evolving global needs. By embracing innovative materials and taking a comprehensive approach, the air conditioning industry can aim toward creating more efficient and environmentally friendly systems. It was concluded that:

1. Traditional materials have served their purpose, but they come with limitations such as cost, environmental impact, durability, and efficiency. This has spurred ongoing research and development efforts to discover better alternatives like advanced composites, eco-friendly refrigerants, and improved insulation materials.

2. Nanostructured materials, with their enhanced thermal properties and improved efficiency, offer significant advantages for air conditioning systems. They promise superior heat transfer, insulation capabilities, and corrosion resistance, potentially overcoming the shortcomings of traditional materials. As nanotechnology advances, these materials are expected to gain traction in air conditioning applications, paving the way for more sustainable and efficient systems.

3. Advanced heat exchanger materials represent another leap forward, providing superior thermal performance, reduced weight, enhanced durability, and better resistance to environmental factors. These materials enable the design of more compact, efficient, and longer-lasting air conditioning systems. Continued technological progress is likely to increase their adoption, fostering innovation in energy-efficient cooling solutions.

4. Sustainable materials play a crucial role by emphasizing renewable resources, recyclability, and minimizing environmental impact. Their use contributes to energy efficiency, lower carbon emissions, and a reduced environmental footprint in air conditioning operations. As sustainability gains prominence, these materials are expected to see wider adoption, promoting greener air conditioning technologies.

5. Smart materials like shape memory alloys and others offer significant potential for improving air conditioning systems through enhanced efficiency, control, and adaptability. Shape memory alloys respond dynamically to temperature changes, suitable for adaptive components and actuators. Meanwhile, thermoelectrics, piezoelectrics, phase change materials, and electrochromic materials contribute to more efficient thermal management and energy usage. Integrating these advanced materials into air conditioning systems can lead to smarter, more efficient, and environmentally friendly cooling solutions.

6. Looking ahead, the future of air conditioning materials holds substantial promise for advancing efficiency, sustainability, and functionality. However, challenges related to cost, scalability, environmental impact, technical integration, and regulatory acceptance must be addressed to unlock the full potential of these innovations. Collaboration among researchers, industry stakeholders, and policymakers will be critical in overcoming these hurdles and driving the development and adoption of next-generation air conditioning materials.

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Conflict of interest

The authors declare that they have no conflict of interest.

Appendices and nomenclature

HVAC	heating, ventilation, and air conditioning
CFCs	chlorofluorocarbons
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
GWP	global warming potential
TiO_2	titanium dioxide
ZnO	zinc oxide
CNTs	carbon nanotubes
Al_2O_3	alumina
CuO	copper oxide
PCMs	phase change materials
PVA	polyvinyl alcohol
PAN	polyacrylonitrile

Ag	silver
Cu	copper
MMCs	metal matrix composites
PMCs	polymer matrix composites
SiC	silicon carbide
AlN	aluminum nitride
BN	boron nitride
PLA	polylactic acid
PHA	polyhydroxyalkanoates
NH_3	ammonia
CO_2	carbon dioxide
ODP	ozone depletion potential
SMAs	shape memory alloys
NiTi	nickel-titanium

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References

[1] Pérez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy and Buildings. 2008;**40**:394-398. DOI: 10.1016/j.enbuild.2007.03.007

[2] Wang D, Zhang J, Tian X, Liu D, Sumathy K. Progress in silica gel–water adsorption refrigeration technology. Renewable and Sustainable Energy Reviews. 2014;**30**:85-104. DOI: 10.1016/j.rser.2013.09.023

[3] Choudhury B, Saha BB, Chatterjee PK, Sarkar JP. An overview of developments in adsorption refrigeration systems towards a sustainable way of cooling. Applied Energy. 2013;**104**:554-567. DOI: 10.1016/j.apenergy.2012.11.042

[4] Yin Y, Qian J, Zhang X. Recent advancements in liquid desiccant dehumidification technology. Renewable and Sustainable Energy Reviews. 2013;**31**:38-52. DOI: 10.1016/j.rser.2013.11.021

[5] Mohammad AT, Bin MS, Sulaiman MY, Sopian K, Al-Abidi AA. Survey of liquid desiccant dehumidification system based on integrated vapor compression technology for building applications. Energy and Buildings. 2013;**62**:1-14. DOI: 10.1016/j.enbuild.2013.03.001

[6] Mohammad AT, Bin MS, Sulaiman MY, Sopian K, Al-Abidi AA. Historical review of liquid desiccant evaporation cooling technology. Energy and Buildings. 2013;**67**:22-33. DOI: 10.1016/j.enbuild.2013.08.018

[7] Fairchild PD, Fulkerson W. Energy Technology R&D and Greenhouse Effect. Saito: Elsevier; 1989. pp. 231-241

[8] Afonso CFA. Recent advances in building air conditioning systems. Applied Thermal Engineering. 2006;**26**:1961-1971. DOI: 10.1016/j.applthermaleng.2006.01.016

[9] Pita EG. Air Conditioning Principles and Systems. 4th ed. New York: Pearson Education; 2003

[10] Lang VP. Principles of Air Conditioning. 3rd ed. CBS Publishers and Distributors. cir.nii.ac.jp; 2018

[11] Prashad M. Refrigeration and Air Conditioning Data Book||. New Age International Publishers; 2015

[12] Althouse AD, Turnquist CH, Braccino AF. Modern Refrigeration and Air Conditioning. 20th ed. Goodheart-Willcox: Textbook; 2016

[13] Wang SK. Handbook of Air Conditioning and Refrigeration. 2nd ed. McGraw-Hill; 2001

[14] Smith JT. A comparison of the CO_2 emission rates of gas-fired and electrically driven chiller/heater machines under dynamic loading. In: CIBSE (Chartered Institution of Building Services Engineers) National Conference in Eastbourne. England; 1995. pp. 151-159

[15] Liu G, Wu Z, Hu M. Energy consumption and management in public buildings in China: An investigation of Chongqing. Energy Procedia. 2012;**14**:1925-1930. DOI: 10.1016/j.egypro.2011.12.1189

[16] Wan KK, Li DH, Liu D, Lam JC. Future trends of building heating and cooling loads and energy consumption in different climates. Building and

Environment. 2011;**46**:223-234. DOI: 10.1016/j.buildenv.2010.07.016

[17] Jon CK. Advances in Air Conditioning Technologies: Improving Energy Efficiency. Singapore: Springer; 2020

[18] Chen X, Su Y, Reay D, Riffat S. Recent research developments in polymer heat exchangers—A review. Renewable and Sustainable Energy Reviews. 2016;**60**:1367-1386. DOI: 10.1016/j.rser.2016.03.024

[19] Dardeer HM, Abbas SA, Ghobashy MM, Gaber GA, Aly MF. Synthesis and characterization of novel chitosan-sodium pyruvate polymer and its derivatives for corrosion feature evaluation of Cu-Ni alloy. Inorganic Chemistry Communications. 2023;**157**:111308. DOI: 10.1016/j.inoche.2023.111308

[20] Gaber GA, Soliman MM, Adel Nasr Z, Hyba AM. Comprehensive investigation of sustainable corrosion inhibitors on Cu–Zn alloy in simulated cooling water: Electrochemical explorations, SEM/EDX analysis, and DFT/molecular simulations utilizing expired bepotastine-B as a green inhibitor. Sustainable Chemistry and Pharmacy. 2024;**37**:101340. DOI: 10.1016/j.scp.2023.101340

[21] Shahen S, Abdel-karim AM, Gaber GA. Eco-friendly Roselle (*Hibiscus sabdariffa*) leaf extract as naturally corrosion inhibitor for Cu-Zn alloy in 1M HNO_3. Egyptian Journal of Chemistry. 2022;**65**(4):351-361. DOI: 10.21608/ejchem.2021.92917.4392

[22] Mohamed LZ, Hamdy G, Gaber GA. Performance of GO/SiO_2, GO/TiO_2, and GO/ZrO_2 nanocomposites coatings as a corrosion barrier layer on Al-Si-Cu-Mg alloy in 3.5% NaCl solution. International Journal of Electrochemical Science. 2021;**16**:210515. DOI: 10.20964/2021.05.13

[23] Gaber GA, Maamoun MA, Ghanem WA. Evaluation of the inhibition efficiency of a green inhibitor on corrosion of Cu-Ni alloys in the marine application. Key Engineering Materials. 2018;**786**:174-194. DOI: 10.4028/www.scientific.net/kem.786.174

[24] Naldzhiev D, Mumovic D, Strlic M. Polyurethane insulation and household products—A systematic review of their impact on indoor environmental quality. Building and Environment. 2019;**169**:106559. DOI: 10.1016/j.buildenv.2019.106559

[25] Gaber GA, Mohamed LZ, Jarvenp A, Hamada A. Enhancement of corrosion protection of AISI 201 austenitic stainless steel in acidic chloride solutions by Ce-doped TiO_2 coating. Surface and Coatings Technology. 2021;**423**:127618. DOI: 10.1016/j.surfcoat.2021.127618

[26] Khan I, Saeed K, Khan I. Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry. 2019;**12**:908-931. DOI: 10.1016/j.arabjc.2017.05.011

[27] Farooq SA, Raina A, Mohan S, Singh RA, Jayalakshmi S, Haq MTU. Nanostructured coatings: Review on processing techniques. Corrosion Behaviour and Tribological Performance, Nanomaterials. 2022;**12**:1323. DOI: 10.3390/nano12081323

[28] Nair V, Parekh AD, Tailor PR. Water-based Al_2O_3, CuO and TiO_2 nanofluids as secondary fluids for refrigeration systems: A thermal conductivity study. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2018;**40**:262. DOI: 10.1007/s40430-018-1177-6

[29] Ahmed F, Khan WA. Efficiency enhancement of an air-conditioner utilizing nanofluids: An experimental study. Energy Reports. 2021;**7**:575-583. DOI: 10.1016/j.egyr.2021.01.023

[30] Bacha HB, Ullah N, Hamid A, Shah NA. A comprehensive review on nanofluids: Synthesis, cutting-edge applications, and future prospects. International Journal of Thermofluids. 2024;**22**:100595. DOI: 10.1016/j.ijft.2024.100595

[31] Natesan K, Karinka S. A comprehensive review of heat transfer enhancement of heat exchanger, heat pipe and electronic components using graphene. Case Studies in Thermal Engineering. 2023;**45**:102874. DOI: 10.1016/j.csite.2023.102874

[32] Ali A, Bahman AM, Aljuwayhel NF, Ebrahim SA, Mukherjee S, Alsayegh A. Carbon-based nanofluids and their advances towards heat transfer applications—A review. Nanomaterials. 2021;**11**:1628. DOI: 10.3390/nano11061628

[33] Ali A, Koloor SSR, Alshehri AH, Arockiarajan A. Carbon nanotube characteristics and enhancement effects on the mechanical features of polymer based materials and structures e a review. Journal of Materials Research and Technology. 2023;**24**:6495-6521. DOI: 10.1016/j.jmrt.2023.04.072

[34] Yang H, Li Y, Yang Y, Chen D, Zhu Y. Effective thermal conductivity of high porosity open-cell metal foams. International Journal of Heat and Mass Transfer. 2020;**147**:118974. DOI: 10.1016/j.ijheatmasstransfer.2019.118974

[35] Boomsma K, Poulikakos D, Zwick F. Metal foams as compact high performance heat exchangers. Mechanics of Materials. 2003;**35**(12):1161-1176. DOI: 10.1016/j.mechmat.2003.02.001

[36] Watari K. High thermal conductivity non–oxide ceramics. Journal of the Ceramic Society of Japan. 2001;**109**(1265):S7-S16. DOI: 10.1016/j.mechmat.2003.02.001

[37] Ha QP, Vakiloroaya V. A novel solar-assisted air-conditioner system for energy savings with performance enhancement, evolving energy-IEF International Energy Congress (IEF-IEC2012). Procedia Engineering. 2012;**49**:116-123. DOI: 10.1016/j.proeng.2012.10.119

[38] Henning H. Solar assisted air conditioning of buildings an overview. Applied Thermal Engineering. 2007;**27**:1734-1749. DOI: 10.1016/j.applthermaleng.2006.07.021

[39] Wang Q, Liu YQ, Liang GF, Li JR, Sun SF, Chen GM. Development and experimental validation of a novel indirect-expansion solar-assisted multifunctional hear pump. Energy and Buildings. 2011;**43**:300-304. DOI: 10.1016/j.enbuild.2010.09.013

[40] Al-Alili A, Hwang Y, Radermacher R, Kubo I. A high efficiency solar air conditioner using concentrating photovoltanic/thermal collectors. Applied Energy. 2012;**93**:138-147. DOI: 10.1016/j.apenergy.2011.05.010

[41] Zambrano D, Bordons C, Garcia-Gabin W, Camacho EF. Model development and validation of a solar cooling plant. International Journal of Refrigeration. 2008;**31**:315-328. DOI: 10.1016/j.ijrefrig.2007.05.007

[42] Kim DS. Feasibility of a compact heat recovery ventilation module with an integrated air-cooled solar absorption air-conditioner.

International Journal of Thermal Sciences. 2011;**50**:1604-1614. DOI: 10.1016/j.ijthermalsci.2011.03.023

[43] Audah N, Ghaddar N, Ghali K. Optimized solar-powered liquid desiccant system to supply building fresh water and cooling needs. Applied Energy. 2011;**88**:3726-3736. DOI: 10.1016/j.apenergy.2011.04.028

[44] Rasuli MA, Torii S. A review on solar air conditioning systems. Journal of Sustainable Energy Revolution. 2024;**4**(1):1-10. DOI: 10.37357/1068/jser/4.1.01

[45] Tazmeen T, Mir FQ. Sustainability through materials: A review of green options in construction. Results in Surfaces and Interfaces. 2024;**14**:100206. DOI: 10.1016/j.rsurfi.2024.100206

[46] Abera YA. Sustainable building materials: A comprehensive study on eco-friendly alternatives for construction. Composites and Advanced Materials. 2024;**33**:1-17. DOI: 10.1177/26349833241255957

[47] Li D, Zhuang B, Chen Y, Li B, Landry V, Kaboorani A, et al. Incorporation technology of bio-based phase change materials for building envelope: A review. Energy and Buildings. 2022;**260**(5):111920. DOI: 10.1016/j.enbuild.2022.111920

[48] Aridi R, Yehya A. Review on the sustainability of phase-change materials used in buildings. Energy Conversion and Management: X. 2022;**15**:100237. DOI: 10.1016/j.ecmx.2022.100237

[49] Nnamchi P, Younes A, González S. A review on shape memory metallic alloys and their critical stress for twinning. Intermetallics. 2019;**105**:61-78. DOI: 10.1016/j.intermet.2018.11.005

[50] Hamid QY, Hasan WZW, Hanim MAA, Nuraini AA, Hamidon MN, Ramli HR. Shape memory alloys actuated upper limb devices: A review. Sensors and Actuators Reports. 2023;**5**:100160

[51] Prabhathan P, Sreekanth KV, Teng J, Ko JH, Yoo YJ, Jeong HH, et al. Roadmap for phase change materials in photonics and beyond. iScience. 2023;**26**(10):107946. DOI: 10.1016/j.isci.2023.107946

[52] Ali BM, Akkaş M. The green cooling factor: Eco-innovative heating, ventilation, and air conditioning solutions in building design. Applied Sciences. 2024;**14**(1):195. DOI: 10.3390/app14010195

[53] Ohenhen PE, Chidolue O, Umoh AA, Ngozichukwu B, Fafure AV, Ilojianya VI, et al. Sustainable cooling solutions for electronics: A comprehensive review: Investigating the latest techniques and materials, their effectiveness in mechanical applications, and associated environmental benefits. World Journal of Advanced Research and Reviews. 2024;**21**(01):957-972

[54] Garcia J, Semedo A. Sustainable CO_2 refrigeration system for fish cold storage facility using a renewable integrated system with solar, wind and tidal energy for Cape Verde—Analyzing scenarios. Sustainability. 2024;**16**(10):4259. DOI: 10.3390/su16104259

[55] Gu X, Ling Y. Research progress of aerogel materials in the field of construction. Alexandria Engineering Journal. 2024;**91**:620-631. DOI: 10.1016/j.aej.2024.02.039

[56] Licardo JT, Domjan M, Orehovački T. Intelligent robotics—A systematic review of emerging technologies and trends. Electronics. 2024;**13**(3):542. DOI: 10.3390/electronics13030542

Chapter 4

Localized Air Conditioning Can Enable Zero-Energy Buildings in South Asia

James Trevelyan

Abstract

Most work on zero-energy buildings has focused on wealthier countries. While these countries urgently need reduce emissions, there also needs to be a focus on the Global South with different social cultures, economic conditions, climate and buildings. South Asia may dominate future energy and greenhouse emissions because of energy demand for cooling. A large proportion of the South Asian population are living and working in conditions beyond human physiological limits, resulting in low productivity, hindering economic development. Replacement of the existing building stock with 'energy-efficient' buildings is unlikely to be economically feasible. Localized cooling and heating offers large energy reductions compared with space cooling and heating while providing similar human comfort. Concentrating the cooling effect of an air conditioner, creating a small microclimate instead of cooling an entire space, allows occupants to enjoy comfort with substantially less energy. Commercial products are already available, and they provide significant economic savings and health benefits. These technologies can help to greatly reduce future South Asian energy requirements and avoid emissions that would occur if existing buildings were to be replaced. Widespread application of this technology could help achieve the UN Sustainable Development Goals and boost human productivity.

Keywords: localized air-conditioning, zero-energy buildings, productivity, climate, energy-efficiency, South Asia, global south

1. Introduction

The notion of a zero-energy building has arisen because of the urgent need to reduce energy consumption to help eliminate greenhouse gas emissions. This chapter focuses on South Asian cities and towns where extreme temperatures force people to endure indoor temperatures well beyond human physiological limits. Reconstructing buildings across South Asia and sub-Saharan Africa to achieve significant reductions in energy demand is likely to be impossible given limited economic resources. However, localized personal cooling (and heating solutions) coupled with PV energy offer affordable solutions that could bring residential building energy demand close to zero with no building modifications.

The fundamental premise behind the study of zero-energy buildings is the need to reduce greenhouse emissions from the building sector, estimated to be 40% of total emissions and 36% of energy demand [1, 2]. Construction is one of the major sources of building greenhouse emissions, particularly the manufacture and transport of concrete, steel and other building materials, estimated to be about 20% of the total lifetime emissions [3]. Contemporary buildings require energy for space heating and cooling, ventilation, refrigeration, water heating, cooking, lighting, appliances and other building services.

It is worth recalling how energy needs for building heating and cooling have become so significant. Practical space heating and cooling technologies emerged in the 19 and 20th centuries that were affordable for many people in wealthy societies. These technologies improved human comfort by compensating for outdoor temperature variations, providing space heating in winter and space cooling for summer months.

These technologies in turn influenced architecture and building design, reducing the former design requirements to limit heat loss in winter and heat gain in summer. For example, buildings could be designed with large windows and other esthetically pleasing features that would have been impractical without winter heating and summer cooling technologies [4]. The shutters that protect windows from excessive heat and cold in older buildings gradually disappeared or remained as non-functional, decorative features. Small niches in thick walls with wooden doors that provided comfortable places for sleeping were no longer needed and larger bedrooms became preferred.

The same technologies also influenced clothing styles preferred by people, even furnishings. Thicker wool apparel formerly preferred for winter clothing gradually fell out of favor, being replaced by much lighter clothes made from cotton and synthetic fibers. Similarly, loose-fitting lightweight styles for summer clothing were replaced by clothes that would have been uncomfortably warm to wear through summer months in earlier buildings [5–8].

Changed building design, furnishings and clothing styles have become so widely preferred that contemporary buildings now require large amounts of energy for space cooling and heating technologies to provide acceptable comfort. With global consensus on the need to reduce greenhouse emissions, there is an urgent need to reassess building designs and standards [9], primarily by reducing building energy consumption. According to Belussi *et al* [2], the most common improvements are insulation, solar photovoltaic (PV) energy generation, draft sealing and energy management control systems such as automatic appliance control by sensing the need for an appliance to be running.

Much of the attention in the literature on zero-energy buildings has focused on passive building design with the aim of eliminating the need for energy to ensure sufficient comfort with the interior climate [10]. However, most improvements are difficult to implement on existing buildings.

South Asia and other countries in the 'Global South' experience far more extreme climates than wealthier nations. South Asian cities can be significantly hotter in summer than surrounding countryside because of the urban heat island effect. First, cities have less shade from trees and vegetation. Second, hard surfaces such as walls, roofs and pavement surfaces become hot in sunlight and can release heat long after sunset. Third, energy-consuming machines such as vehicles, air-conditioners and other appliances release heat into the urban environment. Therefore, people living in cities may experience temperatures greater than 10°C above the temperature of surrounding countryside.

Across South Asia and several other countries, therefore, large populations live in conditions well beyond the limits of human physiology, reducing productivity, helping to explain relatively slow economic development. Healthy sleep is impossible above 30°C (dry bulb) and workplace productivity declines significantly above 27°C (wet bulb). The combination of urbanization, climate warming and urban heat island effects has pushed workplace and sleeping temperatures well above these limits.

Many have argued that vernacular architecture – traditional styles of building – could provide models for buildings with greater energy-efficiency in many countries. For example, well-insulated building designs such as wind houses in Iran and other Middle Eastern countries can be adapted to provide energy-efficient alternatives for the today's concrete, steel and glass buildings. However, these traditional buildings relied on low-paid servant labor for construction, cleaning and structural maintenance, and also required considerable knowledge to know when to open and close ventilation doors [11]. Furthermore, they also relied on the ability for the inhabitants to relocate activities to different parts of the building at different times to seek the greatest degree of comfort. Upper parts of the building facing south (in the northern hemisphere) were warmer in winter, and lower parts of the building away from the sun or shaded by adjacent buildings were cooler in summer [12].

Cities provide economic opportunities, improved health and security by enabling people to specialize their capabilities because other people living nearby can satisfy needs that they cannot satisfy for themselves. However, most cities require people to live in shared buildings divided into apartments. This limits opportunities to relocate domestic activities to more comfortable parts of the building. A top floor apartment facing the western sunlight will be very hot in the afternoon and evening in summer. A ground floor apartment facing away from the sun will be cold in winter.

Unfortunately, re-engineering the fabric of cities in the Global South, particularly in South Asia, replacing existing buildings with conventional zero-energy designs along with widespread application of heat emissive materials for pavements and roofs, is unaffordable. Even if rebuilding were possible, artificial cooling would still be needed on a vast scale, hitherto unimaginable because of the energy demand and greenhouse emissions associated with electricity generation [13–17], even with full implementation of the Kigali amendment to the Montreal Protocol to limit emissions caused by refrigerant gases [18, 19].

In contrast with space cooling and heating, localized cooling (and heating in winter) offer far more affordable solutions that are already commercially available and could be scaled up in time to help reduce future greenhouse emissions and avoid large additional emissions [20]. At the same time, these technologies offer large improvements in health and productivity.

2. Physiological effects of temperature on day-time productivity

A recent and widely cited meta-study provided data on the effect of temperature on labor productivity [21]. The authors analyzed data from 13 empirical sources and showed a sharp decline in productivity above 27°C Wet Bulb Globe Temperature (WBGT).[1] Muscles release heat energy in the course of generating mechanical effort and this heat energy has to be released to the atmosphere, mainly by cooling as a result of evaporating sweat through the skin. As the temperature and humidity rise, less heat can be dissipated from a given area of human skin, reducing the amount of physical effort that can be generated by a person. In self-paced work, people slow or simply stop working when they feel the conditions are too hot to continue [22–26] as shown in studies forecasting the economic implications of climate warming.

Figure 1 represents the findings of 13 empirical studies reported by Day *et al* [21] and shows the variation in reported productivity loss. The findings from all the reported studies are broadly in agreement.

Figure 2 shows weather data from several locations in South Asia superimposed on a chart of temperature and relative humidity showing the sloping region where WBGT is high enough to cause productivity losses. Each small curved line represents the change in conditions through day and night.

Figure 2 shows that most urban centres experience day-time conditions through summer months that cause significant productivity loss with the exception of Pune and Bhopal in the monsoon period. Much of the time in the hot summer months, the urban heat island effect exceeds 3°C as data to be presented below will show.

This means that workplace productivity across South Asia will be significantly reduced in the summer months as people are working in temperatures at which one can expect 10–90% productivity loss.

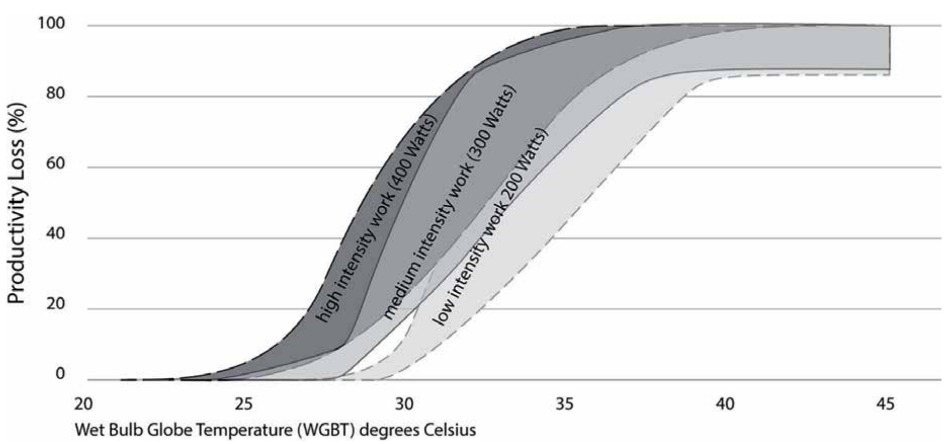

Figure 1.
Productivity loss with increasing temperature, adapted from Figure 1 in [21] for low, medium and high intensity work requiring 200, 300, and 400 Watts output respectively. Low intensity work results have been shown with the lightest shading, and high intensity work results have been shown with the darkest shading.

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[1] WBGT–Wet Bulb Globe Temperature, 0.7 * (Wet bulb temperature) + 0.2*(globe temperature) + 0.1*(dry bulb temperature). A thermometer arranged with the liquid bulb wrapped in a wet tissue provides a measurement of wet bulb temperature. Globe temperature measures the temperature of a black sphere, about 2 cm in diameter, exposed to radiant heat from the sun or other sources.

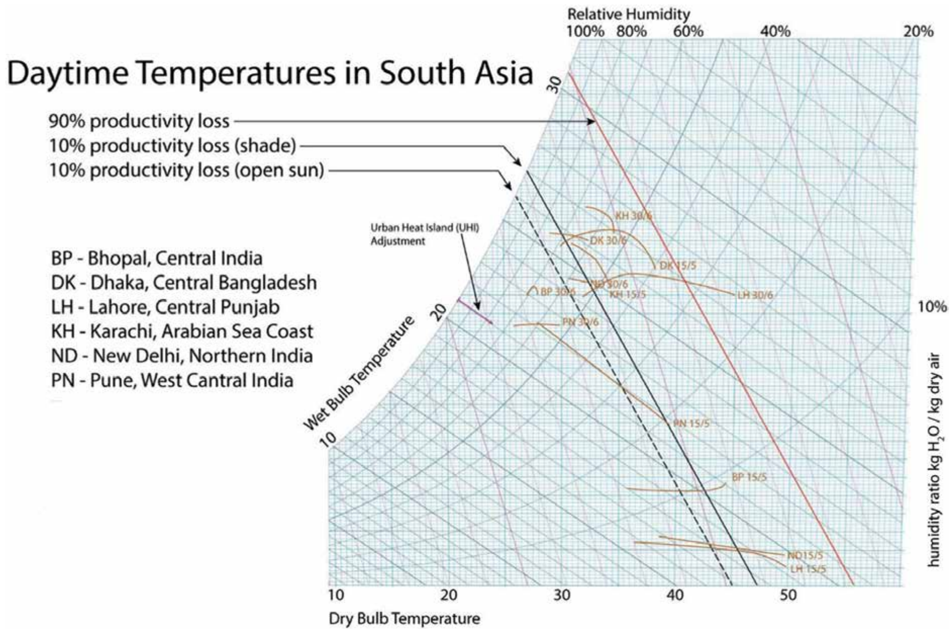

Figure 2.
Psychrometric chart showing South Asian summer climate conditions with a modest 3°C adjustment to account for urban heat-island effects. The curved lines for each location show the change in daytime temperature and humidity between mid-afternoon (typical maximum temperature) and 2 am (typical minimum temperature), adjusted for 3°C urban heat island effect [27].

3. Effect of night temperature on sleep quality

Interestingly, Day et al. [21] did not mention sleep quality directly. However, they acknowledged that none of the studies they found allowed for the effects of high temperatures on sleep quality, referred to as 'biophysical recovery'. Sleep quality data from numerous empirical research reports indicates that the neutral temperature for humans sleeping on a mattress without clothing is about 27°C (neither too hot nor too cold). At that temperature, metabolic heat produced inside the body is balanced by heat lost to the environment.

With clothing and thin bed covers, comfort temperatures range from 19°C to about 25°C (see, for example [28, 29]). A ceiling fan can reduce the apparent temperature by 2°C [30], indicating a maximum temperature for sleeping at 27°C. Above that temperature, the human body will experience sleep loss because there is insufficient cooling to disperse heat from body metabolism and maintain a sufficient reduction in core temperature for normal sleep. The absolute maximum temperature for adequate sleep quality, sleeping with a fan on a string mattress without clothing, is 31°C.

Figure 3 shows typical night-time bedroom temperatures (based on actual measurements) superimposed on a similar graph of temperature and humidity showing the physiological limit for sleeping. The data points reflect actual weather conditions for a typical day in May (15th May 2022), during the hot, dry summer season and for a typical monsoon season day (30th June). It shows that most urban centres experience bedroom temperatures that significantly exceed physiological limits for sleeping.

In rural settings, walled compounds open to the night sky or structures with negligible thermal mass can provide sufficient comfort (**Figure 4**). Sleeping on wooden

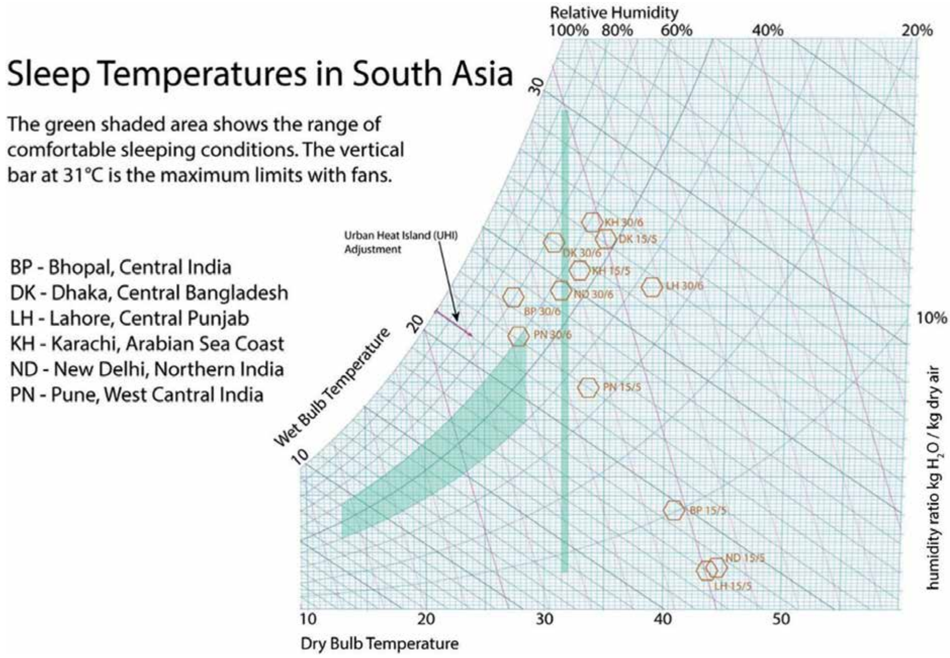

Figure 3.
Psychrometric chart showing estimated night-time indoor South Asian summer climate conditions, based on measurements by the author.

beds with woven string (charpai) allows the entire body to lose heat rather than just the upper half when lying on a thick mattress (**Figure 5**). A clear sky at night has a radiant temperature well below zero, so it acts as an effective radiant heat absorber (though slightly less as the atmospheric CO_2 concentration rises).

Figure 4.
Bamboo and straw huts, an ancient form of zero-energy buildings, provide cooler conditions for sleeping than brick and concrete structures (image by Zeke Tucker, unsplash.com).

Figure 5.
Outdoor bed (charpai) in an Indian home courtyard with a private handpump. (image by Raju Sharma, unsplash.com).

In towns, and cities, conditions are very different. Sleeping outside in walled compounds is usually impossible: only the very wealthy can afford a reasonably large open courtyard in a city. In any case, the very wealthy prefer to sleep indoors with air-conditioners. Many wealthier people can retreat to cooler cellars in their homes.

Most urban dwellers have no freedom to move to cooler locations to sleep, particularly women and children because they rent small rooms which are part of larger buildings. In the image below, taken in an Indian city, the ground floor levels are commercial retail spaces so people have to live, work and sleep in the hotter upper floors (**Figures 6** and 7).

Figure 6.
Typical mixed residential and commercial buildings found in Indian cities (image by Annie Spratt, unsplash.com).

Figure 7.
A small working-class enclave in the back streets of New Delhi, January 2023. Notice the gray backs of water coolers projecting from wall openings, also ladders for reaching upper-level apartments (photograph by author).

Since the 1980s, climate warming has caused earlier and longer periods of extreme heat. However, a much larger temperature increase in urban centres has occurred, known as the "urban heat island effect", increasing the temperature by up to 17°C relative to surrounding open countryside. This effect is particularly strong at night [27, 31].

Inside the buildings, the heavy reinforced concrete slabs and brickwork retain heat gained during the day. Outside, the temperature is typically 40–46°C during the day and 30–35°C at night. The roof and walls exposed to the sun rise to about 50°C or more during the day. This explains why indoor temperatures above the ground floor level remain well above 30°C.

From this data, we can conclude that healthy sleep is impossible without air-conditioning because indoor temperatures are about 5–10°C higher than the upper limit for sleeping with a powerful electric fan, up to 12°C above the limit for sleeping without a fan.

We know that sleep quality decreases with temperatures above 27°C and exposure to extremely high temperatures during heatwaves significantly increases mortality [32, 33]. However, it seems there have been no studies on the effect of prolonged exposure to such high temperatures over several months. In the author's experience, even people who have air-conditioning which is intermittent (due to load shedding) suffer from poor sleep, becoming less able to handle mental and physical work and more irritable through exposure. They resemble a semi-permanent state of exhaustion.

The obvious question is how can people survive such unpleasant conditions?

Many survive the dry heat of April, May and June with water coolers and cope with ceiling fans through the monsoon heat. Wealthier families install their first air-conditioner in a formal sitting room, using it for social occasions to impress visitors. In extreme heat, the entire family move their bedding into that room and sleep together, putting off the thought of how to pay the US$200 electricity bill that will arrive inevitably after a month or so. It is noticeable that none of the South Asian nations have yet been able to match China's industrialization, economic development and rising prosperity and the reduction of productivity caused by months of extreme heat is a possible explanation for this difference.

4. Cooling is essential

The data presented above demonstrates that artificial cooling has become essential for healthy sleeping and productive work in South Asian cities, towns and villages during summer months, and possibly many other countries as well. Planting shade trees, urban greening, and heat-reflective coatings on roofs can help [34]. However, even when combined, these measures cannot reduce temperatures by 10–15°C which is necessary to avoid the need for artificial cooling.

The big question, then, is how can this necessary cooling be provided?

Water evaporation has long been used for cooling and can be very cost-effective when the humidity is below about 35% (**Figure 7**). Once the humidity exceeds 50%, however, evaporative cooling provides little benefit. This occurs across the Indian sub-continent during June with the arrival of the monsoon season and continues until late September, even into October. Evaporative coolers also require maintenance to avoid unpleasant smells. One of the major limitations of evaporative cooling is the demand for clean water, around 240 liters per day for a typical room with about 15–20 sq. meters floor area. Indian cities today cannot meet the basic demands for safe drinking water, though this usually reflects distribution problems rather than water supplies. Cities such as Chennai have completely run out of water in recent times (2001 and again in 2021 [35, 36]).

The alternative cooling technology is refrigeration air-conditioning.

However, conventional space air-conditioning for billions of people is unlikely to be possible within sustainable limits [13, 15]. Isaac and Van Vuuren [13] forecast additional demand at 2700 PJ or 750 TWh by 2050 and 17,000 PJ or 4700 TWh by 2100 (1 TWh is one billion units, BU, used in Government of India reports). Given that hot countries typically use around 50% of power generation capacity on air-conditioning and cooling, this implies that the total power generation in India will have to reach about 10,000 TWh by 2100, 6 times today's total power generation. The need to eliminate greenhouse emissions by mid-century means that this additional demand will be drawn from renewable sources or possibly nuclear power. Hydro-electric potential in India is largely utilized already, and the low average wind strength across the Indian sub-continent will limit wind power resources. While the potential for solar PV is sufficient, this energy will need to be stored for night-time use, raising the cost to about USD 0.10–0.20 per kWh [37]. Once distribution costs are included, the cost for consumers will be about USD 0.30 per unit. The cost of rooftop solar electricity stored in batteries is similar.

The 2016 Kigali Amendment to the Montreal Protocol [18, 19] requires a gradual reduction in the permissible global warming potential (GWP) of refrigerant gases.

India and other lower-income countries have undertaken to commence phasing out HFCs in 2028. Over time, this process will reduce refrigerant emissions which are typically 20% of total emissions associated with air-conditioning [38]. Increasing use of stored solar electricity at night will also result in a gradual reduction in emissions from air-conditioning.

Traditional air-conditioning, along with vehicles and other industrial and domestic electricity use, also contributes to the urban heat island effect, helping to raise ambient temperatures in cities and towns [27, 31].

While the greenhouse emissions and thermal effects resulting from traditional air-conditioning pose significant climate challenges, the other factor limiting their application is economic capacity. It is estimated that about India has an annual demand for about 6 million air-conditioners, with about 60 million already installed [39]. However, while about 7% of homes in South Asia have at least one air-conditioner, only about 2–3% of homes would see air-conditioners being used routinely through the hot season lasting from May till October. The cost of electricity, even though it is largely subsidized, is a major barrier hindering the adoption of air-conditioning by most people. In Pakistan, for example, the cost of electricity for consumers is about USD 0.10–0.18 whereas the generation cost alone is about USD 0.14 per unit sold after allowing for losses and electricity revenue collection shortfalls. Governments across South Asia are struggling to raise enough revenue to cover the cost of subsidies and also maintain the distribution and generation infrastructure. Paradoxically, subsidizing electricity has also significantly reduced incentives to incorporate building insulation and other efficiency measures.

Solar energy from PV is now a cheap alternative to fossil fuel electricity generation. Rooftop panels can provide significant generation to help meet residential electricity demands. However, roof space is limited.

Typical residential houses common throughout South Asian cities such as Delhi measure 4 m wide by 15 m from front to back, have 60 sq. m of roof space and commonly have a family of 6 people on each of two residential levels above commercial space on the lower two floors. In poorer districts, up to 20 people live in the one building.

We can assess how much household energy consumption could be met from roof top solar generation coupled with battery storage. On average, in good conditions, modern panels will provide a peak of 130 Watts per square meter and generate about 250 Watt-hours daily per square meter in summer.

Assuming that the entire roof is covered with about 48 sq. m of panels, also providing shading from much of the direct sunlight at the same time, the generation potential is 6.3 kW peak and 57 kWh daily in May, the hottest month.

With families living on two residential levels, around 27 kWh is needed for lights, fans, food preparation and refrigerators, including inverter power losses from drawing power from batteries while solar input is insufficient. We assume electric cooking and food preparation in place of liquified petroleum gas, the almost universally used domestic fuel today. Assume that a single split air-conditioners rated at 1.8 kW is used to cool one communal room on each level. Running the air-conditioners for 12 hours daily, mostly at night off batteries require 50 kWh including inverter losses. Even under favorable conditions, there is insufficient PV before considering the energy needed for the lower commercial levels of the building.

The large amount of power used for air-conditioners explains why the Government of India co-sponsored a three million dollar prize to incentivize air-conditioning innovation [15]. The joint winners announced in 2022 both demonstrated conventional technologies, combining ventilation, water evaporation and refrigeration cooling, achieving substantial energy efficiencies and reducing climate impact for a typical mid-range split air-conditioner by five times. However, even at scale, these machines will be significantly more expensive and will likely require government regulation or subsidies to encourage adoption.

5. Localizing air-conditioning

Conventional air-conditioning relies on cooling all the air within an enclosed space such as a bedroom or formal lounge room. While people feel cool, nearly all of the energy used for cooling draws heat from the walls, floors, ceiling and furniture. Moderately active people release around 100 Watts of heat, whereas a typical 1.5 ton split air-conditioner used in South Asian homes provides 5500 Watts cooling, while reducing temperature of a 3 x 5 m room by around 9°C. Most users switch on a powerful ceiling fan typically drawing 100 Watts electric power, providing air movement which yields a further 2°C apparent cooling [30].

There are two reasons that explain why so much cooling power is needed.

First, the outdoor temperature during the day is about 44–46°C during the day between about midday and 6 pm.

Second, the external building walls consist of double clay bricks without an air or insulation cavity between them. Many buildings only have single brick external walls. Even if one room is cooled with an air-conditioner, heat will enter from adjacent rooms through single brick internal walls. Even after running a room air-conditioner all night, our measurements have shown that the internal wall temperature is still about 35°C in the morning.

Several different localized cooling approaches have been researched. For example. Some researchers have focused on skin contact cooling devices incorporated into clothing [40]. While these have potential in certain occupations exposed to high temperatures, it is hard to see this technology providing comfort in regions such as South Asia.

There is wide agreement that localized air-conditioning can provide significant comfort improvement and energy savings by cooling a smaller space within a room, avoiding the need to extract heat from the building structure [20].

Kaczmarczyk et al. [41] assessed human thermal comfort and measured ventilation effectiveness in an office environment in which each cubicle was provided with a conditioned air vent above a computer monitor, following a suggestion by Fanger [42]. Most research has focused on office and workspace applications [20] with relatively moderate temperatures and humidity levels up to 30°C and 70% respectively (see also [41, 43–47]). Often the research has been in wealthier temperate countries with the aim of reducing energy consumption and greenhouse gas emissions in those countries (e.g. [48]). Often the researchers classify temperatures such as 26°C, 40% RH as "high room temperature and humidity" [49], conditions which would be considered luxuriously cool for South Asian summers. A few investigations have focused on sleep [50–52], however only one study has focused on sleep quality with personal air-conditioning in tropical conditions [53].

In seeking to extend the climatic range in which localized air-conditioning could be effective, Trevelyan [51, 52] developed a specially designed enclosure, in effect a small room within a room. The enclosure was designed as a bed tent but can be used for work and recreation too (**Figures 8** and **9**).

Figure 8.
Air-conditioned bed tent [52].

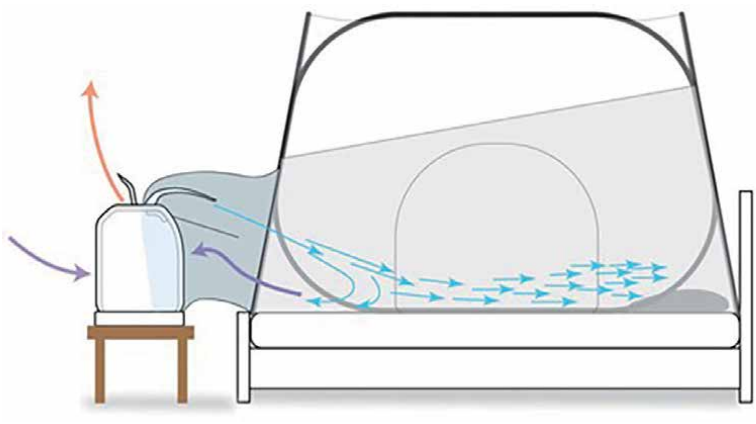

Figure 9.
Air circulation inside the bed tent shown in ***Figure 8****.*

Trevelyan [54] disclosed the arrangement of stratified air flow enabling the cooling to be concentrated at the base of the tent. Relatively impervious panels surround the lower part of the tent ensuring that the relatively denser dehumidified cool air does not spill out of the tent easily, thus enabling an apparent temperature up to 12°C below the room temperature. At the same time, the tent is light and permits free flow of air through the upper part to prevent any significant CO_2 accumulation.

The air conditioner is easily portable (~15 kg) and can easily be detached to provide personal cooling in other locations during the day. Even without the tent, a single unit can provide significant comfort for up to three people seated nearby, for example watching a TV.

Apart from the obvious economic advantages stemming from the very low running cost, Trevelyan's innovation also provides significant health benefits. The bed tent protects occupants from mosquitos and other insects, reducing the risk of insect-borne diseases such as malaria parasites and dengue, Ross River and zika viruses. While two adults and a child can occupy a bed tent, separate sleeping arrangements for larger families can make it easier to handle contagious diseases within a single residence. Open windows allow fresh air ventilation, reducing airborne infection risks. Furthermore, frequent partial and full exposure to high ambient temperatures ensures that the body does not lose its natural acclimatization to heat, with significant physiological benefits [55, 56]. Furthermore, localized air-conditioning enables a degree of privacy within a family which can be important for psychological health [57].

With the building case described above with two residential levels, 4 localized air conditioners described by Trevelyan [52] running for 12 hours daily could meet the cooling needs for the occupants, consuming only 19 kWh power daily, including inverter losses. The low power consumption makes it possible to meet practically all the building energy requirements using rooftop solar. External grid power would still be needed when there is insufficient solar energy produced from the roof and also to support commercial activities in the lower levels of the building.

It should be noted that winter heating is needed in South Asia, especially in January and February when ambient temperatures typically vary from 3°C to about 20°C and building indoor temperatures sit at around 10–12°C. Heated throw rugs provide an extremely energy-efficient localized heating solution using 50–100 Watts per person. It is curious that these simple and effective personal heating solution seems not to have been noticed in published reviews (e.g. [20]).

In terms of Energy Use Intensity (EUI), the residential levels of this typical South Asian building require about 200 kWh/m^2 with conventional air-conditioning and about 140 kWh/m^2 with localized summer cooling and winter heating.

6. Conclusions

Localized heating and cooling solutions could help make zero-energy buildings a reality, even in extreme climate conditions encountered in South Asia and Africa. However, while the technology provides solutions, affordability remains a major challenge. Installing solar panels and battery storage on a typical South Asian residential building will require capital investment far beyond the capacity of most people.

Governments subsidize electricity across South Asia, and are accumulating large financial deficits as a result, while also accumulating a future debt because of insufficient maintenance on existing electricity distribution assets [58] and loss of human potential. While implemented originally to promote economic and social development, these subsidies now reduce incentives to adopt energy-efficiency measures described in this chapter.

Therefore, while the vision of residential buildings in South Asia that are self-sufficient for energy is now technically possible, it will require equivalent or greater ingenuity in the fields of politics, finance and economics to make it a practical reality. In the meantime, a competitive market exists in which customers seek the best solutions that meet their needs within their financial limitations. Some countries have implemented regulations to improve space air-conditioner energy-efficiency.

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Conflict of interest

The author is the inventor and founder of Close Comfort Pty Ltd., a start-up company that designs, manufactures, distributes and sells personal air conditioners, electric throw blankets and associated accessories.

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References

[1] International Energy Agency. 2018 Global Status Report: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. New York: United Nations Environment Program (UNEP); 2018. p. 73. Available from: https://wedocs.unep.org/bitstream/handle/20.500.11822/27140/Global_Status_2018.pdf

[2] Belussi L et al. A review of performance of zero energy buildings and energy efficiency solutions. Journal of Building Engineering. 2019;**25**:100772. DOI: 10.1016/j.jobe.2019.100772

[3] Stephan A, Stephan L. Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate. Applied Energy. 2020;**280**:115932. DOI: 10.1016/j.apenergy.2020.115932

[4] Humphreys M, Nicol F, Roaf S. Adaptive Thermal Comfort: Foundations and Analysis. London, UK: Routledge; 2020

[5] Roaf S, Brotas L, Nicol F. Counting the costs of comfort: Editorial. Building Research and Information. 2015;**43**(3):269-273. DOI: 10.1080/09613218.2014.998948

[6] Nicol F, Humphreys M, Roaf S. Adaptive Thermal Comfort: Principles and Practice. London, UK: Routledge; 2012

[7] Nicol F. The limits to accepted indoor temperature. In: Roaf S, Finlayson W, editors. 1st International Conference on: Comfort at the Extremes: Energy, Economy and Climate. Dubai: Heriot Watt University; 2019: Ecohouse Initative Ltd. pp. 23-31

[8] Nicol JF, Roaf S. Rethinking thermal comfort. Building Research and Information. 2017;**45**(7):711-716. DOI: 10.1080/09613218.2017.1301698

[9] Williams J et al. Less is more: A review of low energy standards and the urgent need for an international universal zero energy standard. Journal of Building Engineering. 2016;**6**:65-74. DOI: 10.1016/j.jobe.2016.02.007

[10] Gupta N, Tiwari GN. Review of passive heating/cooling systems of buildings. Energy Science and Engineering. 2016;**4**(5):305-333. DOI: 10.1002/ese3.129

[11] Foruzanmehr A, Vellinga M. Vernacular architecture: Questions of comfort and practicability. Building Research and Information. 2011;**39**(3):274-285. DOI: 10.1080/09613218.2011.562368

[12] Soleymanpour R, Parsaee N, Banaei M. Climate comfort comparison of vernacular and contemporary houses of Iran. Procedia - Social and Behavioral Sciences. 2015;**201**:49-61. DOI: 10.1016/j.sbspro.2015.08.118

[13] Isaac M, Van Vuuren DP. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy. 2009;**37**(2):507-521. DOI: 10.1016/j.enpol.2008.09.051

[14] Allen M et al. In: Masson-Delmotte V et al., editors. Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate

Change, Sustainable Development, and Efforts to Eradicate Poverty, Summary for Policymakers. Geneva: Intergovernmental Panel on Climate Change (IPCC); 2018. p. 34

[15] Campbell I, Kalanki A, Sachar S. Global Cooling Prize: Solving the Global Cooling Challenge - How to Counter the Climate Threat from Room Air Conditioners. Boulder, Colorado, USA: Rocky Mountain Insititute; Available from: http://rmi.org/wp-content/uploads/2018/11/Global_Cooling_Challenge_Report_2018.pdf; [Accessed: December 1, 2018]

[16] Sharma M, Chaturvedi V, Purohit P. Long-term carbon dioxide and hydrofluorocarbon emissions from commercial space cooling and refrigeration in India: A detailed analysis within an integrated assessment modelling framework. Climatic Change. 2017;**143**(3):503-517. DOI: 10.1007/s10584-017-2002-4

[17] Velders GJM, Fahey DW, Daniel JS, McFarland M, Andersen SO. The large contribution of projected HFC emissions to future climate forcing. Proceedings of the National Academy of Sciences. 2009;**106**(27):10949. DOI: 10.1073/pnas.0902817106

[18] United Nations Environment Programme Ozone Secretariat. The Kigali Amendment (2016): The Amendment to the Montreal Protocol Agreed by the Twenty-Eighth Meeting of the Parties. United Nations, New York, NY, USA: Kigali; 2016. Available from: https://ozone.unep.org/treaties/montreal-protocol/amendments/kigali-amendment-2016-amendment-montreal-protocol-agreed [Accessed: April 24, 2021]

[19] Li Y-X, Zhang Z-Y, An M-D, Gao D, Yi L-Y, Hu J-X. The estimated schedule and mitigation potential for hydrofluorocarbons phase-down in China. Advances in Climate Change Research. 2019;**10**(3):174-180. DOI: 10.1016/j.accre.2019.10.002

[20] Rawal R, Schweiker M, Kazanci OB, Vardhan V, Jin Q, Duanmu L. Personal comfort systems: A review on comfort, energy, and economics. Energy and Buildings. 2020;**214**:109858. DOI: 10.1016/j.enbuild.2020.109858

[21] Day E, Fankhauser S, Kingsmill N, Costa H, Mavrogianni A. Upholding labour productivity under climate change: An assessment of adaptation options. Climate Policy. 2019;**19**(3):367-385. DOI: 10.1080/14693062.2018.1517640

[22] Kjellstrom T, Briggs D, Freyberg C, Lemke B, Otto M, Hyatt O. Heat, human performance, and occupational health: A key issue for the assessment of global climate change impacts. Annual Review of Public Health. 2016;**37**(1):97-112. DOI: 10.1146/annurev-publhealth-032315-021740

[23] Borg MA et al. Occupational heat stress and economic burden: A review of global evidence. Environmental Research. 2021;**195**:110781. DOI: 10.1016/j.envres.2021.110781

[24] Zhu J, Wang S, Zhang B, Wang D. Adapting to changing labor productivity as a result of intensified heat stress in a changing climate. GeoHealth. 2021;**5**(4):e2020GH000313. DOI: 10.1029/2020GH000313

[25] Humphrys E, Goodman J, Newman F. Zonked the hell out: Climate change and heat stress at work. The Economic and Labour Relations Review. 2022;**33**(2):256-271. DOI: 10.1177/10353046221092414

[26] Morrissey MC, Brewer GJ, Williams WJ, Quinn T, Casa DJ. Impact of occupational heat stress on worker productivity and economic cost. American Journal of Industrial Medicine. 2021;**64**(12):981-988. DOI: 10.1002/ajim.23297

[27] Raj S, Paul SK, Chakraborty A, Kuttippurath J. Anthropogenic forcing exacerbating the urban heat islands in India. Journal of Environmental Management. 2020;**257**:110006. DOI: 10.1016/j.jenvman.2019.110006

[28] Lan L, Tsuzuki K, Liu YF, Lian ZW. Thermal environment and sleep quality: A review. Energy and Buildings. 2017;**149**:101-113. DOI: 10.1016/j.enbuild.2017.05.043

[29] Lan L, Lian ZW, Lin YB. Comfortably cool bedroom environment during the initial phase of the sleeping period delays the onset of sleep in summer. Building and Environment. 2016;**103**:36-43. DOI: 10.1016/j.buildenv.2016.03.030

[30] Nicol F. Adaptive thermal comfort standards in the hot–humid tropics. Energy and Buildings. 2004;**36**:628-637. DOI: 10.1016/j.enbuild.2004.01.016

[31] Ballinas M, Baradas VL. The actual urban heat island in Mexico City. In: 8th International Conference on Urban Climate (ICUC 8) and 10th Symposium on the Urban Environment. Vol. W5/222. Dublin, Ireland: University College Dublin; 2012. DOI: 10.13140/2.1.3669.4081

[32] Hansen A, Soebarto V. The epidemiology of health and mortality at extremes. In: Roaf S, Finlayson W, editors. 1st International Conference on: Comfort at the Extremes: Energy, Economy and Climate. Dubai: Heriot Watt University; 2019: Ecohouse Initative Ltd. pp. 10-22

[33] Khosla R, Jani A, Perera R. Health risks of extreme heat. BMJ. 2021;**375**(2438):2. DOI: 10.1136/bmj.n2438

[34] Santamouris M. Urban Heat Island mitigation. In: Newton P, Orasad D, Sproul A, White S, editors. Decarbonising the Built Environment: Charting the Transition. Singapore: Palgrave Macmillan; 2019. pp. 337-355

[35] Bloomberg. How Chennai, One of the world's Wettest Major Cities, Ran out of Water. India: The Economic Times; 2021

[36] Coelho K. Of Engineers, Rationalities and Rule: An Ethnography of Neoliberal Reform in and Urban Water Utility in South India. Tucson: Anthropology, University of Arizona; 2004. Available from: http://hdl.handle.net/10150/280681

[37] Jülch V. Comparison of electricity storage options using levelized cost of storage (LCOS) method. Applied Energy. 2016;**183**:1594-1606. DOI: 10.1016/j.apenergy.2016.08.165

[38] P. Brodribb and M. McCann. Cold Hard Facts 3. Department of the Environment and Energy. Available from: https://www.environment.gov.au/protection/ozone/publications/cold-hard-facts-3 [Accessed: May 27, 2020]

[39] Japan Refrigeration and Air Conditioning Industry Association. World Air Conditioner Demand by Region. Available from: https://www.jraia.or.jp/english/statistics/ [Accessed: May 27, 2020]

[40] Song W, Wang F. The hybrid personal cooling system (PCS) could effectively reduce the heat

strain while exercising in a hot and moderate humid environment. Ergonomics. 2016;**59**(8):1009-1018. DOI: 10.1080/00140139.2015.1105305

[41] Kaczmarczyk J, Melikov A, Fanger PO. Human response to personalized ventilation and mixing ventilation. Indoor Air. 2004;**14**:17-29. DOI: 10.1111/j.1600-0668.2004.00300.x

[42] Fanger PO. Indoor air quality in the 21st century: Search for excellence. Indoor Air. 2000;**10**(2):68-73. DOI: 10.1034/j.1600-0668.2000.010002068.x

[43] Kosonen R. An analysis of a flexibility chilled beam system in hot and humid climate. In: Clima 2013 11th REHVA World Congress and 8th International Conference on IAQVEC. Vol. 2019. Prague, Czech Republic: REHVA, Federation of European Heating, Ventilation and Air conditoning Associations; 2013

[44] Kosonen R, Zhao W, Lestinen S, Yan C, Kilpeläinen S. Boosting comfort locally with personal micro-climate systems. In: Roaf S, Finlayson W, editors. 1st International Conference on: Comfort at the Extremes: Energy, Economy and Climate. Dubai: Heriot Watt University; 2019: Ecohouse Initative Ltd. pp. 333-339

[45] Law T. The Future of Thermal Comfort in an Energy-Constrained World. Hobart, Tasmania: Architecture and Design, University of Tasmania; 2013

[46] Law T, Sargison J, Fay R, Banbury S. Ductless task air-conditioning. ASHRAE Transactions. 2012;**118**(1):367-375

[47] Melikov AK, Knudsen GL. Human response to an individually controlled microenvironment. HVAC and R Research. 2007;**13**(4):645-660. DOI: 10.1080/10789669.2007.10390977

[48] Warthmann A, Wölki D, Metzmacher H, Van Treeck C. Personal Climatization systems—A review on existing and upcoming concepts. Applied Sciences. 2019;**9**(1):35. DOI: 10.3390/app9010035

[49] Melikov AK, Skwarczynski MA, Kaczmarczyk J, Zabecky J. Use of personalized ventilation for improving health, comfort, and performance at high room temperature and humidity. Indoor Air. 2013;**23**(3):250-263

[50] Zhou X, Lian Z, Lan L. Experimental study on a bedside personalized ventilation system for improving sleep comfort and quality. Indoor and Built Environment. 2014;**23**(2):313-323. DOI: 10.1177/1420326X13504317

[51] Trevelyan JP. Localised air conditioning enables comfort with a sustainable energy demand. In: Hood D, editor. Dynamic EcoLibrium - Sustainable Engineering Society Conference (SENG 2015). Canberra, ACT, Australia: Engineers Australia; 2015. p. 21

[52] Trevelyan JP. Localised air conditioning: Comfort with sustainable energy demand. In: Roaf S, Finlayson W, editors. 1st International Conference on: Comfort at the Extremes: Energy, Economy and Climate. Dubai: Heriot Watt University, Ecohouse Initative Ltd; 2019. pp. 340-349. Available from: https://windsorconference.com/wp-content/uploads/2019/04/CATE2019_Proceedings-compressed.pdf

[53] Lim M. Study of Thermal Comfort and Sleep Quality of Singaporeans. Singapore: Mechanical Engineering, National University of Singapore; 2022

[54] Trevelyan JP. Localised personal air conditioning system. Australian Official Journal of Patents. 2015318813, 2015

[55] Pallubinsky H et al. Regular passive exposure to heat induces beneficial effects on cardio-metabolic health. In: Dubai SR, Finlayson W, editors. 1st International Conference on: Comfort at the Extremes: Energy, Economy and Climate. Edinburgh, Scotland, UK: Heriot Watt University; 2019: Ecohouse Initative Ltd. pp. 89-101

[56] Périard JD, Travers GJS, Racinais S, Sawka MN. Cardiovascular adaptations supporting human exercise-heat acclimation. Autonomic Neuroscience. 2016;**196**:52-62. DOI: 10.1016/j.autneu.2016.02.002

[57] Banglani A. In: Dawn Newspaper, editor. To AC or Not to AC: The Middle Classes Struggle for Privacy. Karachi; 2022. p. 2

[58] Zhang F. In the Dark: How Much Do Power Sector Distortions Cost South Asia? Washington DC, USA: World Bank International Bank for Reconstruction and Development; 2019. p. 261

Chapter 5

Heat Pipe Heat Exchangers for Air-Conditioning Applications

Vikrant Venkataraman

Abstract

Next-generation air conditioning and cooling technologies must be environmentally friendly and sustainable. Using residual and renewable heat, wherever possible, to generate cooling will go a long way in reducing energy demands from cooling needs. This is particularly important in hot and tropical climates where for most part of the year, temperatures are almost always above 30°C, resulting in enormous amounts of energy for cooling. In this chapter, we investigate how residual/waste heat from Solid Oxide Fuel Cells and other heat sources can be integrated into an absorption refrigeration system to generate cooling. An outline of the broad system, followed by detailed methodology for component and system development and fundamental thermodynamics, will help the reader grasp the concepts better.

Keywords: Solid Oxide Fuel Cells, heat pipes, advanced heat transfer, sustainable cooling, thermal energy

1. Introduction

Humans need a comfortable temperature indoors when the outside ambient temperature is in the extremes – either very cold or very hot. This is where climate conditioning and control systems come into play, providing the perfect temperature so that people can enjoy themselves and live comfortably. Extreme cold and hot ambient temperatures exacerbate the need for deploying heating ventilation, and air conditioning (HVAC) systems and units for climate control since uncomfortable temperatures can lead to a range of illnesses and problems [1].

People living in hot and tropical climates, such as Southeast Asia, the Middle East and Africa, experience temperatures above 30°C for the most part of the year and up to 50°C in the hottest summer months, which can last anywhere between 1 and 2 months. Out of the roughly 2.8 billion people living in the hottest parts of the earth, the regions mentioned above, only 8% have access to air-conditioners (AC) as compared to 90% ownership in the United States of America and Japan, which are not typically considered to be hot and tropical [1]. Now, this puts almost 35% of the world's population in a situation where people have to struggle to attain thermal comfort due to the simple reason of not being to afford the unit and its corresponding operating costs. The energy needed for cooling and air conditioning is enormous [1] and is bound to only increase in the coming decades [1] due to rise in population numbers, rise in living standards of people and migration of people from rural to urban areas. It is estimated that the energy needs from space cooling will triple by 2050 [1]. Air-conditioners and electric fans used for cooling rooms and spaces account for 20% of the total electricity demand of buildings around the world [1]. Some studies claim this number to be between 40 and 60% of the total electricity demand of buildings [2]. This constitutes a major chunk of the energy needs and cutting down this percentage will free up electrical energy (electricity) to be used for other purposes in other applications, for example, charging of Electric Vehicles (EVs) or for electrolysis for hydrogen production. Electrical energy is a high-quality form of energy or, in thermodynamic terms, high in exergy, whereas thermal energy is a low-quality form of energy or low in exergy. Wherever possible, if a low-quality form of energy can perform the same task as a high-quality form of energy, one can expect considerable savings in energy.

Whilst district heating systems, to supply hot water for room heating, are widely prevalent and deployed in the western part of the world, the same cannot be said for district cooling systems, although the projects and plants for district cooling systems are on the rise and becoming a standard, especially in rich developed countries (such as Singapore, Saudi Arabia) that fall under the category of 'Hot, humid, or tropical'. These district cooling systems supply chilled water at approximately 10°C via piped networks to buildings, which can then be circulated in closed spaces for space cooling. Some studies [3] question the effectiveness of chilled water circulation via radiators (akin to those used for hot water circulation) for effective space cooling. The reason for this is simple. When hot water, at 50 or 60°C is being circulated through the radiators, to heat the room during winter, the temperature gradient for heat transfer is at least 40 or higher (depending on the ambient temperature of the room). When chilled water at 10°C is circulated through the radiator, to cool the room during summer, the temperature gradient for heat transfer is 30 or below (depending on the ambient temperature of the room) and this results in ineffective heat transfer and, thus ineffective cooling of the room as required for thermal comfort. To achieve a higher temperature gradient with chilled water, it must be cooled even further, and this will consume an additional amount of energy and is more cumbersome than installing an electric air-conditioner or an electric fan. Detailed energy studies must, however, be carried out to have a comparison between the costs of operating a district cooling system in comparison to individual air-conditioning units.

The number of electrically driven air-conditioners deployed globally is roughly around 2 billion [4], and with the growing demand for cooling, it is envisaged that two-thirds of households around the world will possess an air-conditioner by 2050. This in turn leads to higher need for electrical energy per household and if this electrical energy does not come from renewable sources, it leads to higher CO_2 emissions and this vicious cycle continues as the demand for space cooling grows. Cooling contributes roughly between 3.4 and 4% of global emissions [5], and reducing this percentage is one step towards climate protection.

Electrically driven air-conditioning units (both large and small) used today are based on vapour compression (VC) technology, and these are the kinds of units that people usually buy when they seek respite from the heat. This works great when there are only a few units installed and the electricity grid is strong. However, this is not the most sustainable solution for the reasons just explained above. The most efficient air conditioners cost a lot to purchase but provide savings in the long run [4], but customers tend to opt for the cheaper ones, which are low on energy efficiency, and this inefficiency puts considerable strain on the electricity grid and can account for over half of the peak electricity demand during the hottest days. Just like how the world is transitioning to generating more renewable electricity via solar and wind, it is also vital to generate heat using solar energy and also use residual heat, from systems such as Solid Oxide Fuel Cells and others, to the maximum extent possible in order to bring down the electrical energy needs from cooling. This is where technology development in thermally driven cooling and refrigeration systems will play a crucial role.

The higher the ambient temperature, the higher the need for space cooling and the corresponding energy demand. The need for thermally driven cooling systems also arises from the fact that the cost of building, maintaining and operating electricity networks and systems to cater to peak demand is two to four times the cost of that needed for baseload electricity generation [1]. It is envisaged that thermally driven cooling systems will help in reducing both the peak and baseload demand in electricity and thereby primary energy consumption and in turn green house gas (GHG) emissions provided they are engineered and designed to meet the end-user requirements.

This chapter will look into how Solid Oxide Fuel Cells and other heat sources can be integrated into an absorption refrigeration/cooling system to generate cooling. Utilising residual and renewable heat will help make cooling more sustainable and less energy-intensive. Some of the key aspects that will be looked into in this chapter are as follows:

- What sources of heat can be tapped into? And how can heat be transported?
- What role can heat pipes play in modern heat exchangers and heat transport networks?
- How can heat-driven cooling systems reduce energy demand and in turn CO_2 emissions?

2. Technologies for sustainable cooling

In this section, we will take a look at the technologies that will help progress sustainable space cooling. The technologies that can make this happen are *Solid Oxide Fuel Cells*, *Absorption Refrigeration System*, *Solar Thermal Energy Systems* and *Heat Pipes*. By integrating these technologies in a holistic way, the electricity demand for cooling can be drastically reduced. The key to doing so is to harness renewable heat sources (Solar Thermal), integrate secondary heat sources (Solid Oxide Fuel Cells) and develop an individual unit or a system (driven by thermal energy) that is able to cool down the space and achieve the temperature needed for thermal comfort.

2.1 Solid oxide fuel cell

A Solid Oxide Fuel Cell (SOFC) is a high-temperature electrochemical device that converts chemical energy of fuel to electricity and high-quality heat. The temperature of operation of current state-of-the-art SOFC cells is between 600 and 800°C [6–8], and research is underway to further bring down the operating temperature. An SOFC is a multi-fuel compatible device, meaning a wide range of fuels can be used for power generation, and this aspect is critical for future power generation systems. However,

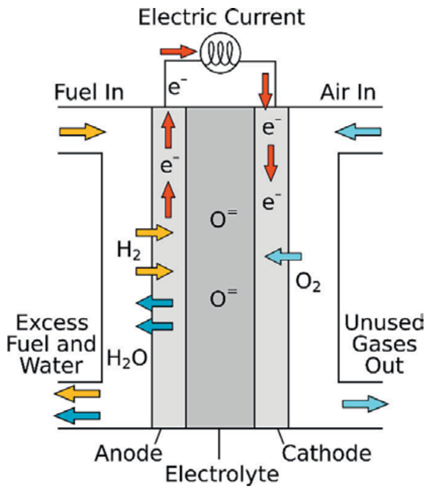

Figure 1.
Schematic of solid oxide fuel cell [9].

amongst the different fuels, only hydrogen, methane and biogas (after cleaning) can be directly fed into the SOFC stack. The rest of the fuels warrant a fuel reformer or a cracker prior to the stack so that the fuel is reformed or conditioned to an extent that is compatible with the stack.

The basic schematic of a single solid oxide fuel cell is shown in **Figure 1**.

When many cells are put together, a stack is formed, and stacks can then be assembled together along with other auxiliary components (such as heat exchangers, pumps, sensors, and blowers) to form a system. SOFC systems for power generation based on biogas or biomethane as fuel is envisaged to be a game changer in the power generation business due to the high efficiencies achievable and low emissions generated. SOFCs powered by biogas will complement solar, wind and other renewable sources of electricity generation. Biogas is 100% renewable and can be generated with current technologies at prices that are acceptable for the market [10]. The electrical efficiency of such a system is close to 55% and the combined heat & power (CHP) efficiency is close to 90% [11].

The reader is encouraged to refer to standard textbooks on high-temperature fuel cells [12] for detailed and in-depth information on different technical aspects of SOFCs.

2.2 Absorption refrigeration system

Absorption refrigeration system, also known as vapour absorption refrigeration system (VARS) is a thermally driven system which requires heat rather than electricity as input to drive the compressor. The compressor in a VARS is the desorber and the absorber together. A schematic of the VARS is shown in **Figure 2**.

The desorber, rectifier, condenser, refrigerant pre-cooler (Refgr pre-cooler in **Figure 2**) and solution heat exchanger form the high-pressure part of the VARS, and the evaporator, absorber and solution pump form the low-pressure part of the VARS. Key advantage of the VARS is that the amount of electricity needed to run the system is significantly lower when compared to VC systems. The reason for this is because in a VARS, it is the liquid that is pumped to a higher pressure, whereas in a VC system, it is gas which needs to be compressed to a higher pressure. Compressing a gas is more

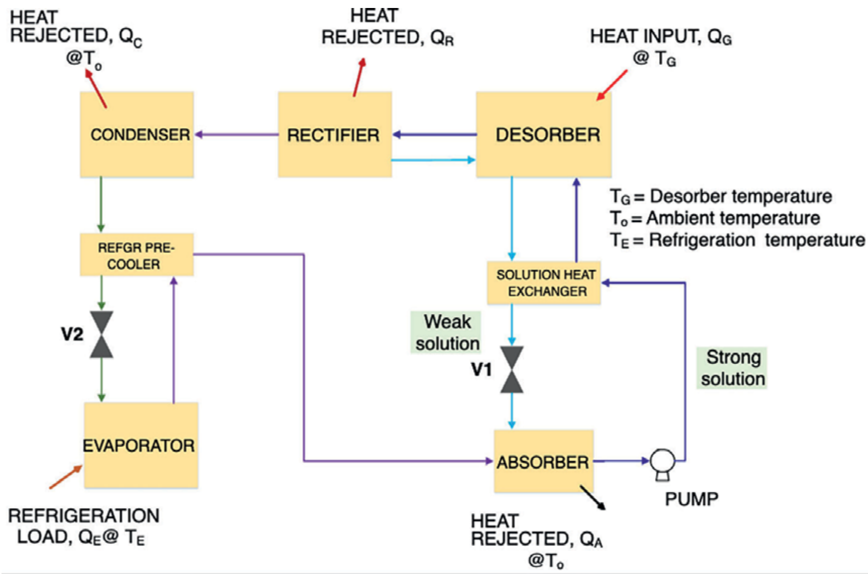

Figure 2.
Schematic of vapour absorption refrigeration system.

energy-intensive than compressing a liquid, and that is the fundamental difference between the two cooling systems in terms of energy consumption levels.

The temperature needed at the desorber of the VARS is between 100 and 200°C, depending on the amount of cooling and evaporator temperature needed [13]. A temperature of 100°C at the desorber end, along with sufficient thermal energy is deemed to be sufficient for maintaining a temperature between 18 and 24°C at the evaporator (needed for thermal comfort), and this is easily achievable from renewable or residual heat. More detailed information on absorption systems can be found in [14].

2.3 Heat pipes

Heat pipes are isothermal devices that simply transfer heat from one end to another. They are able to transport large quantities of heat by making use of the latent heat capacity (change from liquid phase to vapour phase and back to liquid phase) of the working fluid present inside it. The basic schematic of a heat pipe is shown in **Figure 3**.

A heat pipe has three sections, namely *evaporator*, *adiabatic,* and *condenser*. The outer shell of the heat pipe is made of metal, and there is a porous wick structure inside the metal, which helps transport the working fluid from one end to the other end of the heat pipe. Some heat pipes also function without the wick structure. The evaporator section is the place where heat is added to the heat pipe, which then gets transported all the way to the condenser section where heat is expelled.

The key advantages that heat pipes [15] have are:

- Very high thermal conduction
- Fast response to thermal loading
- Quiet operation

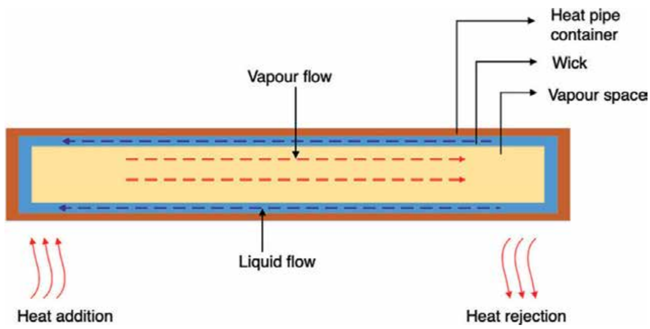

Figure 3.
2D schematic of heat pipe.

- Reliability
- Absence of moving parts
- Well-defined temperature of delivery

The above advantages make them an ideal candidate for transporting heat in the most efficient manner from the place of generation (source) to the place of use (sink). Heat pipes come in different shapes with different materials and working fluids for different applications, which makes them highly versatile. The reader is referred to standard textbooks on heat pipes [15, 16] to gain in-depth knowledge of these devices.

Some of the common working fluids used in heat pipes and their useful temperature range are given in **Table 1**. The choice of the working fluid will determine the thermal performance of the heat pipe and the temperature range in which it can be operated for use in an application.

2.4 Solar thermal energy system

A solar thermal energy system is able to capture sunlight (solar energy) and convert it to thermal energy by means of a collector. They are usually classified into low, medium and high-temperature collectors depending on the temperature required for the end application that they are catering to. Temperatures anywhere between 30 and 1000°C [17] are achievable with solar thermal technology. Amongst solar thermal

Working fluid	Useful temperature range (°C)	Boiling point at atmospheric pressure (°C)
Water	30–200	100
Toluene	50–200	110
Flutec PP9	0–225	160
Heptane	0–150	98
Thermex	150–350	257
Flutec PP2	10–160	76

Table 1.
Commonly used working fluids in heat pipes.

Figure 4.
Schematic of solar energy thermal system (non-concentrating type) [20].

collectors, there are two types: *non-concentrating* type and *concentrating* type. In the non-concentrating type, the area that intercepts the solar radiation is the same as the area that absorbs the solar energy. In the concentrating type, the area that intercepts the solar radiation is several times greater than the absorber area. The former is easy to install, does not require a special tracking system and is cost-effective, but the downside is achievable temperatures are limited to 200°C. This is the type that is installed at most residential homes and buildings. Even though the maximum temperature is limited to 200°C, it is not an issue as far as its integration with VARS is concerned as the maximum temperature needed at the desorber is 200°C.

The basic principle of operation of a non-concentrating type of solar collector is as follows [18, 19]: A tube collector is installed on the roof of a building, on the surface that is exposed to sunlight. The tubes in the tube collector hold a heat transfer fluid, for example, water or propylene glycol-water mixture, which gets heated by solar insolation. The heat transfer fluid then evaporates and transfers its heat to a thermal energy storage unit (which usually contains water) and flows back to the tube collectors for the process to start all over again. One such design is shown in **Figure 4**.

There are textbooks and tools [21, 22] that are widely available which help in the design of such solar thermal collectors. The reader is highly encouraged to refer to these sources for deeper insights and knowledge.

Now that we have some understanding and insights into these four technologies, let us take a look at how they can be integrated together to enable cooling solutions that are sustainable and less energy intensive.

3. Ways and means to tap residual and renewable heat

Just as innovation has progressed in the field of solar cells, for generating electricity, and has reached widespread market penetration, the same must be achieved for tapping solar thermal energy and residual thermal energy wherever and whenever possible. This heat can then be immediately used for space cooling or stored for later use for other purposes. Tapping solar thermal energy for hot water generation is quite well known. However, tapping thermal energy and using it to drive a cooling system in a continuous manner is still a challenge, but if done correctly will make space cooling sustainable and environment friendly.

As mentioned earlier in Section 2, a temperature between 100°C and 200°C is needed at the desorber end of the VARS, and this can easily be achieved by tapping heat either from SOFCs or from solar. In this process, heat pipes will play a key role in tapping and transporting this heat in the most effective and efficient manner.

3.1 Tapping heat from Solid Oxide Fuel Cells

As mentioned in Section 2.1, SOFCs are high-temperature devices, and this means there is immense scope for tapping residual heat from these units and systems. The heat from an SOFC system can either be directly taken from the stack or from the exhaust of the SOFC system. If one does not make use of the residual heat from an SOFC, then it is dissipated to the environment, and that means high-quality exergy (which can be put to work) is permanently lost to the environment.

There are couple of ways for transferring heat from a solid oxide fuel cell system to the desorber of the VARS [23]. Some of the ways are mentioned below.

3.1.1 Direct plugging at both ends

With direct plugging, the heat pipe is embedded on both ends *viz.* The SOFC stack and the desorber of the VARS are shown in **Figure 5**.

The temperature at the SOFC stack side is between 600 and 800°C, and that at the desorber side is around 200°C maximum. Hence, some metal blocks need to be placed between the SOFC and desorber in order to achieve temperature compatibility at both ends. This is because the heat pipe is an isothermal device. The design of the individual heat pipes between the metal blocks needs to be done carefully in order to achieve the desired heat transfer. Through this design, not only is thermal energy (or residual energy) transferred to the desorber, but the SOFC stack temperature is also maintained at the desired operating value, which is critical for stack operation.

3.1.2 Direct plugging at one end

In this design, the heat pipe is embedded only at the desorber end, and the other end is either

- Placed adjacent to the SOFC stack within the insulation – Option 1

(or)

- Exposed to hot cathode exhaust – Option 2

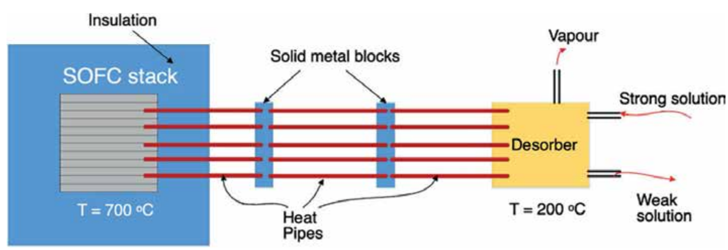

Figure 5.
Direct plugging of heat pipes at both SOFC and desorber end [23].

Both options offer flexibility as far as heat transfer to the heat pipe(s) is concerned. In the former, the heat pipe can be moved around anywhere in the space between the stack and insulation, to vary the heat flux that gets into the heat pipe whilst in the latter, the cathode exhaust flow rate and temperature can be varied which in turn varies the heat flux and in turn transfer rate. **Figures 6** and **7** show one visualisation of how this concept can be realised.

3.1.3 Use as a heat exchanger

In this configuration, there is no plugging of the heat pipes either at the desorber or at the SOFC end instead, it is used as a heat exchanger in which thermal oil is

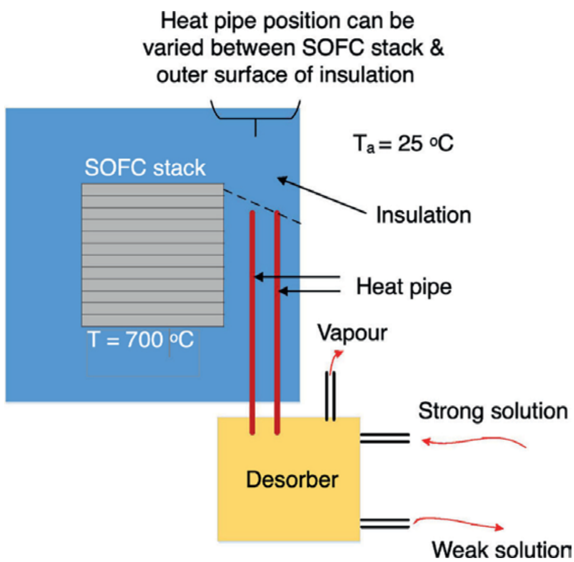

Figure 6.
Direct plugging only at desorber end, option 1 [23].

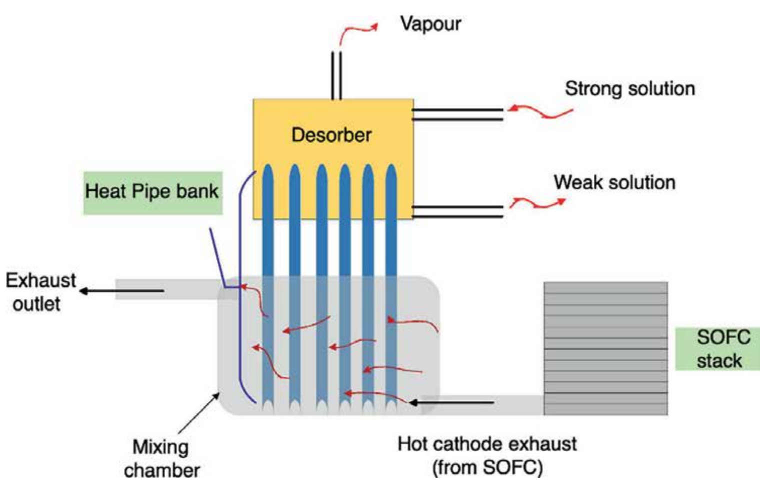

Figure 7.
Direct plugging only at desorber end, option 2 [23].

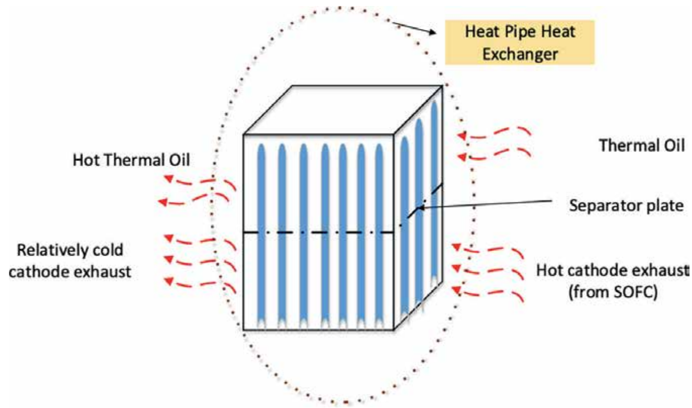

Figure 8.
Use of heat pipes in a heat exchanger configuration [23].

heated by the hot cathode exhaust to the required temperature. The hot thermal oil is then used as a coupling fluid in the desorber. The thermal oil can also be replaced with any other heat transfer fluid that is compatible with the operating temperature range needed at the desorber. **Figure 8** shows this concept.

3.2 Tapping heat from solar

Heat (or thermal energy) can easily be tapped from solar radiation using solar thermal collectors mentioned in Section 2.4. These devices convert solar radiation into heat, which gets absorbed into a heat transfer fluid (HTF) and then transported to the specific application where thermal energy is needed. It is envisaged that both the temperature and quantity of heat that can be achieved from solar radiation are sufficient to drive the desorber of the VARS.

The ways in which the heat can be transferred to the desorber of the VARS is as follows:

3.2.1 Direct transfer via HTF

In this method of heat transfer, the HTF directly transfers heat to the desorber of the VARS. The heat transfer will be in a closed loop cycle from the solar thermal collector to the desorber of the VARS and back, as depicted in **Figure 9**. There is one heat transfer loop involved, and the control panel ensures the flow rate and temperature of the HTF at the desorber inlet are in line with the cooling output desired by the VARS.

3.2.2 Indirect transfer via heat pipes

In this method of heat transfer, the HTF transfers heat at the evaporator section of the heat pipe heat exchanger. This heat is then transported along the length of the heat pipe and given out at the condenser section, which is directly embedded in the desorber of the VARS. This method is to be employed where the HTF cannot be directly coupled to the desorber of the VARS. The heat transfer comprises two loops – first from the HTF to the heat pipe and second from the heat pipe to the desorber. The schematic of this concept is shown in **Figure 10**.

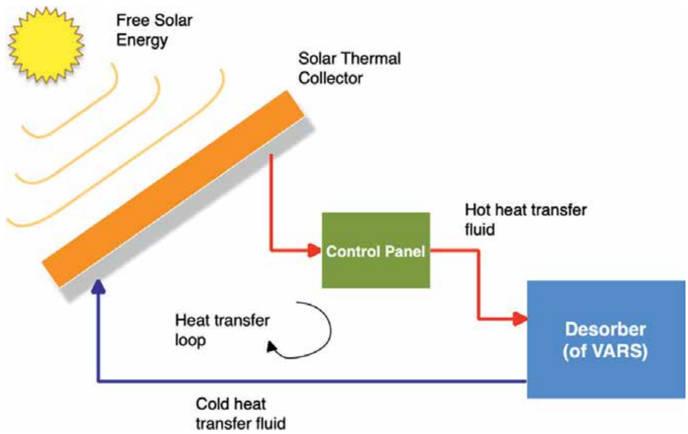

Figure 9.
Direct transfer to desorber via heat transfer fluid.

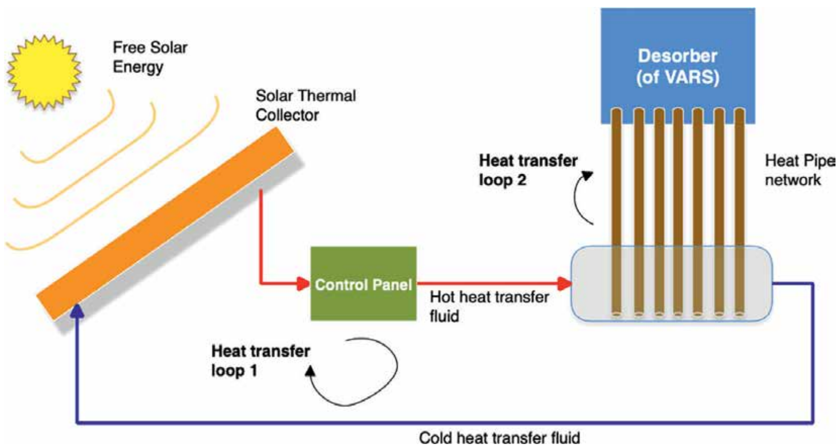

Figure 10.
Indirect heat transfer to desorber via heat pipes.

The role of the control panel once again is to regulate the flow and temperature of the HTF.

3.2.3 Direct plugging at both ends

In this concept, the heat pipes are directly embedded in the solar thermal collector at one end and on the desorber at the other end. This facilitates the direct transfer of heat from the solar thermal collector to the desorber of the VARS. The schematic representation of this concept is shown in **Figure 11**. Heat pipes in this configuration need to be twisted and bent in order to route them appropriately.

3.3 Why heat pipes are better than conventional heat exchangers?

The heat (or thermal energy) available from SOFCs is classified as residual heat, and solar energy is classified as renewable heat. The reason why they have

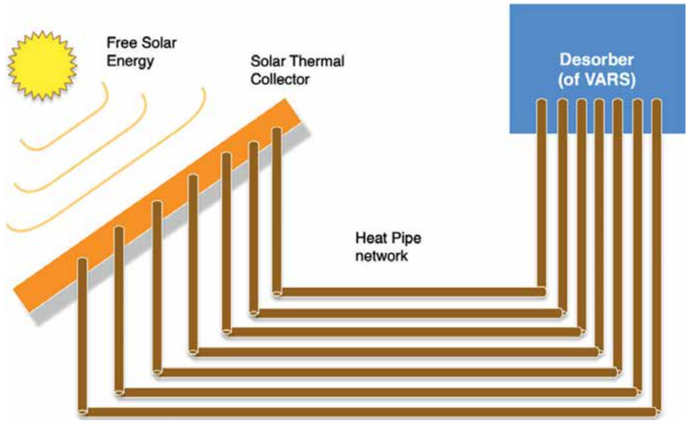

Figure 11.
Direct plugging at both ends.

been termed so is because the thermal energy that can be tapped from an SOFC is the by-product of the electrochemical combustion process, and the thermal energy that can be tapped from solar energy is abundantly and freely available. Once the heat can be tapped effectively from the respective sources, it needs to be transported to the end location where it will be used. It will be most ideal if the temperature at which heat is tapped from the source is the same as the temperature at which heat is delivered to the sink because this gives the possibility to bring down the temperature if needed and also to tweak the heat flux levels. This is where heat pipes come into play as they are extremely efficient in transporting heat, and there is very little temperature drop along the heat pipe. One can say that they act like a thermal bridge. If the same process were to be done via conventional heat exchangers, then there would be a lag in the thermal response, and also, the temperature and quantity of heat delivered could be lower than that of what is possible via a heat pipe and will warrant a whole range of coupling fluid circuitry (pumps, valves regulators etc.)

Heat pipes, being isothermal devices, have the capability of transporting large quantities of heat with a very high thermal response, and all this can be done by tweaking the designs of the heat pipe. They can also be twisted and bent into several shapes, and that makes it convenient to move heat from the place it is produced to the place where it is needed (in this case, mainly VARS).

Heat pipes can be used in the following areas of a VARS:

- Desorber
- Absorber
- Evaporator &
- Condenser

At the desorber, heat pipes aid in boiling the refrigerant-absorbent solution, generating refrigerant that then circulates through the rest of the cooling system components. Heat pipes can transport heat out of the condenser, and heat pipes can aid in getting heat into the evaporator. Finally, at the absorber where the process is exothermic, heat pipes can once again aid in removing heat from the component to the ambient.

The key advantage that heat pipes have over conventional heat exchangers [2] (e.g., plate heat exchangers, shell and tube, and tube and fin) is summarised in the points below

i. The thermal response, which is the speed at which a device responds to sudden changes in temperature, of the heat pipe is orders of magnitude higher than conventional heat exchangers.

ii. High compactness and extremely flexible in arrangements.

iii. Complete separation of hot and cold fluids.

iv. Unidirectional heat transfer. This means the heat pipe acts like a thermal diode.

v. Modularisation – Each heat pipe can be considered as a separate entity, and this adds resilience to the heat pipe heat exchanger, preventing a single point of failure.

vi. Heat pipes can be less bulky than conventional heat exchangers.

vii. Ease of maintenance.

viii. Relatively less equipment in fluid circuitry.

4. System design and integration

Now that we have looked into the technologies that are needed and will enable generate cooling from thermal energy, it will be of interest to the readers to gain further insights on how this can be accomplished for apartment buildings, individual homes and other community living houses, especially for countries that fall under the 'hot and tropical' category. This section provides some designs on how heat-driven cooling systems can be implemented, configured and designed for different scenarios and use cases.

The key in reducing dependence on electricity (or electrical energy) for space cooling, especially in hot and tropical climates, is to develop a small- and medium-scale VAR system (or other heat-driven cooling systems) that ideally has a similar volume footprint when compared to a VC system and can generate sufficient cooling for thermal comfort. These systems must be able to cool the space and maintain a temperature between 18 and 24°C, which is the requirement in most cases.

4.1 Solar heat-driven VARS: one apartment building

Solar heat, also defined as renewable heat, as mentioned earlier in this chapter, is freely available for over 200 days in a year (or 12 hours × 200 = 2400 hours) [24] in hot and tropical countries, and this can be made use of in operating a thermally driven cooling system. One way to practically implement them in an apartment building is given in **Figure 12**.

As seen in **Figure 12**, the building has four individual apartments, each of which needs an air-conditioning unit. The VARS unit, with all its components, is to be packaged

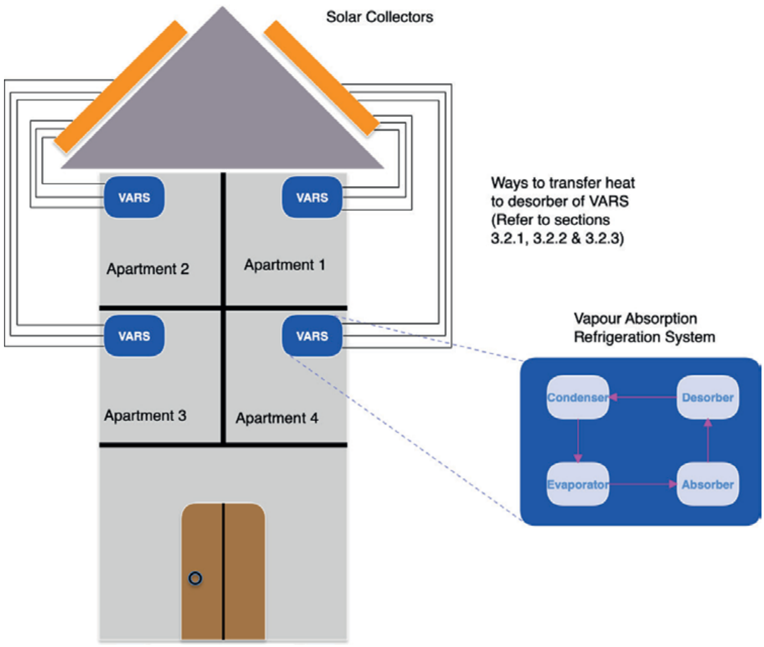

Figure 12.
Solar heat-driven VARS for one building.

in such a way that the evaporator is inside the space (of the building) which needs cooling, and the rest of the components, *viz.* desorber, absorber and condenser, are placed outside the space. This is because the condenser and absorber release heat, and the desorber needs to be supplied with external heat. The thermal energy for driving the VARS comes from the solar collectors installed on the roof of the building, and the means to transfer heat to the desorber is from one of three ways mentioned in Section 3.2. If heat transfer fluid is used to supply heat at the desorber, then they have to be channelled via pipes and brought down to the individual units installed at various apartments. In case heat transfer to the desorber is via heat pipes then these have to be routed appropriately along the building structure and also brought down to the individual units.

The same concept can be extended to buildings with more than four apartments.

4.2 VARS coupled with Solid Oxide Fuel Cells: one apartment building

Many of the apartment buildings in developing countries have a diesel-based generator on their premises in order to supply electrical power during outages. This diesel-based generator comes into action only when there is an interruption in the grid electricity supply and thus does not run continuously. Replacing this diesel-based generator with an SOFC system running continuously on biogas will not only complement renewable electricity supply, by adding resilience to the network, but also will lead to an environmentally friendlier way of generating electricity with high efficiency. The efficiency of diesel-based generators is around 25% [25] and depends on the operating conditions. The SOFC system is not only going to generate electricity but also sufficient heat to tap into. The individual VAR units are placed at each of the apartments, in the manner described in Section 4.1, and the heat to each of these VAR units is supplied via one of three ways described in Section 3.1. The same concept

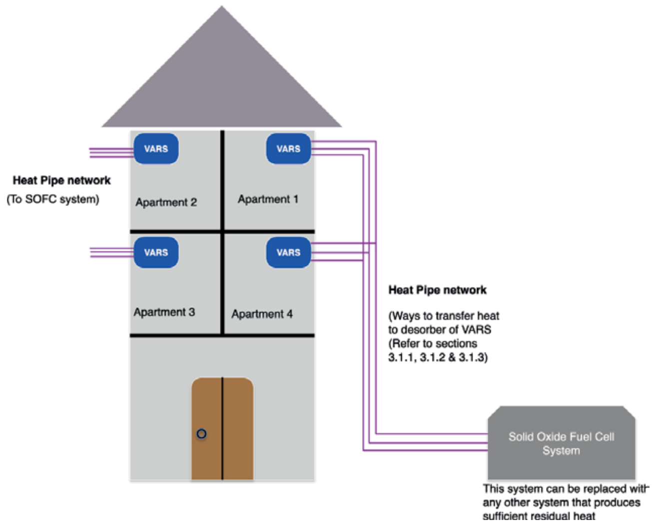

Figure 13.
VARS coupled with Solid Oxide Fuel Cells.

can of course be extended to buildings with more apartments, the only pre-requisite being the existence of an SOFC system at the premises of each apartment building.

Note: The SOFC system can also be replaced with another system that generates sufficient residual heat. **Figure 13** shows the visualisation of this concept.

4.3 VARS using residual or renewable heat: multiple apartment building

It can very often be the case that in many developing countries (under the category of 'hot and tropical climate'), most of the buildings do not have any sources of renewable or residual heat integrated or built into the structure. Also, for newer buildings, if the latest building standards and codes were not followed then they too have no provision for tapping residual/renewable heat. In this case, how can thermally driven cooling systems be installed in these apartments? Or the main question is how to get the necessary amount of thermal energy to the individual VAR unit installed in these buildings if the customers bought one?

One way to do this is to have a centralised location for each neighbourhood which can generate both renewable and residual heat and then transfer this thermal energy via a suitable heat transfer fluid to each of the apartment buildings. The heat transfer fluid supplied to each of the buildings should have sufficient heat and temperature levels needed to drive the combined heat load of all desorbers of the VAR units in that building. For example, the centralised location can use advanced solar collectors which can generate heat at a higher temperature and then transfer this to an HTF, or the centralised location can have a larger biogas-driven SOFC generator and then transfer the residual heat to the HTF or it can use a combination of both renewable and residual heat in transferring heat to the HTF which is ultimately distributed to the buildings. It is envisaged that this is a more effective and practical approach rather than a district cooling system where chilled water at 10°C is supplied to buildings. For reasons mentioned in the introductory part of the chapter, circulating chilled water via suitable conduits inside space may not produce the desired cooling effect needed for thermal comfort.

A diagrammatic representation of this concept is presented in **Figure 14**.

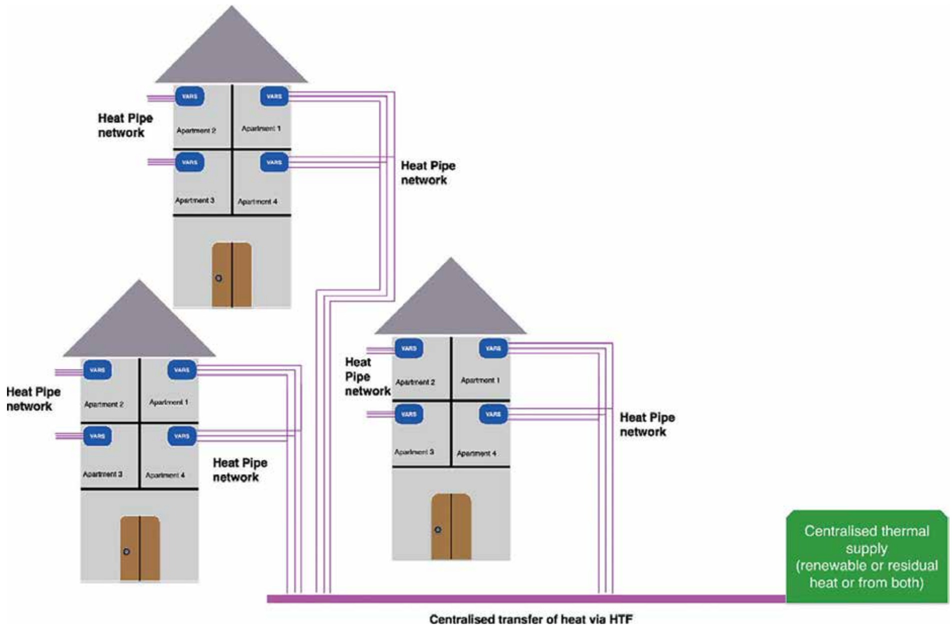

Figure 14.
VARS using residual or renewable heat – Centralised supply.

4.4 Design of heat pipe heat exchangers and heat transfer solutions

One of the important aspects in heat-driven cooling systems is the availability of heat in ample quantities and at the temperature needed to run the thermally driven cooling system. As heat pipes are an effective and efficient link between sources of heat (both renewable and residual) and sink, it is quintessential to look at some of the designs and configurations that the heat pipe heat exchangers must have in order to accomplish this task. In order to make heat-driven cooling systems a reality, heat pipe heat exchangers or heat pipe networks are needed in the following areas:

a. At the desorber

b. Between SOFC stack/system and heat transfer fluid

c. Between SOFC stack/system and desorber

d. Between solar collector and desorber

e. Between heat transfer fluid and desorber

f. At the condenser and absorber of the VARS

g. Between centralised heat transfer and individual apartments

Some designs on how these heat transfer networks must look in given in **Figure 15** (absorber integrated with heat pipes), **Figure 16** (between centralised heat transfer fluid and desorber of individual VARS), and **Figure 17** (at multiple locations in a complete system).

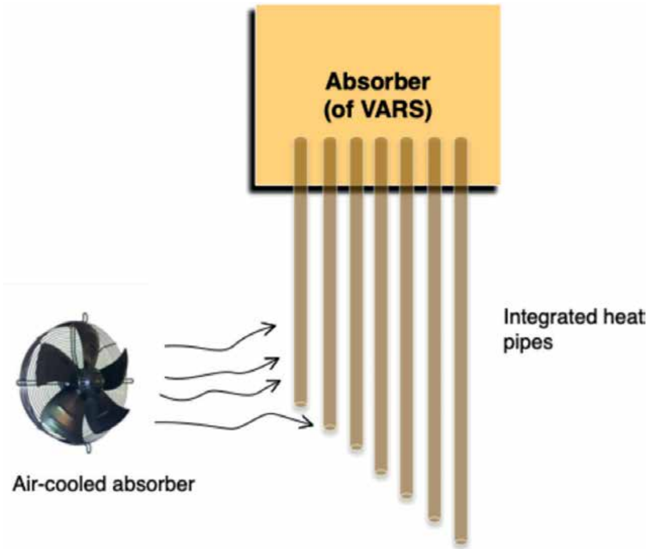

Figure 15.
Air-cooled absorber with heat pipes.

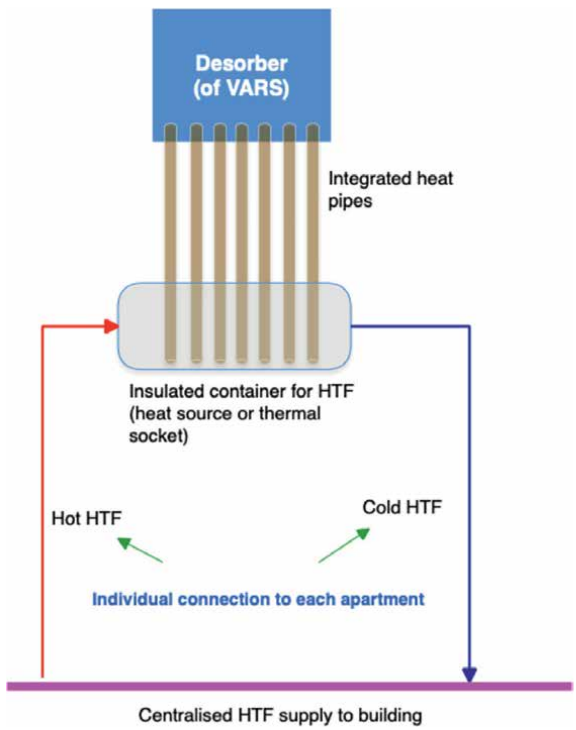

Figure 16.
Heat pipe heat exchanger connected to centralised heat transfer fluid.

Solar radiation is widely available in ample quantities in countries that need air-conditioning systems for the most part of the year, and also the technology (solar thermal) for tapping this renewable heat is widely available. On the other hand, SOFC is a new

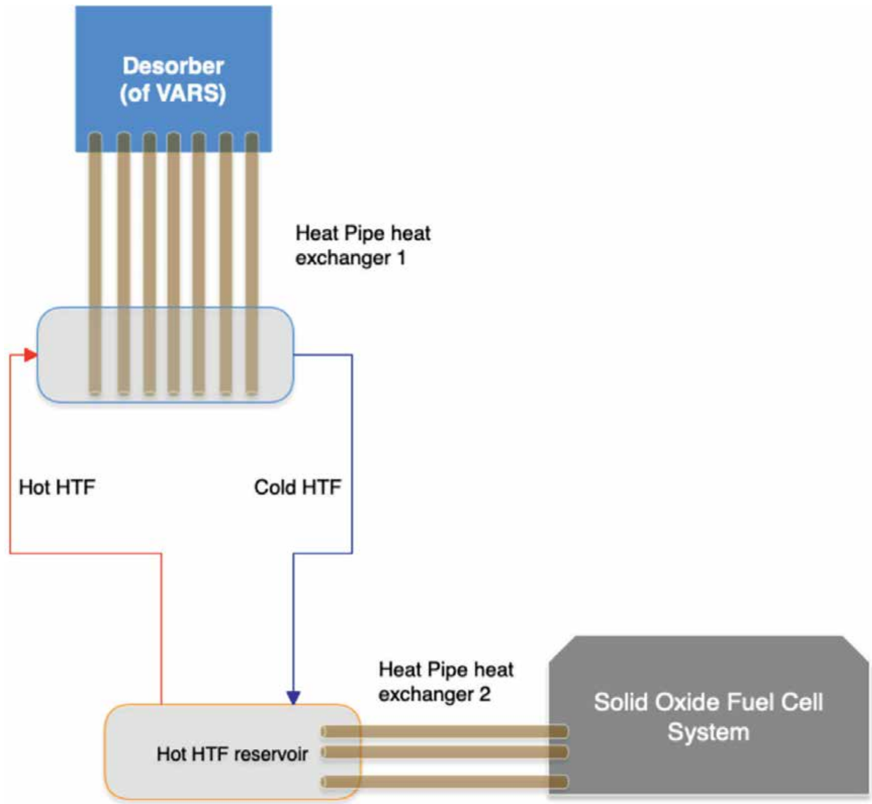

Figure 17.
Heat pipe heat exchanger at multiple locations in a system.

technology and relatively expensive; however, together with biogas as a fuel, it is envisaged to play a greater role in the power generation market, and when that happens, systems for tapping heat must be readily available to make use of the high-quality residual heat. System designers and developers may use a combination of renewable and residual heat sources to supply the required quantity of heat and in doing so they will need to invent different designs of heat pipe-based heat exchangers and networks besides the examples and figures shown above. Other advancements in micro-channel heat transfer are also expected to advance the deployment of thermally driven cooling systems.

To make thermal-driven cooling systems a reality, a *thermal socket*, akin to an electrical socket, must be made available to each apartment or house. What this thermal socket will do is to provide the thermal energy needed when a small-scale VARS is installed at the apartment/house.

Note: The term *thermal socket* is coined and introduced for the first time in this chapter and also in the broad context of HVAC. This term needs to be expanded and defined further to elaborate on its importance, and this is out of the scope of this chapter. The readers are advised to contact the author or the publisher for further details.

4.5 Methodology for system design and development

It is very well known that thermally driven cooling systems work, but they are not widely implemented on a small scale. So, what can be done to implement them widely? There are a number of components involved in the thermally driven cooling system (VARS) that warrant detailed engineering calculations, simulation, design and manufacturing. This section provides an insight into which components and sub-systems need in-depth engineering and development and what key aspects need to be looked into. For reasons of brevity, detailed calculations are not presented, but only the methodology and approach are presented here. The reader can use these together with other standard textbooks to carry out detailed calculations for each of the components.

i. Heat Source –

The most important driver that is going to make the VARS work is the availability of thermal energy. Having sufficient thermal energy in the right quantity and temperature levels is quintessential for the successful operation of VARS. Calculating this is quite straightforward. Data on renewable and residual heat available in different countries that fall under the category of 'hot and tropical' can easily be made available and checked if they are sufficient to drive a cooling system. The sizes of cooling units that these heat sources must cater to range from 0.75 ton of air-conditioning to 2 tons of air-conditioning. One ton of air conditioning is roughly able to cool down 12,000 BTU of air per hour or provide 3.5 kWh of cooling. In the examples presented here, thermal energy from solar insolation for a particular building or area can easily be calculated, and the amount of thermal energy from a solid oxide fuel cell system can be calculated based on the size and operating conditions of the system. Calculations for other residual sources of heat can also be made and checked to see if the quantity and temperature of heat is sufficient to drive a VARS or group of VARS.

ii. Heat Transport –

The next important and vital link to this whole concept is the capture and transport of the generated heat. This is where heat pipes come into play. Once the quantity of heat to be transported is determined and the temperature of operation is established, then the individual heat pipe and in turn the heat pipe heat exchanger can be designed to meet the application requirements. The reader is encouraged to read textbooks on heat pipes [15, 16] on how to go about choosing different aspects of heat pipe – type, outer material (container of heat pipe), working fluid, screen size, flow limitations etc.

Design and development of heat pipes for thermally driven cooling systems should be carried out for different types and sizes of cooling systems that one wants to have in their product portfolio. Some of the technical aspects that warrant attention are:

- Heat flux at the evaporator and condenser end of the heat pipe.
- Fluid flow aspects of the working fluid inside the heat pipe.
- Enhancing the surface area at the evaporator and condenser end of the heat pipes.
- Limitations on the length of the heat pipe with the heat transport capability.
- Thermal response of the heat pipe to fluctuating heat levels.

iii. VARS unit –

Once the heat source and the heat transport means have been identified and engineered, the next step in the puzzle is to design, engineer, and develop a compact VARS with a similar footprint to that of the VC system. The main components that warrant attention are as follows:

a. Desorber & absorber

The desorber and the absorber together act as the thermal compressor in a VAR system and take over the role of the electric compressor (in a VC system). It is at the desorber where the heat input takes place, and the refrigerant-absorbent solution boils off. Depending on the refrigerant-absorbent solution used and the cooling range desired, the mass flow rate of refrigerant needed for cooling must be calculated based on the amount of heat supplied. Along with the quantity of refrigerant generated, the quality of refrigerant generated must also be calculated. Desorber designs for incorporating heat pipes or the heat transfer fluid directly must be carried out coupled with fundamental physics processes such as two-phase flow, boiling and vapour flow dynamics. Along with fundamental studies, engineering of the desorber for materials, shape and structural robustness must also be carried out.

The absorber is the place where the refrigerant vapour coming from the evaporator is mixed with the weak solution coming from the desorber to regenerate the strong solution, which is then pumped back to the desorber. The mixing process is exothermic and generates heat and this heat needs to be removed and heat pipes can play a vital role in compact absorber designs by instantly removing the heat generated from the mixing process and transferring it to the ambient. Similar to the desorber, the absorber also needs studies and analysis on fundamental physics processes such as mixing of vapour into liquid, flow dynamics and heat transfer.

b. Condenser & Evaporator

These two components are quite straightforward, and the designs can easily be taken and adapted from the VC system. The condenser is the place where the refrigerant loses heat and turns to liquid, the heat being rejected to the ambient, and the evaporator is the place where the heat from the space to be cooled is absorbed by the liquid refrigerant, turning it back to vapour. It would be preferred to have both these components air-cooled in order to reduce the complexity of the VARS and to make its installation easy in households.

A sample flow chart for the design of a directly coupled SOFC-VAR system is given in **Figure 18**. Similar processes can be developed for integration with other sources of heat.

iv. Control unit

A control unit is absolutely essential for smart and energy-efficient operation of the VARS. More control and sensor information will aid in better use of energy

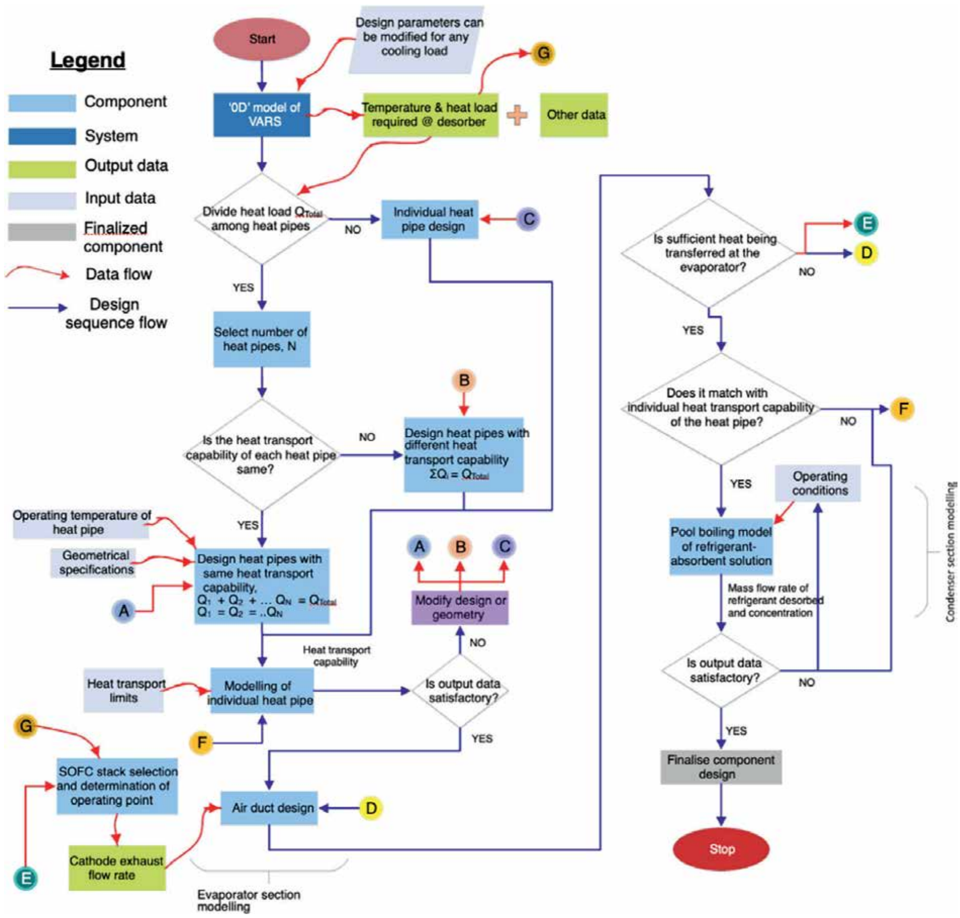

Figure 18.
Flow chart for design of directly coupled SOFC-VAR system [26].

needed by the cooling system and also its operation. The control unit must be able to adjust and control the following:

a. The heat input needed at the desorber.

b. The refrigerant production rate at the desorber based on the cooling need at the evaporator.

c. The pumping speed of the solution pump depends on the cooling needs.

d. The concentration difference between strong and weak solutions and its effect on energy efficiency.

e. Calculating the deficiency in heat input and communication with the heat source.

This is a topic that warrants special attention on its own, and the possibilities and use cases are endless. The design of the VARS and its interaction with the heat sources are the main factors that affect the control strategy and in turn the design of the control unit.

v. Working fluids and heat transfer fluids

A number of working fluids can be used in heat pipes, and a range of heat transfer fluids can be used to transfer heat from the source to the heat pipe. Of course, it goes without saying that one must strive to use fluids that are environmentally friendly. Particular attention must be paid to the heat transport capability of these fluids, their degradation during the course of cyclic operation, their compatibility with materials that they will come in contact with, and the flow dynamics needed.

With the above-mentioned methodology, together with advanced engineering and development, it is indeed possible to design and operate a cooling system that is driven by thermal energy and that can work in a continuous manner.

5. Energy savings

The hypothesis that we have been working with throughout this entire chapter is that a system which is able to operate and run on residual or renewable thermal energy wherever and whenever possible will definitely bring down the primary electrical energy needs.

Let us look at the amount of energy needed to run a conventional air-conditioner (based on VC technology) and compare it with the energy needs of an air-conditioner based on VARS technology. Air-conditioners are usually categorised in 'tons' for the amount of air they are able to cool. The most common household air conditioners range between 0.75 and 2 tons [27, 28], and the corresponding cooling power for the respective tonnage is shown in **Table 2**.

This means a 1 ton air-conditioner is able to provide roughly 3.5 kW of cooling per hour. Based on the air-conditioners available in the market, split ACs are more energy efficient than window ACs, resulting in lower energy consumption and both types are based on vapour compression technology. **Figure 19** shows the average electrical energy consumption of window and split ACs and compares it to a small-scale VARS. The values shown in this graph correspond to the window and split ACs achieving a room temperature between 18 and 24°C and the small-scale VARS achieving a room temperature of −20°C. It is to be emphasised that lower is the need for the temperature of the room to be higher is the energy needed for running the compressor of

Ton	Cooling power (kWh)
0.75	2.637
1.0	3.516
1.5	5.275
2.0	7.033

Table 2.
Tonnage of household air conditioners [27].

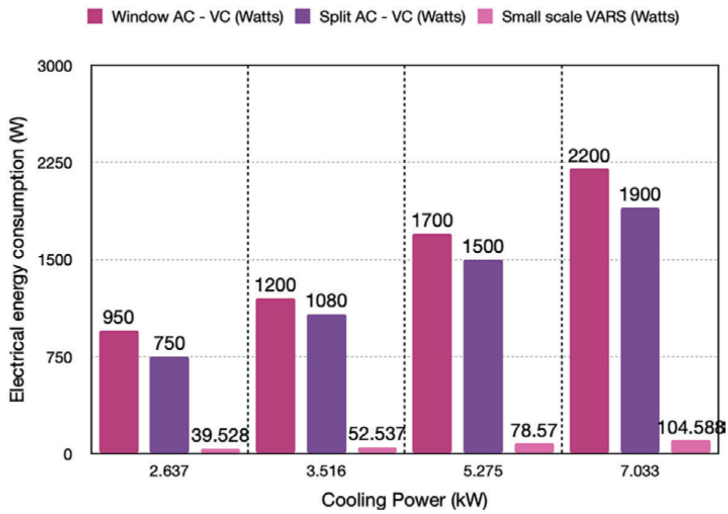

Figure 19.
Electrical energy consumption of VC versus VARS cooling system.

the air-conditioning unit (based on VC system). Hence, here, we are comparing the operational scenario for VARS under extreme conditions with that of the VC unit under milder operating conditions. What we see here is that the electrical energy consumption of the VARS is roughly 4.5% of that of the VC system when the VARS is operating under extreme conditions and this number is bound to be even lower if the VARS was operating for temperatures between 18 and 24°C. The major electrical energy-consuming component of VARS is the solution pump, and the number presented in the graph corresponds to the electrical needs of the solution pump. Even if we add a few fans (for the air-cooled condenser & absorber and a fan for the evaporator to blow air on the evaporator coils) and some electronics to the VARS, the electrical energy consumption is not expected to exceed 15% of that of the VC system.

So, what this means is there is tremendous scope somewhere in the range between 85 and 95% for electrical energy reduction if thermally driven cooling systems were made widely available for home air-conditioning. From the graph in **Figure 19**, if we take a 1-ton air-conditioner, which provides 3.5 kW of cooling per hour and this air-conditioner is thermally driven, then it consumes just 52.5 W per hour as compared to 1200 W with a VC-based unit. If one multiplies this by the total number of air conditioners in a country (hot and tropical), then the amount of electricity savings is tremendous.

It will be good to get a complete view of the energy needs of the VARS, as what was presented above is just the electrical energy needs. **Table 3** summarises the total energy needs for both types of cooling systems for 1 ton of air conditioning. Units running on VARS technology have a coefficient of performance (COP) of just 0.8 compared to units running on VC technology, which have a COP of roughly 3. Now, that makes them relatively inefficient; however, the advantage is that they run on free thermal energy. The VARS needs a total energy of 4.452 kWh out of which 4.4 kWh is from thermal energy, which is tapped for free and made use of.

How does the savings or reduction in electrical energy translate to savings or reduction in CO_2 emissions? This is quite straightforward to determine. Based on what the source of the electricity is for a particular area or province or country, the related

	Vapour compression system	Vapour absorption system	Remarks
Cooling power generated (kWh)	3.515	3.515	Cooling power achieved per hour
Electricity consumed (kWh)	1.2	0.052	This is the electrical energy requirement
Thermal energy needed (kWh)	—	4.4	This energy is assumed to be free—either renewable heat or residual heat
COP	3	0.8	

Table 3.
Theoretical values of energy needs for an AC unit based on VC and VARS technology.

CO_2 emissions from that process or method of electricity generation is well known or can be calculated. This kind of data quantified as grams of carbon dioxide-equivalent emitted per kWh of electricity generated can also be obtained from [29]. Hence, for every kWh of electricity that can be saved, either by increased efficiency or other means, the need for its generation can be reduced and therefore, directly reduce the amount of CO_2 generated. However, one must keep in mind that this applies only when the method of electricity generation is not 100% from renewables because if the electricity generated is totally from renewables, then there are no CO_2 emissions, but even in that case, the saved electrical energy can be used for other purposes as mentioned earlier in the chapter. The reader must keep in mind that these are just the direct emissions coming out of the process of electricity generation and not the lifecycle emissions which will warrant a detailed life cycle analysis (LCA).

6. Conclusions

There is a direct correlation between ambient temperature and space cooling energy needs. The higher the ambient temperature, the greater the need for space cooling and, therefore, the higher the energy needed for running the cooling system. Thermally driven space cooling and refrigeration systems have a huge market potential, provided the system and the unit is developed to a size and scale that can compete with the current vapour compression-based systems in terms of bulkiness and ease of installation. The thermal compressor (desorber plus absorber) in a small-scale VARS must have a volume footprint similar to that of the electrical compressor in a VC system in order to act as a contender to replace it, and this is absolutely key in the widespread adoption of VARS.

As cooling takes up 20% of the total electricity demand in buildings and other places, replacing the total energy demand for cooling with freely available residual or renewable thermal energy will go a long way in reducing the energy needs from cooling. As we have seen, there is scope for reducing electrical energy requirements anywhere in the range between 85 and 95% when implementing thermally driven cooling systems. For example, even if a modest 10% of the cooling needs can be met by using thermal energy and not electrical energy, then the available electricity can be used for other purposes as the demand for electrical energy keeps rising every year. Electrical energy has high-quality exergy and should be used for applications that absolutely warrant it.

It was elaborated in this chapter that two vital aspects crucial to make thermally driven cooling systems work are the availability of thermal energy in sufficient quantities and the transport of this thermal energy (heat) to the thermally driven cooling system. The former is available in copious amounts in 'hot and tropical countries' in the form of solar energy whilst the latter is enabled by the use of heat pipes and heat pipe heat exchanger networks. These two aspects will solve more than 50% of the technical challenges in making thermal-driven cooling systems a reality. The ways and means to tap and transfer residual and renewable heat were detailed in sections 3.1 and 3.2, and the role that heat pipe heat exchangers will play in the broader context was detailed in Section 4.3. There is immense scope for making thermally driven cooling systems a reality with technological advancements in the areas of heat pipes and desorbers.

7. Future outlook

The ultimate goal for us as a society should be to be able to provide affordable space cooling solutions to people and countries who simply cannot afford to buy expensive technology, and this must be done by using renewable and residual heat as much as possible. Just like heating is essential to living and working comfortably in cold countries, the same is true for cooling in hot and humid countries. A lot of people in the developing world who fall under the category of 'Hot and humid' tolerate the extreme heat every single day solely for the reason that they just cannot afford to buy the system, and even if they can buy it cannot afford to pay the huge operating costs that tag along with it.

One may argue that if there is sufficient renewable electricity generation for all needs and demands (which will definitely be in the future after 2050), then one can simply use conventional air-conditioning units based on VC technology. But the counterargument will be why not develop units and systems that are able to run on free thermal energy and reduce dependence on electricity (or electrical energy)? Technology-wise if both are possible, then systems running on residual thermal energy will ensure that electrical energy can be directed to other purposes such as EV charging, energy storage or hydrogen production or any other new application(s) that may get invented in the coming decades, etc.

Designing a working unit for different tons of air conditioning and providing appropriate thermal interfaces (the *thermal socket*) with thermal specifications (temperature, heat flow, etc.) will instil confidence in the minds of end users and policymakers alike. This way, units can be installed anywhere, and the thermal source can be flexible.

People have preferences and this is true for any technology; some may want electrically driven cooling systems, and some may want thermally driven cooling systems. It is like some people want solar panels installed on their roof in order to reduce their operating costs through a certain time period and being sustainable, whereas some prefer to use grid electricity and wait till the grid is decarbonised. The same goes for thermally driven cooling systems. Some people will be fascinated by the idea of minimising operating costs of their cooling system and will be the first uptakers whilst some may still stick with the proven electrically driven air-conditioners. But whatever the case, if one is able to make a system work in an alternate way with free or residual energy, then people will see the value and benefit in it and will be more than open and willing to make the change, and this is what thermally driven cooling systems are expected to do.

Of course, there will be challenges that need to be solved, but the first step is to be proactive and find an initial project where such a system can be implemented and demonstrated.

Conflict of interest

The author declares no conflict of interest with anyone or any institutional body.

Notes/thanks/other declarations

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Appendices and nomenclature

AC	air conditioner
CHP	combined heat and power
COP	coefficient of performance
EV	electric vehicle
GHG	green house gas
HTF	heat transfer fluid
HVAC	heating ventilation and air conditioning
LCA	life cycle analysis
SOFC	solid oxide fuel cell
VARS	vapour absorption refrigeration system
VC	capour compression

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References

[1] Motherway B, Dean B, Dulac J, Morgan T, Remme U. The Future of Cooling–Opportunities for Energy Efficient Air Conditioning, Report by International Energy Agency. France: IEA Publications, International Energy Agency; 2018

[2] Ding Y, Guo Q, Guo W, Chu W, Wang Q. Review of recent applications of heat pipe heat exchanger use for waste heat recovery. Energies. 2024;**17**:2504. DOI: 10.3390/en17112504

[3] Circulating Chilled Water through the Existing Central Heating System [Internet]. Available from: https://www.theguardian.com/notesandqueries/query/0,5753,-24934,00.html#:~:text=SPECULATIVE%20SCIENCE-,In%20hot%20weather%2C%20would%20it%20be%20possible%20to%20cool%20the,the%20exisiting%20central%20heating%20system%3F&text=Yes%2C%20but%20it%20wouldn't,radiators%20and%20the%20surrounding%20air [Accessed: 20 July 2024]

[4] The Cooling Dilemma Amid Climate Change [Internet]. Available from: https://www.unicef.org/innocenti/cooling-dilemma-amid-climate-change [Accessed: 19 July 2024]

[5] Writer JW. What Is Sustainable Cooling and How Can it Help Tackle the Climate Crisis? [Internet]. 2023. Available from: https://climatechampions.unfccc.int/what-is-sustainable-cooling-and-how-can-it-help-tackle-the-climate-crisis/ [Accessed: 19 July 2024]

[6] Solid Oxide Stacks for Fuel Cell Systems [Internet]. Available from: https://elcogen.com/products/solid-oxide-stacks-for-fuel-cell-systems/ [Accessed: 19 July 2024]

[7] Solid Oxide Technology [Internet]. Available from: https://www.ceres.tech/technology/ [Accessed: 19 July 2024]

[8] Solid Oxide Technology [Internet]. Available from: https://www.bloomenergy.com/technology/ [Accessed: 19 July 2024]

[9] Solid Oxide Fuel Cell [Internet]. Available from: https://en.wikipedia.org/wiki/Solid_oxide_fuel_cell [Accessed: 19 July 2024]

[10] What Is Biogas? [Internet]. Available from: https://www.nationalgrid.com/stories/energy-explained/what-is-biogas# [Accessed: 20 July 2024]

[11] Langnickel H, Rautanen M, et al. Efficiency analysis of 50 kWe SOFC systems fueled with biogas from waste water. Journal of Power Sources Advances. 2020;**2**:100009. DOI: 10.1016/j.powera.2020.100009

[12] Singhal S. High Temperature Solid Oxide Fuel Cells–Fundamentals, Design and Applications. Amsterdam, The Netherlands: Elsevier; 2004. ISBN 1493303813, 9781493303816

[13] Performance of a LiBr Water Absorption Chiller Operating with Plate Heat Exchangers [Internet]. Available from: https://e-archivo.uc3m.es/rest/api/core/bitstreams/42801bf9-3eb4-4e0f-8564-30d51effe2ab/content [Accessed: 20 July 2024]

[14] Herold KE, Rademacher R, Klein SA. Absorption Chillers and Heat Pumps. 2nd ed. Boca Raton, Florida, USA: CRC Press; 2016. ISBN 9781498714341

[15] Silverstein CC. Design and Technology of Heat Pipes for Cooling and Heat Exchange. 1st ed. Boca Raton, Florida, USA: CRC Press; 1992. ISBN 9780891168591

[16] Reay D, McGlen R, Kew P. Heat Pipes–Theory, Design and Applications. 6th ed. Amsterdam, The Netherlands: Elsevier; 2013. ISBN 9780080982663

[17] Solar Thermal Collector. ScienceDirect [Internet]. Available from: https://www.sciencedirect.com/topics/engineering/solar-thermal-collector#chapters-articles [Accessed: 19 July 2024]

[18] What Is Exactly Solar Thermal Energy? [Internet]. 2016. Available from: https://www.bmwk-energiewende.de/EWD/Redaktion/EN/Newsletter/2016/20/Meldung/direkt-account.html [Accessed: 19 July 2024]

[19] Solar Explained, Solar Thermal Collectors [Internet]. 2024. Available from: https://www.eia.gov/energyexplained/solar/solar-thermal-collectors.php#:~:text=Non%2Dconcentrating%20solar%20collectors&text=A%20flat%20metal%20plate%20that,absorber%20to%20reduce%20heat%20loss [Accessed: 19 July 2024]

[20] Copper Tank Solar Water Heater [Internet]. Available from: https://www.indiamart.com/proddetail/100lpd-solar-water-heater-16953394255.html [Accessed: 19 July 2024]

[21] Platzer W, Stieglitz R. Solar Thermal Energy Systems–Fundamentals, Technology, Applications. Cham: Springer; 2024. ISBN 9783031431722

[22] Online Calculation Tool for Solar Thermal System [Internet]. Available from: https://online.tsol.de/en/ [Accessed: 20 July 2024]

[23] Venkataraman V. Thermal modelling and coupling of a heat pipe integrated desorber with a solid oxide fuel cell. Applied Thermal Engineering. 2019;**147**:943-961. DOI: 10.1016/j.applthermaleng.2018.10.131

[24] List of Cities by Sunshine Duration [Internet]. Available from: https://en.wikipedia.org/wiki/List_of_cities_by_sunshine_duration [Accessed: 20 July 2024]

[25] Diesel Generator Fuel Consumption Guide [Internet]. Available from: https://www.bluedm.com.au/blog/diesel-generator-fuel-consumption-guide-/#:~:text=heavy%20duty%20use.-,The%20efficiency%20of%20diesel%20generators%20is%20expressed%20as%20their%20fuel,for%20your%20power%20requirements%20here [Accessed: 20 July 2024]

[26] Venkataraman V. Coupling of a solid oxide fuel cell with a vapour absorption refrigeration system for refrigerated truck application [thesis]. UK: University of Birmingham; 2017

[27] Window AC Vs Split AC Energy Consumption [Internet]. 2024. Available from: https://www.acsize.com/window-ac-and-split-ac-energy-consumption/ [Accessed: 20 July 2024]

[28] How Much Does Air-Conditioning Cost to Run? [Internet]. 2023. Available from: https://www.climamarket.eu/blog/en/how-much-does-air-conditioning-cost-to-run/ [Accessed: 20 July 2024]

[29] Carbon Intensity of Electricity Generation [Internet]. 2024. Available from: https://ourworldindata.org/grapher/carbon-intensity-electricity?time=1996 [Accessed: 20 July 2024]

Chapter 6

Comparative Exergetic Assessment for the Modernization of Synthetic Fluids by Natural Refrigerants Used in Residential and Commercial Cooling and Air Conditioning Applications

Eraldo Cruz dos Santos, Carlisson Arnaud de Azevedo, Caio Luiz de Carvalho Macêdo, Luiz Felipe Pinheiro Oliveira, Fernando Lucas Alves da Silva, Luis Gabriel Brito Mota and Ismael dos Santos Marinho

Abstract

Currently, in the world, there is a real race, involving several manufacturers that search for more efficient refrigerant fluids, with the need to develop new refrigerants to replace the fluids currently being used in air conditioning and refrigeration systems, aiming to maintain or improve the performance of such systems, reducing their electrical energy consumption. Therefore, this work intends to be another contribution to this scenario and aims to carry out an exergy analysis comparative of the operating characteristics of a residential Chiller system, in which the natural fluid R-290 was used, operating at 60 Hz, and at 70 Hz. The HC R-290 was compared with the HCFC fluid R-22 in the same indirect expansion refrigeration system. For comparison purposes, the main operating parameters of the systems were observed, such as pressures and temperatures, electrical energy consumption, and exergy of the system components. When working with both fluids at 60 Hz, the only negative point for the HC was the higher suction pressure, indicating that the chilled water temperatures were lower with R-22. Under normal conditions, the results expected in this work were obtained, in which HC presented satisfactory behavior, with energy and exergy efficiency values higher than those obtained for HCFC, for the same local psychrometric conditions, being an excellent alternative for replacing the R-22 fluid in air conditioning and refrigeration systems.

Keywords: exergetic analysis, refrigeration, HVAC-R, natural refrigerant, air conditioning

1. Introduction

This study was produced and developed at the Climatization and Thermal Comfort Laboratories – ClimatConT and Refrigeration of the Federal University of Pará – UFPA and aims to analyze types of refrigerant fluids used in air conditioning and refrigeration systems, replacing the current fluids used commercially, aiming to maintain the safety conditions of the systems, with the lowest environmental impact and evaluating their performance and thermal efficiency indexes.

In a refrigeration or air conditioning system, a set of refrigerant fluids are used, many of which are already discontinued or have ceased production, as is the case of hydrochlorofluorocarbons – HCFCs, such as the R-22 synthetic refrigerant fluid, but there is still a large quantity of these fluids in stock and that continues to be used by the systems. This work proposes to provide support for decision-making on system modernization, taking as a reference the energy and exergy analyses of the system components.

Over the past 60 years, due to global economic development, the use of refrigerants has increased considerably in many countries. In order to prevent environmentally harmful substances from was continuing to be used by countries, especially in air conditioning and refrigeration systems, numerous meetings and gatherings have been held in various countries around the world.

A highlight was the creation of the Montreal Protocol (1987) in Canada, which restricted the use of chlorofluorocarbon refrigerants (CFCs, such as R-11), leading to COP 26 in Scotland in 2021, which discontinued the use of carbon dioxide (CO_2) in such industrial systems.

Long before the Montreal Protocol, several studies were carried out, and in them, the destruction of the ozone layer and the increase in global warming were proven. To monitor the evolution, indicators were created such as, the Global Warming Potential (GWP) and the Ozone Depletion Potential (ODP). Since then, several fluids have been used, analyzed, and those that have been proven to present some type of damage, or that contribute to global warming, have been discontinued, had their production terminated, or were banned in air conditioning, heating and refrigeration systems.

Even so, nowadays, the indiscriminate use of some fluids such as HCFCs (R-22) still continues to harm the environment, as when these substances are released into the atmosphere during maintenance processes, for example, there is an increase in global warming, or simply, they destroy the earth's protective ozone layer.

It is necessary to know which quantities, by mass, of the R-22 refrigerant fluid are greater than those of the R-290 fluid because although the two fluids are compatible, when it comes to the compressor lubricating oil, the working pressures and temperatures of the system, are different parameters, which implies a loss of system efficiency.

Thus, starting from the contextualization of the use of refrigerant fluids in refrigeration systems, where new substitutes were sought for the fluids currently used, this work was designed and carried out with the objective of observing the behavior and evaluating whether it would be possible to use natural fluids, with a low degree of contribution to global warming, in a water and air cooling system, simulating a commercial air conditioning system, which was set up on a Chiller test bench in the laboratory, where comparative exergy results were obtained between two types of refrigerant fluids, in order to serve as input in the selection of refrigerants for air conditioning and refrigeration systems.

In this work, what is expected is to present a set of comparative characteristic curves of the parameters used in the energy and exergy analyses of the synthetic fluids R-22 and the natural fluid R-290, operating in a refrigeration system at frequencies of 60 Hz and 70 Hz.

2. Contextualizing the use of refrigerant fluids

Since the 1950s, researchers from various international organizations have realized that the use and release of refrigerants into the local atmosphere has a direct impact on our planet, causing global warming and the destruction of the ozone layer. As a result, annual monitoring of the global effects caused by these fluids has been created. Since then, with the popularization, initially of refrigeration systems and, later, of air conditioning systems, the massive use of these industrial equipment has worsened the conditions of the Earth's protective layers, such as the Ozone Layer [1].

Numerous world events were held and, at each event, solutions were sought for this scenario, which is getting worse every day, with the sharp increase in residential, commercial and industrial refrigeration, and with the air conditioning of environments: residential, commercial, industrial and automotive, the use of refrigerant fluids has grown significantly, but without effective actions to control the maintenance of these systems.

According to the International Energy Agency – IEA, with the pollution generated, as societies grow technologically, in recent years, there has been an increase in global emissions of carbon dioxide – CO_2 related to energy, which are around 33 Gigatons, and the concentration of CO_2 in the atmosphere is greater than 420 parts per million – ppm [2].

According to Ref. [1], in Brazil, in the areas of air conditioning and refrigeration, it is common to obtain, from the responsible installation technicians, information on the modernization of systems or on the replacement of refrigerant fluids used in refrigeration and air conditioning equipment, but without informing the criteria or parameters used in the process.

Companies in the air conditioning and refrigeration sectors, which produce refrigerant fluids, are looking for fluids to replace hydrochlorofluorocarbons – HCFCs, such as R-22 and Hydrofluorocarbons – HFC, such as R-410A, considering that production and the commercialization of HCFCs have already been interrupted in Brazil, and HFCs are being discontinued from 2024 onwards, even so, there are still large stocks of fluids produced and stored for use. In this sense, it is necessary to identify or prepare new fluids, in order to use parameters to maintain the energy and exergy efficiency of the systems.

These are CO_2 emissions which it is generated directly as a product of a reaction; however, other chemical compounds used in industry and commerce are also as polluting as CO_2 and, with pollution factors, hundreds to thousands of times more intense than carbon dioxide. This factor is called Global Warming Potential – GWP, to account for its pollution potential (global warming) in relation to CO_2, which has a GWP equal to 1 [1].

Among these chemical compounds are the refrigerant fluids used in heating, refrigeration and air conditioning systems, such as trichlorofluoromethane, known as refrigerant R-11 and dichlorofluoromethane, or R-12. These fluids were mass produced interrupted in Brazil in the 1990s [3].

In Brazil (2023), the refrigeration and air conditioning markets account for approximately 82% of the consumption of refrigerant fluids, which will have less availability as deadlines for discontinuation or production stoppage approach, as is the case with R410a fluid. Therefore, refrigerant changes during a retrofit or new installation are certain, and everyone interested in the planet needs to understand the paths that the market is proposing [1, 4].

Thus, all these developments described above, in summary, imply transformations for the HVAC-R market as a whole. Designers, installers, suppliers and customers will need to conduct updates (or even component replacements) on their already installed systems.

However, there are already several reports of serious accidents involving technicians who believed they were working with a type of fluid, such as HFC R-134A, whose ASHRAE flammability and toxicity classification is A1, that is, a non-flammable and non-toxic refrigerant, in a refrigeration system, when in fact some other technician had already replaced the system fluid with R-290, whose flammability and toxicity classification is A3, that is, this is a flammable and non-toxic refrigerant fluid [1, 3].

These refrigerants have, respectively, GWP values equal to 4750 and 10,910, which means that releasing 1.0 kg of R-11 into the atmosphere represents pollution caused by the release of approximately 5000 kg of CO_2. For R-12, this value represents almost 11,000 kg of CO_2 released into the atmosphere for each kg of this refrigerant [1, 3].

Table 1 shows the types of refrigerant fluids most used in air conditioning and refrigeration systems, regarding their composition, ODP, GWP and ASHAE Safety Classification [1, 4, 5].

Number/Name	Chemical Formula/Composition	ODP	GWP	ASHAE Safety Classification
CFCs				
R – 11	CCl_3F	1	4750	A1
R – 12	CCl_2F_2	1	10.900	A1
HCFCs				
R – 22	$CHClF_2$	0.055	1810	A1
HFCs				
R – 32	CH_2F_2	0.0	650	A1
R – 134a	$C_2H_2F_4$	0.0	1430	A1
R – 404a	R–125 = 44 %; R–143a = 52 % and R–134a = 4%	0.0	3.920	A1
R – 410a	R-32 (50%), R-125 (50%)	0.0	2090	A2L
HFOs				
R – 1234yf	$C_3H_2F_4$	0.0	4	A2L
R – 1234ze	$C_3H_2F_4$	0.0	6	A2L
R – 449a	R–125 = 24,7%; R–32 = 24,3%; R–134a = 25,7%; R–1234yf = 25,3%;	0.0	1396	A1
Natural Refrigerants (NRs)				
R – 290	C_3H_8	0.0	~5	A3
R – 600a	C_4H_{10}	0.0	~5	A3

Table 1.
Types of refrigerant fluids used in air conditioning systems.

As can be seen in **Table 1**, many of the refrigerant fluids used in air conditioning systems seek to present themselves as ecological fluids, which do not harm the environment where they are used; however, fluids such as R-22, R-134a and R-410a and its likely replacement R-449a, have a strong contribution to global warming, not living up to what is disclosed by resellers and manufacturers of these products [1].

A viable solution to this scenario would be the collection of these discontinued or banned refrigerant fluids, by resellers, technicians and engineers, who work directly in the areas of air conditioning and refrigeration, through appropriate collection and storage procedures, so that companies' recyclers, created in each state in Brazil, can give a new destination to the current fluids used.

This is a slow solution process, and many technicians, due to lack of financial resources, knowledge and technical training, still today many professionals release fluids from air conditioning and refrigeration systems into nature, without worrying about their consequences, this being a common practice. And, even Brazil, having signed the Kigali amendment, in 2024, there are still no concrete actions for control, storage and reuse or disposal of these types of products in the various Brazilian states.

Precisely because of these two factors mentioned above, the refrigerant fluid research and development industry has been seeking to improve systems that use refrigerant fluids, whether for heating, refrigeration and air conditioning, with a focus on reducing electricity consumption, combined with the use of fluids that are less aggressive to the environment. Some of these fluids are hydrocarbons – HC; among them, the most used are Propane (R-290) and Isobutane (R-600a), with the main advantage being the low GWP value which is equal to 3.0 for both fluids [6–8].

In addition to this advantage of having a low level of pollution (global warming), according to [3], several studies indicate that mechanical vapor compression systems that operate with these HCs present better energy performance when compared to the synthetic fluids currently used.

3. Working methodology

For the development of the experiment, a test bench was built with a Chiller system for air conditioning environments on the premises of the UFPA Refrigeration Laboratory to carry out applied research, consisting of a condenser unit and an evaporator unit, with a set of temperature sensors and pressure, for measuring all local psychrometric parameters and during tests.

3.1 Test bench

For the experiment, an Elgin condensing unit with 1.5 hp. of power, with a capacity of 1.6 kW of refrigeration for the R-22 fluid, was used to cool an insulated container with a volume of water equal to 40 liters, as shown in **Figure 1(a)–(d)**, a water pump with a flow rate of approximately 6.0 l/min and a forced air heat exchanger for circulating water at low temperatures to simulate thermal load.

The condenser unit of Chiller test bench, **Figure 1(a)**, and the water cooler evaporator, **Figure 1(b)** have the equivalent length of 15 meters of 5/8″ internal diameter copper piping, without fins, as shown in **Figure 1(c)**.

The circulation system shown in **Figure 1(d)** for the secondary evaporator consists of a 1/3 cv water pump with a fixed flow rate of 6.0 l/min.

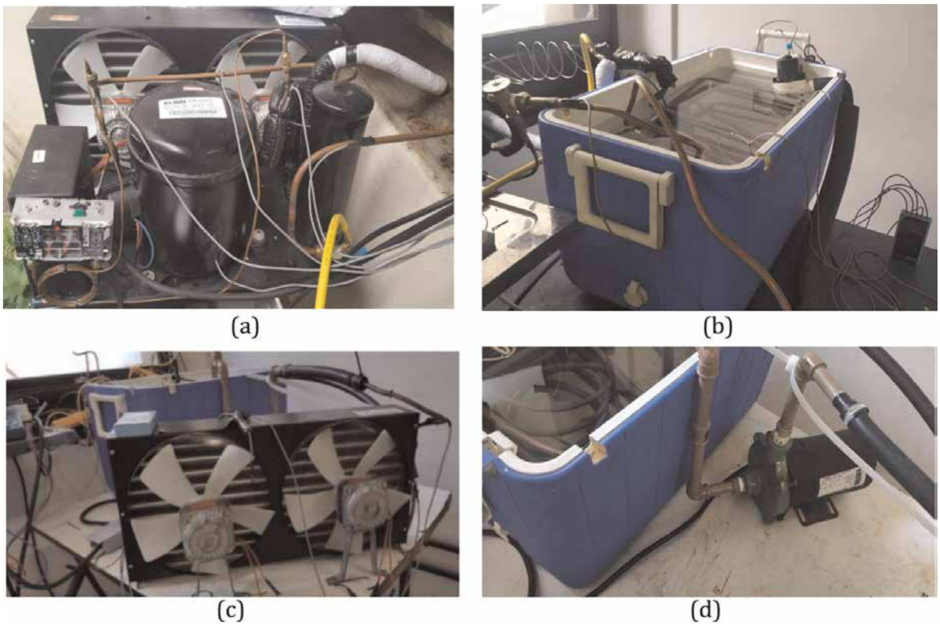

Figure 1.
Chiller test bench: (a) Condenser unit, (b) Evaporator unit, (c) Cooling system and (d) Water circulation system.

To exchange the heat of the secondary fluid with the ambient air, a split-type evaporator unit was used, initially sized for refrigerant fluid and with a nominal capacity of 1.6 kW, with an airflow of 350 m^3/h.

3.2 Refrigeration cycle

The water-cooling system is carried out by the mechanical vapor compression refrigeration system, shown in **Figure 2**; the evaporator coil is submerged in the water reservoir, in which fluid circulates at low pressure and temperature in a mixed state, absorbing the heat from the liquid while the liquid is circulated by a centrifugal pump to a heat exchanger between air and water to obtain an air-conditioned environment with lower temperature and humidity. The first part of the experiment was testing the R-22 fluid in the simulator; no adaptation to the condensing unit was necessary as the equipment was designed to work with this fluid.

All fluid that was initially in the condensing unit was collected and treated, after which the main and secondary fluid evaporator was installed, pressurizing the entire system with dry nitrogen for 24 hours at the end of the procedure to ensure that there were no leaks.

The test bench set up for the experiment can be represented by the refrigeration cycle diagram shown in **Figure 2**, for the ambient temperature and pressure, of the place to be air-conditioned, that is, T_0 and p_0:

With the verification completed, the system evacuation process began to remove moisture and other non-condensable gases that could cause damage to the system and consequent loss of performance.

For the cooling test, the R-22 load used was 1.2 kg, which was the load necessary until the system's liquid sight glass showed that only fluid in the liquid phase existed at the inlet of the expansion device.

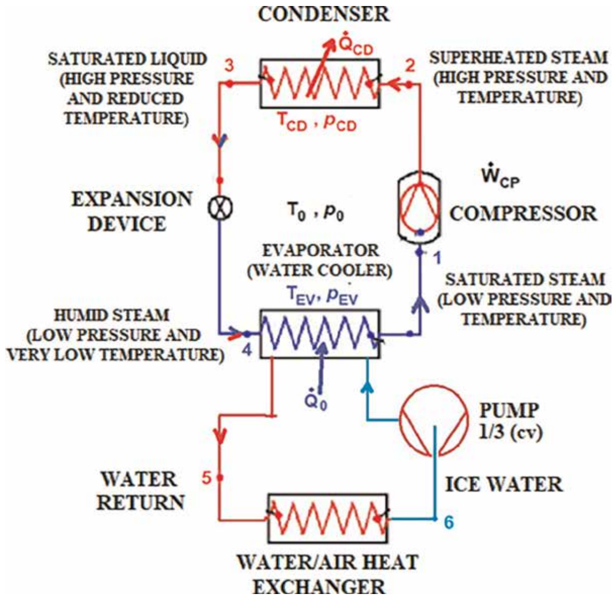

Figure 2.
Schematic of the water-cooling system.

After collecting the synthetic fluid, the system was completely cleaned and 0.650 kg of R-290 was loaded. The procedure for operating the system with R-290 fluid was the same as R-22 [4].

3.3 System data collect

Data collection on the constructed test bench was carried out at intervals of 10 minutes, for a total period equivalent to 150 minutes, where the following information was collected:

- Suction, discharge, expansion device inlet and outlet pressures and evaporator coil inlet and outlet pressures,
- Heat exchanger air inlet and outlet temperatures,
- Temperatures of suction, discharge, compressor body, inlet and outlet air passing through the condenser,
- Temperatures of the chilled water reservoir and exchanger return,
- Electric current and voltage during operation.

From these data, the following were calculated: the mass flow, the real power consumed by the system; overheating; subcooling; the cooling capacity of the system; the cooling effect; the COP; the work of the compressor; the capacity of the evaporator; the capacity of the condenser; exergies and exergy efficiency.

3.4 Thermodynamic analysis of the basic refrigeration cycle

Applying steady-state conditions to the energy equations for each stage of the cycle, shown in **Figure 2**, the following parameters were obtained [4]:

$$\dot{W}_{CP} = \dot{m}_f \cdot (h_1 - h_2) \tag{1}$$

where Eq. (1) represents the work performed by the compressor, in kW, in an isentropic process, during its operation, with $\dot{m}_f$ being the mass flow of refrigerant fluid, in (kg/s) and h_1 is the value of the enthalpy at the inlet of the compressor, in (kJ/kg) and h_2 is the enthalpy at the compressor outlet, in (kJ/kg).

Eq. (2) represents the rate of the amount of heat rejected in the condenser – $\dot{Q}_{CD}$, in kW, where h_2 is the value of the enthalpy at the condenser inlet, in (kJ/kg) and h_3 is the enthalpy at the condenser outlet, in (kJ/kg), the unit of the amount of heat [1, 4]:

$$\dot{Q}_{CD} = \dot{m}_f \cdot (h_2 - h_3) \tag{2}$$

For Ref. [2], the mass flow rate – $\dot{m}_f$ of refrigerant fluid, in kg/s, can be calculated by Eq. (3):

$$\dot{m}_f = \frac{\dot{Q}_0}{(h_1 - h_4)} \tag{3}$$

where $\dot{Q}_0 = \dot{Q}_{EV}$ represents the refrigeration capacity of the cycle, in (kW), and this value can be calculated by Eq. (4):

$$\dot{Q}_{41} = \dot{Q}_0 = \dot{Q}_{EV} = \dot{m}_f \cdot (h_1 - h_4) = \dot{m}_L \cdot (h_6 - h_5) \tag{4}$$

Eq. (4) represents the rate of quantity of heat absorbed in the evaporator, h_4 is the enthalpy value at the evaporator inlet, $_h1$ is the enthalpy value at the evaporator outlet, $\dot{m}_L$ mass flow of water from the cooler, in kg/s, h_5 is the heat exchanger inlet enthalpy and h6 is the heat exchanger outlet enthalpy.

The energy of the expansion device is obtained by an isenthalpic process, that is, $h_3 = h_4$.

Eq. (5) represents the efficiency of the ideal cycle, that is, the efficiency of the First Law of Thermodynamics [1]:

$$COP_{1^{\circ}Law} = \frac{\dot{Q}_0}{\dot{W}_{CP}} = \frac{\dot{m}_L \cdot (h_5 - h_6)}{\dot{m}_f \cdot (h_2 - h_1)} \tag{5}$$

However, the real system is different from the ideal, so the theoretical system was idealized, starting from an adaptation of the Carnot cycle to real conditions, namely:

- Modification of the compressor entry point, which changed from admitting the fluid still in the mixing phase to a more advanced point where the fluid is already completely saturated vapor due to the constructive characteristic of the compressors used since the liquid phase is practically incompressible.

- During compression, even if it occurs isentropically, there is an increase in the temperature of the fluid; thus, the efficiency of the cycle is also lower than that observed in the Carnot cycle.

- The isentropic expansion process is ideal but is not used in reality due to the high cost of components. These are just some modifications that make the theoretical cycle different from the Carnot cycle and justify its lower efficiency.

3.5 Exergetic analysis of the basic refrigeration cycle

For Ref. [9], energy analysis evaluates how energy is used in the system, based on the first law of thermodynamics; however, there is no accounting for spontaneous processes and irreversibilities that may occur during the operation of the system, such as the balance of energy does not consider the way in which energy is degraded. At this point, exergy analysis is considered, which complements the system's energy information by using the second law of thermodynamics as a basis, that is, it takes into account the entropy in each process, allowing the calculation of the real efficiency of the equipment, informing the amount of work that can be performed by the system.

Exergy efficiency, in one of its many definitions, is the following: "is the ability to produce the desired effect without loss or with minimal waste of the resource used." Being calculated by Eq. (6) [9, 10]:

$$\psi = \frac{Generated\ exergy}{Exergy\ supplied} \tag{6}$$

where ψ is the exergy generated and the value in the analyzed component and the exergy supplied is the total value of exergy that the system obtained for operation.

The exergy analysis carried out by [11–13] applied to a refrigeration system is calculated for each component separately. The specific exergy – e_x, in kJ/kg, of the system components was obtained using Eq. (7):

$$e_x = (h_x - h_0) - T_0 \cdot (s_x - s_0) \tag{7}$$

where h_X and s_X are, respectively, the enthalpy and entropy at the observed point, h_0 and s_0 are, respectively, the enthalpy and entropy in relation to the ambient temperature, and T_0 is the temperature of the refrigerated environment [1, 4].

According to Ref. [2] for the evaporator, exergy relates to the entry and exit of fluids in it, that is, $\dot{m}_L = \dot{m}_5 = \dot{m}_6$ and $\dot{m}_f = \dot{m}_1 = \dot{m}_4$, following the numerical sequence in **Figure 2**, we arrive at Eqs. (8) and (9):

$$E_{EV,Ent} = \dot{m}_f \cdot (e_1 - e_4) - \dot{Q}_0 \cdot \left(1 - \frac{T_0}{T_{EV}}\right) \tag{8}$$

or

$$E_{EV,Q} = \dot{Q}_0 \cdot \left(1 - \frac{T_0}{T_{EV}}\right) - \dot{m}_L \cdot (e_5 - e_6) \tag{9}$$

where $\dot{m}_L \cdot (e_5 - e_6)$ represents the water vapor exergy, T_0 is the ambient temperature and TEV is the evaporation temperature, both in (K).

The irreversibility of the evaporator – I_{EV}, in kW, can be calculated by Eq. (10):

$$I_{EV} = T_0 \cdot \left[(\dot{m}_L \cdot s_5 - \dot{m}_f \cdot s_1) - (\dot{m}_f \cdot s_4 - \dot{m}_L \cdot s_6)\right] \tag{10}$$

Next, the component evaluated was the compressor, with the total exergy of the compressor being defined – E_{CP}, in kW, is obtained by Eq. (11):

$$E_{CP} = \dot{m}_f \cdot (e_2 - e_1) - \dot{W}_{CP} \quad (11)$$

where $e_2 - e_1$ is the difference between the specific input and output exergies of the compressor, $\dot{W}_{CP}$ is the electrical power consumed by the compressor, in kW.

For the refrigeration cycle condenser, the exergy equation – E_{CD} is obtained by Eq. (12):

$$E_{CD} = \dot{m}_f \cdot (e_2 - e_3) + \dot{Q}_{CD} \cdot \left(1 - \frac{T_0}{T_{CD}}\right) \quad (12)$$

where $\dot{Q}_{CD}$ is the thermal power rejected in the condenser, in (kW) and T_{CD} is the condensation temperature, in (K).

And for the expansion device, since there is no heat generation or power consumption, we have Eq. (13) for total exergy of the expansion device – E_{DE}:

$$E_{DE} = \dot{m}_f \cdot (e_4 - e_3) \quad (13)$$

Therefore, using Eq. (14), the exergy efficiency can be calculated – η_{Ex} applied to a refrigeration system can be calculated as: [1, 4, 9].

$$\eta_{Ex} = \eta_{2^\circ Law} = COP_{1^\circ Law} \cdot \left(1 - \frac{T_0}{T_{CD}}\right) = \frac{\dot{m}_L \cdot (e_5 - e_6)}{\dot{m}_f \cdot (e_2 - e_1)} \quad (14)$$

In this way, by applying the data obtained during the tests to these equations, information related mainly to the effective performance of the equipment can be obtained.

3.6 Results

Two tests were carried out on the refrigeration system with the R-22 fluid, the first at a frequency of 60 Hz, two tests with the R-290 fluid at a frequency of 60 Hz and two tests with the R-290 fluid at a frequency of 70 Hz, all lasting 150 minutes in order to observe how the system behaves according to ambient conditions, the operation before and after the chilled water circulation pump was compared.

The main cause of this event is linked to the fact that the thermostatic expansion valve works with a fluid in the bulb calibrated to the R-22 response, and because R-290 absorbs more energy per mass, the device was unable to maintain a continuous flow, which ended up harming the temperature reduction, since the evaporation temperature suffered directly from this fluctuation in values.

Figures 3 and **4** show the variations in suction and discharge pressures, respectively, for the two refrigerant fluids and for the evaluated frequencies.

For both the 60 Hz and 70 Hz frequencies, in **Figure 3**, there was a variation between pressures of 57 to 61 psig, and for R-22, the variation with temperature stabilization was between pressures of 58.5 to 59.5.

It can be seen in **Figure 4** that for the frequency of 60 Hz, the lowest pressure of R-290, the average pressure value was 237 psig, which shows an advantage over R-22, which had an average pressure of 255 psig, indicating a reduction of the compression ratio, since the suction pressure values were similar, with the reduction in discharge

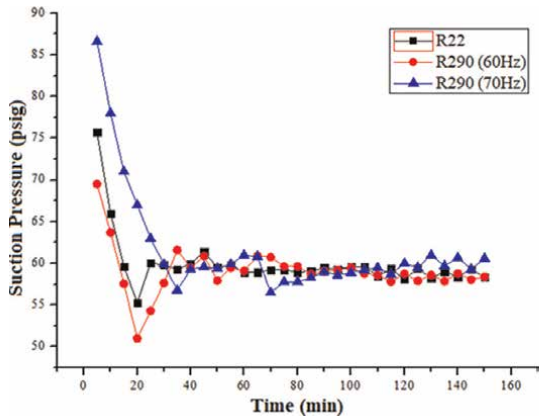

Figure 3.
Refrigerant fluid suction pressures over time.

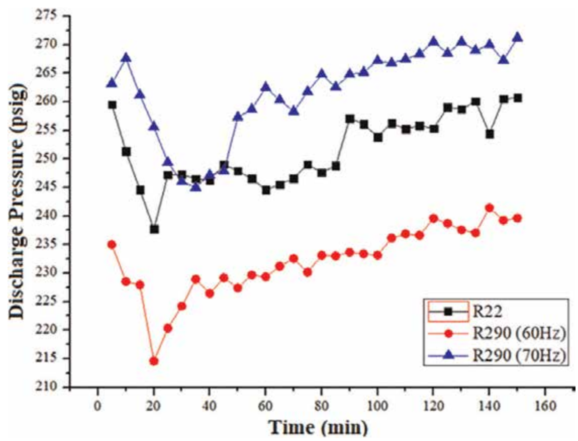

Figure 4.
Refrigerant fluid discharge pressures over time.

pressure, the mechanical efforts on the compressor are reduced in addition to the reduction in electrical energy consumption.

For the frequency of 70 Hz, the value of the average discharge pressure of the refrigerant R-209 was 265 psig, exceeding that of R-22; this fact is associated with the compressor operating outside the working speed, which is fixed at 60 Hz, which caused an increase in temperature in general and thus an increase in condensation pressure.

The graph in **Figures 5** and **6** shows how the mixture saturation temperature varied during the tests.

As seen in the graph in **Figure 5**, the Chiller system running with R-22 fluid, with the compressor for R-22 and the expansion device calibrated for R-22, the lowest evaporation temperatures were reached, with values varying minimally around 0.5°C, while the system, after changing the R-22 fluid to R-290, was unable to reduce the evaporation temperature below 2°C, even with the increase in volumetric displacement caused by the operating frequency of 70 Hz.

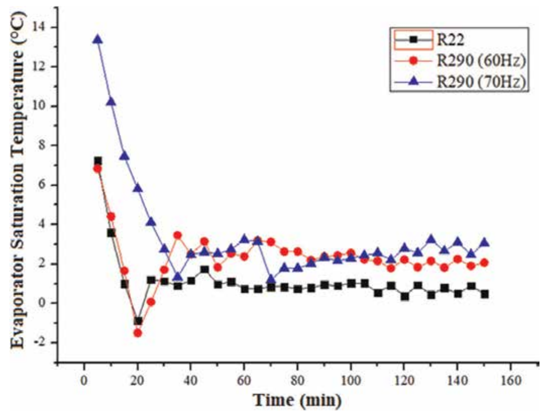

Figure 5.
Fluid saturation in the evaporator temperatures over time.

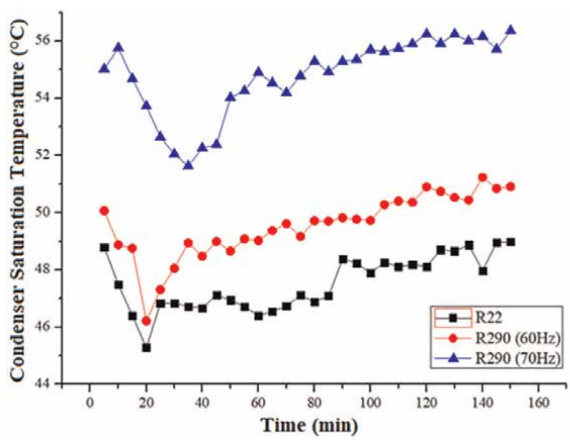

Figure 6.
Fluid saturation temperatures over time: (a) and (b) in the condenser.

It can be seen in **Figure 6** that for the frequency of 60 Hz, in the same way, that the saturation temperature in evaporation was high compared to R-22, the fact is repeated for the natural fluid now in condensation, with temperatures of saturated fluid varying at values close to 50°C, for R-22, the temperature was close to 48°C even though the pressure at this point was above the values collected for R-290.

Figures 7 and **8** lists the compressor powers and the mass flow rate for the two types of refrigerant fluids and at different frequencies.

The highest saturation temperature depends only on the chemical composition of the fluid. For the 70 Hz frequency, the temperature values are close to 55°C, once again indicating non-standard compressor operation, confirmed by the increase in electrical energy consumption. However, the higher condensation temperature indicated the greater temperature difference between the R-290 fluid and the external air in the heat exchange in the condenser, facilitating the conversion of the fluid from a superheated vapor state to liquid at high pressure at the condenser exit.

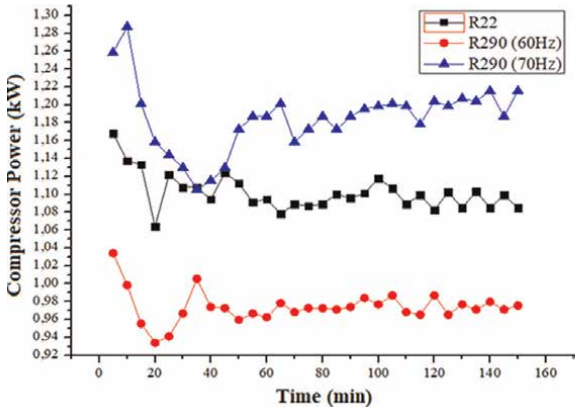

Figure 7.
Electrical energy of Compressor powers consumption.

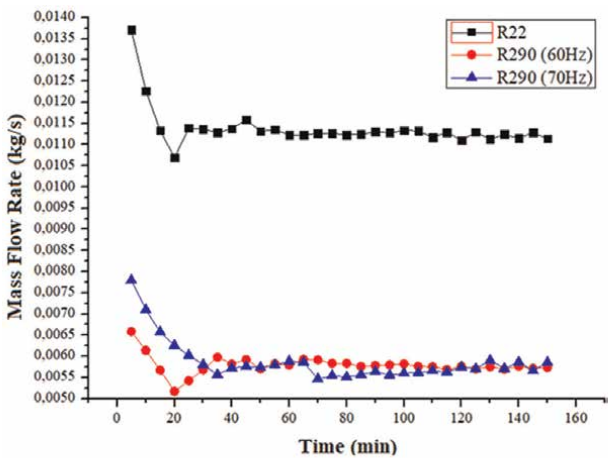

Figure 8.
Mass flow rate.

The consumption recorded for R-22 served as a reference for the evaluation of R-290, which for the 60 Hz frequency was lower; however, as explained in **Figures 7** and **9**, the saturation temperature during evaporation was higher than that of R-22, so consumption was lower due to a lower capacity to absorb energy while the system was running on natural fluid.

The average refrigeration power absorbed by R-290 at 70 Hz was 2.7 kW, while for R-22 it was 2.65 kW, a difference of 1.85%. At a frequency of 60 Hz, the average power absorbed in the evaporator was 2.5 kW, 7.41% lower than the frequency of 70 Hz and 5.66% lower than the power produced by R-22 [10, 13].

For the frequency of 70 Hz, the consumption is well above the reference value for the R-22 fluid, which agrees with the fact that the single-phase electric motor, when forced to work outside the nominal frequency, causes excessive energy losses in the form of heat, observed in the increase in electricity consumption of the refrigeration system.

It can be seen in **Figure 8** that the values calculated for the R-22 fluid match the absorbed thermal load compared to R-290; the average specific mass of the synthetic refrigerant was 21.61 kg/m^3, while the specific mass of the average natural fluid was

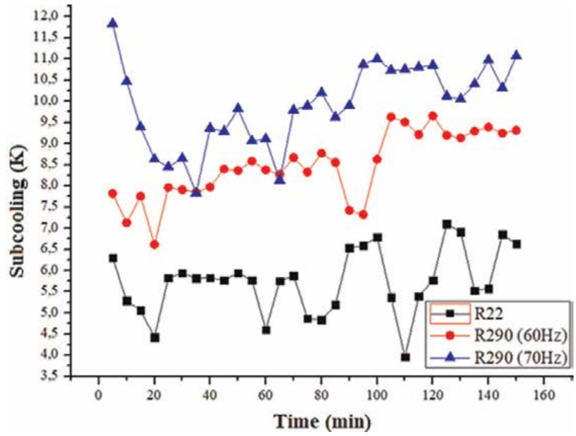

Figure 9.
Subcooling of liquid processes.

11.02 kg/m^3 for the 60 Hz frequency and 11.17 kg/m^3 for the 70 Hz frequency, which explains the values close to 0.0115 kg/s for R-22 circulating in the system and 0.0057 kg/s for the natural fluid. These values present a significant difference in terms of the amount of refrigerant fluid to be used within the refrigeration system.

In air conditioning and refrigeration systems, subcooling and superheating processes help maintain equipment operating conditions.

The refrigeration capacity obtained with the system running with synthetic and natural fluid and with different frequencies, at the beginning, a considerable difference was observed between the R-22 fluid and the R-290 at 60 Hz, when the R-22 yielded approximately 6.75 kW and the R-290 at 60 Hz yielded only 4.5 kW, however throughout the tests this difference reduced.

The average power absorbed by R-290 at 70 Hz was 2.7 kW, while for R-22, it was 2.65 kW, a difference of 1.85%. At a frequency of 60 Hz, the average power absorbed in the evaporator was 2.5 kW, 7.41% lower than the frequency of 70 Hz and 5.66% lower than the power produced by R-22.

Figures 9 and **10** show the results of the subcooling and superheating processes carried out during the tests.

This agrees with the fact that the greater the temperature difference between the condensation saturation and the ambient air temperature, the greater the amount of heat transferred from the hot fluid to the cold fluid. Therefore, the R-290 fluid, both for frequencies of 60 Hz and 70 Hz, obtained the highest subcooling values due to its higher saturated condensation temperature, since the ambient air temperature did not vary significantly between the tests.

Subcooling also ensures that the fluid that reaches the expansion device is in a liquid state, this way, only liquid at high pressure is expanded in the thermostatic valve, which guarantees the efficiency of the process in the evaporator.

In addition to the energy analysis, the exergy factors and irreversibility's for the system were calculated as a way of complementing the explanations of the system's characteristics and mainly the negative points that occurred when increasing the operating frequency from 60 Hz to 70 Hz.

Figure 11 shows the results of the exergy analyzes calculated for the refrigeration system condenser.

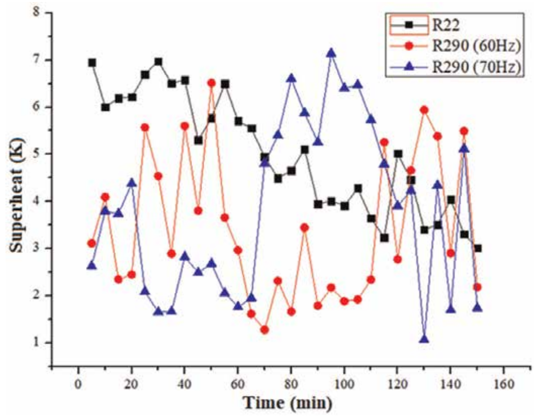

Figure 10.
Superheating of steam processes.

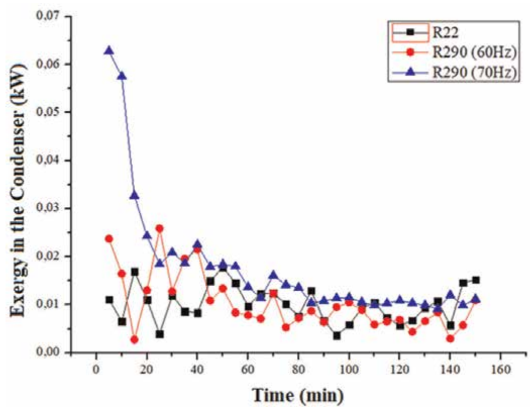

Figure 11.
Calculated exergy for the condenser.

For the condenser, the average calculated exergy values for both R-22 and R-290 at 60 Hz were close to 0.007 kW, with little difference for the exergy value for R-290 at 70 Hz which increased to 0.013 kW.

As the condenser is a component in which the variation in availability generated a low irreversibility value, that is, it was not a piece of equipment that contributed to the increase in electrical energy consumption during the tests.

The graph in **Figure 12** shows the calculated exergy data in the refrigeration system evaporator.

For the evaporator, the calculated values showed little difference between R-22 and R-290 at 70 Hz, being in the range of 0.04 kW; however, the values for R-290 at 60 Hz were unexpected, since the value was almost four times lower, as shown in **Figure 12**.

It is known that some authors such as Ref. [7, 14], mention that the difference in viscosity, being much smaller in R-290 compared to R-22, can cause a more efficient heat exchange in the evaporator, which causes a reduction in the entropy of the system and reduces the final exergy value [7, 14].

During tests at the UFPA Refrigeration Laboratory, shown in **Figure 12**, the evaporator generated irreversibility's at values between two and four times greater

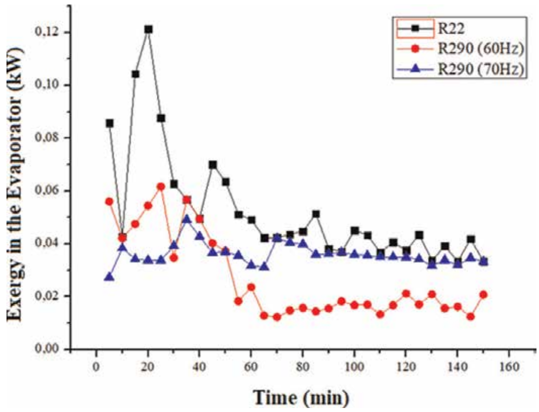

Figure 12.
Calculated exergy for the evaporator.

compared to the condenser. Being the highest average value calculated for R-22, followed by the average value calculated for R-290 at 70 Hz.

The calculation of exergy in the expansion device generated values that attracted more attention since being a component developed for operation with R-22 fluid, it still generated the highest energy value when comparing fluids and operating frequencies.

When observed in the steady state, the calculated irreversibility's were, respectively, 0.16 kW, 0.13 kW and 0.10 kW, for R-22, for R-290 at 70 Hz and R-290 at 60 Hz.

Again, possibly the lower viscosity of R-290 reduced the variation in entropy and enthalpy at the inlet and outlet of the expansion device, causing lower irreversibility. Even so, the expansion device generated exergies up to eight times greater than the evaporator.

One of the advantages of exergy analysis over energy analysis is exactly the consideration of the variation in entropy in each component, as shown in the graph in **Figure 13**, which shows the variation in exergy calculated for the component with the highest energy consumption of the entire system, the compressor.

The main point of energy analysis is the calculation of the COP, which is the amount of power absorbed in the evaporator over the electrical power consumed by the equipment during operation. For the evaluated system, the COPs were calculated for the three tests and the data were plotted on the graphs in **Figures 14** and **15**.

This value agrees with the increase in electrical consumption even above the value collected for operation with R-22 and generating a COP equal to 4.21% at an evaporation temperature above that at which R-22 works, that is, the COP value would be even lower if the evaporation pressure had been reduced and the exergy value would also exceed the value of 0.52 kW, as the entropy difference would increase.

The exergy analysis also provides the system efficiency factor, making a relationship between the availability in the evaporator and the total electricity consumption of the equipment [1, 10, 13, 14].

In the steady state, as in **Figure 14**, the calculated COP for the R-22 was 3.491; for the R-290, with a frequency of 60 Hz, it was 3.570, an increase of 2.26% and 3.344 for the frequency of 70 Hz, a reduction of 4.21%, respectively, when compared to the synthetic fluid. Again, this indicates that the increase in

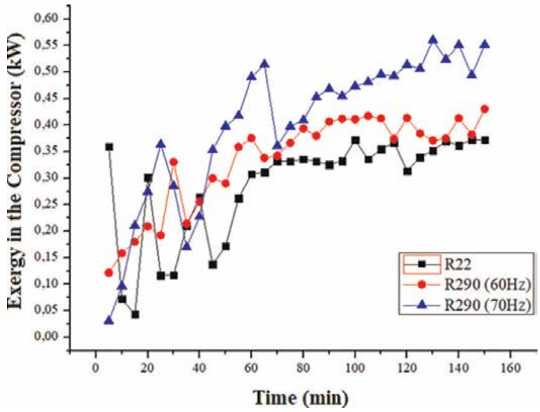

Figure 13.
Calculated compressor exergy.

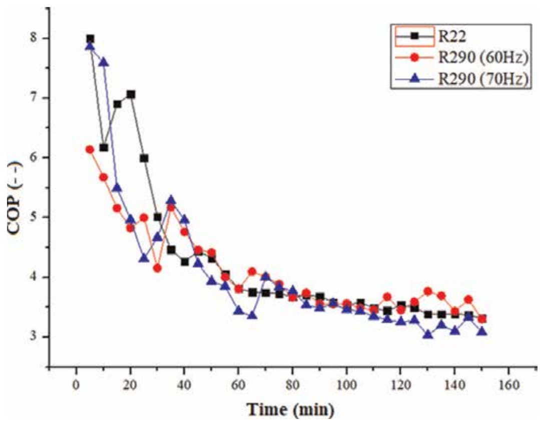

Figure 14.
Refrigeration system performance coefficient.

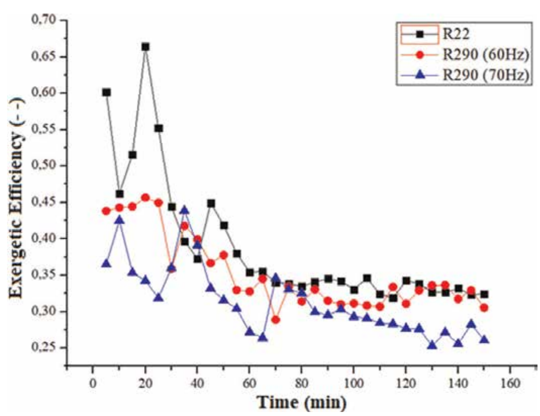

Figure 15.
Exergetic efficiency of the refrigeration system.

Thermodynamic Properties	Refrigerant Fluids		
	R-290 (60 Hz)	**R-290 (70 Hz)**	**R-22**
Exergy in the compressor (kW)	0,37	0,52	0,33
Exergy in the evaporator (kW)	0,02	0,04	0,04
Exergy in the expansion device (kW)	0,10	0,13	0,16
Exergy in the condenser (kW)	0,007	0,013	0,007
COP	3570	3344	3491
Exergetic Efficiency (%)	32	27	34

Table 2.
Summary of exergy properties.

frequency made the compressor less efficient, even with the increase in volumetric displacement.

Figure 15 shows the result of the exergetic analysis in the refrigeration system.

It is important to remember that even though R-290 at 60 Hz has a COP value greater than that of R-22, this difference was due to the fact that the evaporation temperature of R-290 was higher, where the average of R-290 was 2.2°C and R-22 averaged 0.8°C.

In addition to the energy analysis, the exergy factors and irreversibility of the system were calculated as a way of complementing the explanations of the system's characteristics and mainly the negative points that occurred when increasing the operating frequency from 60 Hz to 70 Hz.

It is known that some authors, such as Refs. [7, 14], mention that the difference in viscosity, being much smaller in R-290 compared to R-22, can cause a more efficient heat exchange in the evaporator, which causes a reduction in the entropy of the system and reduces the final exergy value [7, 14].

In steady state, the exergetic efficiency values, as shown in **Figure 15**, were 34% for R-22 and 32% for R-290 at 60 Hz, while the efficiency for R-290 at 70 Hz was 27%, as shown in **Table 2** summarizes the main properties related to the use of energy and exergy by the system.

The observation focuses on the following detail: the pressure and temperature values for R-290 at 60 and 70 Hz had a difference of 2%, so the temperature of the chilled water was the same for both tests, which contributes to the idea that there was a drop in the electrical efficiency of the engine being driven by the frequency inverter, confirmed by the increase in condensing pressure and power consumption.

4. Conclusions

Taking into account the psychrometric conditions of the UFPA Refrigeration Laboratory, it is possible to state that the tests to obtain data and the development of energy and exergy analyses were satisfactory, as they presented the differences and similarities between the two types of refrigerant fluids analyzed, providing subsidies and conditions for replacing R-22 fluid with R-290.

The statement made above meets the needs listed by the national and international market, as the refrigerant fluid R-22 was already discontinued in 2015; even so, in

Brazil, this is the fluid most used in air conditioning systems, and it is as a substitute, the R-410a fluid, as is known, will be discontinued in 2024, that is, it will be necessary to use a refrigerant fluid to replace the fluids currently used.

Even so, after completing the experiments and obtaining the calculations and graphs of the refrigeration system components, some characteristics can be highlighted:

- The use of flammable fluid, when operated by responsible and instructed technicians, did not generate the slightest concern during operation.
- The use of natural refrigerant in a system originally designed for use with synthetic refrigerant resulted in a reduction in evaporator power of 2%, however, it increased COP by 3%.
- R-290 at a frequency of 60 Hz obtained an exergy efficiency only 2% lower than R-22 operating at 60 Hz.

As it is a flammable fluid, there are risks associated with the uncontrolled use of R-290, which are minimized mainly by qualifying refrigeration technicians to respect the rules necessary to carry out maintenance and monitoring of this type of system.

In this way, this work adds to several others carried out, agreeing that the use of the natural fluid R-290 is a refrigerant with excellent thermodynamic characteristics for application in mechanical vapor compression refrigeration systems (mainly at low condensation saturation pressure), high enthalpy (which helps to reduce the amount of mass required in the system), compatibility with mineral lubricating fluid (eliminating the use of highly hygroscopic synthetic lubricating fluids) and, as made clear in this work, the reduction of electrical energy consumption.

According to the thermodynamic analysis developed for hydrocarbon fluids, it can be observed:

- That natural fluids reduce the pressure levels developed in the condenser and evaporator.
- Hydrocarbons have lower compressor discharge temperatures, providing longer useful life for these components.
- The use of R-290 fluid and mixtures involving hydrocarbons provides a tripling of the latent heat of vaporization in relation to R-134a. This factor leads to a reduction of around 50% in the need for mass refrigerant charge in the refrigeration system for the same equipment capacity.
- The coefficient of performance of the system with hydrocarbons and mixtures showed an increase of around 5% in relation to R134a. Consequently, less compression work is required for hydrocarbons in relation to R134a due to their thermophysical properties related to density in the liquid and vapor phases.

Analyzing the results of the exergy analysis carried out in the residential Chiller system, it is important to realize that the R-290 fluid, operating at a frequency of 60 Hz, presents itself as being the best condition to be used as a replacement fluid for

R-22, in refrigeration and air conditioning systems, making it necessary to observe a reduction in the quantity of fluid, in mass, to be placed in the systems, in addition to the temperature and pressure conditions of evaporation and condensation, including the subcooling and superheating processes during installation of systems.

It is important to note that, in Brazil, even with the use of R-22 fluid permitted until 2015, with a total ban in 2030, there are still many air conditioning and refrigeration systems in normal operation using this HCFC. It is necessary to develop a strategic plan for recycling or definitive disposal of this and other discontinued or banned refrigerants in the world, avoiding the practice of releasing these fluids into the local atmosphere during system maintenance.

One of the viable solutions would be the creation or adaptation of companies to reuse or dispose of these fluids, in addition to providing training on the use and disposal of refrigerant fluids for technicians, engineers and other people involved in the refrigerant fluid chain in each of the States. from Brazil.

Although R-290 fluid is classified by ASHAE as a flammable refrigerant, it has a very low GWP and ODP equal to zero. This is a natural tendency to replace the current refrigerant fluids used, and this work proved that the R-290 refrigerant is one of the best substitutes for R-22. However, there is a need to carry out training for those involved with the systems, for their perfect use and destination, in air conditioning and refrigeration systems.

Thus, it is possible to use the existing compressor platform for synthetic refrigerant fluids with very few modifications for operation with natural fluid, reducing the cost of research and development, in addition to reducing the use of oils with a complex chemical composition that is quite aggressive to the environment and mainly the focus on reducing electricity consumption, which brings together the objectives of always benefiting the Environment, Sustainability and the rational use of electricity seeking to reduce pollutant emissions.

In the same way as was carried out with the R-22 fluid, other research is being carried out in the UFPA Refrigeration Laboratory in order to carry out new energy and exergy analyses of the systems, aiming to replace these fluids, such as ammonia and R-410a fluid, for other refrigerants that do not contribute to global warming or the degradation of the Earth's Ozone layer.

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References

[1] Santos EC, Macêdo CLL, Azevedo CA, Araújo R, Gomes SS, Baía L, et al. An Experimental Study of Synthetics and Natural Refrigerants Gases. Low – Temperature Technologies. London, United Kingdom: IntechOpen; 2020. pp. 77-100. DOI: 10.5772/intechopen.89119

[2] Global Energy Review. International Energy Agency (IEA). 2021. Available from: https://www.iea.org/reports/global-energy-review-2021/co2-emissions [Accessed: October 20, 2023]

[3] National Refrigerants. Product Data Summary and Thermodynamics Tables. 2020. Available from: https://secureservercdn.net/198.71.233.194/m9v.7b6.myftpupload.com/wpcontent/uploads/2020/03/R11_RefGuid.pdf?time=1666358535 [Accessed: March 6, 2023]

[4] Macedo CLL, Monteiro HCM, Santos EC, Azevedo CA, Miranda DFB, Junior DSTM, et al. Análise Experimental de um Ar Condicionado tipo Split Operando com os Gases Hidrocarbonetos Propano e Isobutano em Comparação ao Halogenado R-22. revista Dialética. Vol 8. São Paulo, Brasil, 2023. pp. 9-28. DOI: 10.48021/978-65-252-7011-1-C1

[5] ASHRAE. Fundamentals. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers; 2001

[6] ASHRAE. ASHRAE Handbook Refrigeration (SI EDITION). Atlanta, USA: ASHRAE; 2018

[7] Ji W, Chong G, Zhao C, Zhang H, Tao W. Condensation Heat Transfer of R134a, R1234ze(E) and R290 on Horizontal Plain and Enhanced Titanium Tubes. International Journal of Refrigeration. 2018;**93**:259-268. DOI: 10.1016/j.ijrefrig.2018.06.013

[8] Choudhari C, Sapali SN. Performance Investigation of Natural Refrigerant R290 as a Substitute to R22 in Refrigeration Systems. International Conference on Recent Advancement in Air Conditioning and Refrigeration, RAAR. Vol. 19. Bhubaneswar, India: Elsevier, Energy Procedia; 2016. pp. 346-352. DOI: 10.1016/j.egypro.2017.03.084

[9] Rosen MA, Dincer I. Exergy Analysis of Heating, Refrigerating and Air Conditioning – Methods and Applications. 1st ed. Elsevier INC.; 8 Aug 2015. DOI: 10.1016/C2013-0-06800-4

[10] Shilliday JA, Tassou SA, Shilliday N. Comparative energy and exergy analysis of R744, R404a and R290 refrigeration cycles. International Journal of Low-Carbon Technologies. 2009;**4**: 104-111

[11] Fajar TKB, Bagas PR, Ukhi S, Alhamid MI, Lubis A. Energy and Exergy Analysis of Na R410a Smal Vapor Compression System Retrofitted with R290. Case Studies in Thermal Engineering. Vol. 21. Elsevier; 2020. [Article 100671]. DOi: 10.1016/j.csite.2020.100671

[12] Park K, Jung D. Performance of R290 and R1270 for R22 applications with evaporator and condenser temperature variation. Journal of Mechanical Science and Technology. 2008;**22**:532-537. DOI: 10.1007/s12206-007-1028-3

[13] Siang JT, Leda J. Physical Properties Analysis of Environmentally Friendly Refrigerant on The Convective Heat Transfer Coefficient. Geographia

Technica – Open Access. 2020;**15**:133-142. DOI: 10.21163/Gt_2020.151.30

[14] Wijeysundera NE. Principles of Heating, Ventilation and Air Conditioning with Worked Examples. 1st ed. World Scientific Publishing; 26 Dec 2015. ISBN 13: 978-9814667760

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