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Study on the Optimized Energy Consumption Indicators of the Cooling Systems in One of the Hospital Buildings in Oman

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ABSTRACT

Energy is a fundamental need for a country, and buildings in various sectors consume a significant amount of fossil-based energy, contributing to greenhouse gas emissions and global warming. Poor design, improper installation, inefficient usage, and low-efficiency equipment are some factors that contribute to energy waste. Air conditioning is a significant part of this energy consumption, with the demand for air conditioners worldwide increasing at about 17%. Quick development in the economy of Oman has also resulted in population growth and the use of effective cooling facilities. The country is a Net Zero Emissions country to ensure that it meets the goals of the Paris Agreement of ensuring that the increase in global temperature does not go to more than 1.5℃. To do so, Oman has drawn a Vision Document (VD) to investigate alternative technologies that can be employed in sustainable development. The research paper is aimed at optimizing the energy consumption indicators at a hospital in Muscat, Oman. The entire hospital complex has numerous structures, and the majority of them are cooled with the help of central types of air conditioning systems. The primary building is equipped with 12 chillers to feed cool water to the different air-handling units, with each machine being equipped with a primary pump and two secondary chilled water pumps, and chillers. The buildings are 24 hours air-conditioned, and air-conditioning consumes 5060 percent of the energy usage. Through Co tangible performance benchmarking with the help of the key metrics Coefficient of Performance (COP), Energy Efficiency Ratio (EER), and Seasonal Energy Efficiency Ratio (SEER), it is indicated that the study reveals those opportunities to achieve significant gains in efficiency. This study encourages similar studies in other types of buildings in Oman, aiming to develop a holistic framework for energy optimization in Oman's cooling systems.

1. INTRODUCTION

The majority of the world's energy consumption is attributed to fossil fuels, which in turn release environmental polluting gases such as CO_2, NO_2, greenhouse gases (GHGs), etc. These gases are the root causes of global warming, and throughout the world, scientists, engineers, and political leaders have been working for many years to address the climate crisis. Since 2013, Berkeley Earth, a nonprofit research organization in California, has been working on its own analyses of global mean temperature change parallel to the work of the IPCC. Their conclusion is that the year 2023 was the warmest ever recorded on earth since 1850, and it was considerably and unquestioningly warmer than that in 2016 [1]. Scientific evidence that exists today is not only adequate to prove that global warming is accelerating but also makes the world aware of the fact that planet earth, by increasing its temperature beyond 2℃, will reach an irreversible tipping point and hence be prone to inevitable devastation. Some of the life-threatening impacts of global warming/increase in Earth temperatures are the melting of polar ice, which makes sea levels rise and flood much of the world; more floods and droughts; loss of biological diversity; shortage of food and water, etc. Global warming and other devastating effects of poverty and environmental degradation augment one another or work together in the world, and they threaten the world's societies with far-reaching consequences. Human beings should cut down emissions in a bid to preserve the planet to be inhabited in future habitation [2].

The building sector consumes a substantial part of the energy. Building energy is measured in Energy Performance Index (EPI), i.e., kWh/m²/year. The building's biggest single point of consumption is HVAC. Heat is a silent killer. It is hard to say when it becomes lethal and how it should have happened, particularly in warm countries like Oman, where high temperatures are considered a natural occurrence. Buildings in Oman consume an estimated 76-83% of electricity, compared to a global average of 40%, with cooling systems accounting for a substantial portion of this energy use [3]. HVAC is the largest contribution to EPI in any building. In most buildings, chillers or unitary types of air conditioners do the cooling. Global energy demand for cooling is expected to triple in the coming decades, according to the International Energy Agency. This increase would further stress electricity grids and release more GHGs. As the planet gets warmer, demand for cooling goes up. In addition, as populations continue to grow, more air conditioners are installed [3].

Throughout the world, scientists, researchers, engineers, and politicians are working to address the major climate issue to protect the planet from disaster. The Paris Climate Agreements, 2015, made a bold (and needed) commitment to limit global warming to 1.5 degrees Celsius above pre-industrial levels. Various renowned institutions have been working for many years to reduce GHG emissions through international protocols. During its last initiative in a recent attempt of the United Nations Environmental Program (UNEP) that was presented at COP 28, some 70-80 world governments signed the Global Cooling Pledge that will tackle the issue of cooling technologies, including the problems. A growing list of countries has signed the pledge and committed to taking immediate steps to improve the sustainability of cooling systems [4, 5].

It is an indisputable fact that energy consumed by the building cooling sector contributes significantly to energy and GHG emissions consumption, which in turn makes energy efficiency in cooling systems irreplaceable, particularly in light of global action to tackle climate change, sustainable development, and resource utilization. The resultant effect is that the energy efficiency improvement process in these systems can offer a lot of economic, environmental, and social benefits. The energy efficiency of a cooling system is highly important in addressing the global problems of sustainability, particularly in a hot world like that of the Sultanate of Oman. Energy consumed, operating costs, and consumption of GHGs are aggravated by the use of traditional methods of air conditioning (AC). The commitment by Oman to the Paris Agreement to reduce global warming and ensure it does not rise above 1.5℃ brings to the fore the importance of the optimization of energy consumption to attain national and global sustainability objectives in cooling systems (United Nations, 2016). Although technological progress has continued to be developed, there is a major shortcoming in measuring procedural examination and the establishment of energy-efficient cooling frameworks across different types of buildings in Oman [6, 7].

The magnitude of the challenge is demonstrated by preliminary research developed in a hospital complex with a total AC plant capacity of 300 TR. The complex consumed 2,257,190 kWh in November 2023 alone, proving the principle of innovative interventions that can be optimized in the area of energy consumption. Through comparison of performance according to the important measures, such as the Coefficient of Performance (COP), Energy Efficiency Ratio (EER), and Seasonal Energy Efficiency Ratio (SEER), this paper found the means of achieving significant efficiency improvement. These findings provide, however, only an initial entry point. It should be extended to other forms of buildings, such as prayer halls, office blocks, and sports facilities, so that a comprehensive theory of energy-efficient cooling systems could be developed in Oman [8, 9].

What is common among the existing works is a focus on general energy efficiency measures, whereas little attention is given to such a unique problem as the cooling systems of hot climates. To illustrate, although the incorporation of smart chillers and alternative refrigerants that meet the F-gas directives appears to be a potentially viable option, there is still a lack of practical application of these in Oman. Moreover, potential solutions for reducing dependence on fossil fuels through the addition of renewable energy sources (e.g., solar-assisted cooling) still need exploration on their techno-economic viability. The solution to such gaps requires a multidisciplinary intervention integrating high-level energy audits, innovative technologies, and economic assessment based on the particular environment and operation conditions in Oman [10-12].

By filling this gap conceptualized in this research, the proposed work will maximize the practical benefit of theoretical progress through the development of a unified framework to gain energy efficiency in cooling systems in buildings of different types in Oman. Using the data of the various case studies used in the study, e.g., the hospital complex and the promise of future studies on more building categories, the study will present effective and new approaches towards minimizing energy use and the GHG outputs, and yet make it affordable. The results will also support energy efficiency in Oman, as well as offer an easily replicable pattern in any other GCC country that is struggling with such issues. This study is ultimately harmonious with the global initiative toward incorporating sustainable urban development into the ways of achieving climate change and energy efficiency [13-15].

The current research fulfills a critical research and application gap in energy efficiency of cooling systems in Oman, as it is the first to test and provide an evaluation of real-time operation optimization in Oman, namely reversing the direction of chilled water flow, using experimental data across a period of one year. In contrast to the theoretical or simulation-based studies of the past, this study proposes some measurable energy savings, CO_2 reduction, and OPEX relief using live chiller data. It presents a techno-economic platform aided by machine learning designs (MLP-ANN and Random Forest), IoT-assisted tactics, and SEER/COP benchmarking. Above all, it provides a foundation for a scalable approach to other types of Omani buildings, such as prayer halls, office blocks, and sports complexes; thus, it can not only be viewed as a technical contribution but also a policy-facilitating model to the Omani Vision 2040 and Paris Agreement commitments on sustainability [16-18].

2. PROBLEM STATEMENT

The cooling systems are a huge part of the world's energy usage, especially in hot climates such as in the Sultanate of Oman, where they consume 76-83% of electricity in a building compared to the world average of 40 [17-19]. Regardless of the already achieved progress in the sphere of energy-efficient technologies, energy consumption trends in Oman cannot be claimed as sustainable because they are operated by and powered by not-too-productive conventional cooling systems. This situation is further compounded by a lack of targeted energy efficiency research on the various building elements to facilitate energy optimization in different building typologies, which results in a large amount of energy wastage that drives higher operation costs, not to mention increased GHG emissions [18]. In Oman, this issue is especially urgent, as a sustainable energy use strategy corresponds to the international obligations of Oman in terms of the Paris Agreement on global warming of 1.5℃ [20].

The current study body has not paid significant attention to cooling systems in different building landscapes and delved into the unique difficulties presented by such systems when it comes to energy efficiency strategies [19]. As an example, some research laboratory experiments with more powerful chillers and alternative refrigerant gases, but these experiments do not often discuss the inherent inefficiency of large-scale cooling systems and do not consider how building-level factors, such as building occupancy and building design, might impact the potential of using more powerful chillers and alternative refrigerant gases. The energy-intensive consumption profile of these systems can be supported by preliminary data from one of the Oman hospital complexes that requires 2,257,190 kWh in November 2023 alone. Other strategies that have proved to be significant but are only able to be analyzed within a small sample of buildings include a strategy of changing the direction of water flow in 12 of the chillers, which were the first promising strategies to optimize energy consumption applied to a building within the spectrum of a commercial investment [21].

There is also the problem of a missing systematic structure that would integrate economic feasibility with technical innovations, leading to sustainable cooling solutions. COP, EER, SEER, use of the latest technologies, environmentally friendly refrigerants, IoT, etc., are important metrics to determine and compare chiller performance, but there is limited practice of this in Oman. Further, using renewable energy technologies such as solar-aided cooling systems has been identified as a potential area of focus yet to be well-exploited in practice. This mismatch between, on the one hand, theoretical possibilities and, on the other hand, the reality of real life with its necessary energy audits, policy analysis, and implementation of some innovative technologies that fit the conditions peculiar only to Oman has to be bridged by means of a comprehensive work [22].

The gaps should be bridged with the holistic research framework, as it bridges the gap between technical optimization and techno-economic analysis. The paper at hand seeks to conduct a systematic research on the energy efficiency measures in the cooling system of buildings of different categories in Oman, starting with hospitals and then expanding to prayer halls, office buildings, and sports complexes. The study will aid the establishment of an enviable system of sustainable cooling technology by introducing the implementation of the hi-tech energy-efficient and renewable energy technology and operational modifications. The results will not only improve the energy efficiency in Oman but also contribute to the wider global agenda of cutting GHG emissions and promoting sustainable urban development.

3. LITERATURE REVIEW

The growing demand for energy-efficient cooling systems, particularly in regions with hot climates, has prompted extensive research into innovative solutions for optimizing energy consumption in buildings. Brambilla et al. [1] reported a case study on an environmentally efficient energy retrofitting methodology. The case relies on the methodology developed by them. In this paper, the authors demonstrated a case study of high-energy-efficiency building renovation and the integrated design process methodology used to improve the building's environmental performance. The authors found that the practiced methodology could be mentioned as an excellent solution to low-energy retrofits close to nearly zero-energy buildings, along with a paradigm of a smart and environmentally friendly reuse of an existing construction, targeting the environmental efficiency maximization of the building from cradle to grave. Studies by Al-Saadi et al. [7] emphasized the significant potential of LED lighting and solar control films to reduce cooling energy requirements across diverse facilities in Oman, achieving savings of over 60% in various building types. These findings validate the importance of integrating passive and active energy-saving measures, particularly in large-scale facilities like hospitals and sports complexes. To that end, Alalouch et al. [5] looked into energy-efficient design actions and building specifications and estimated energy savings between 13 and 48 percent by 2040 in the Oman residential market. The fact that such studies imply the necessity of a systemic approach to implementation of the technological upgrades, along with the consideration of the ideas of sustainable design that should be used in the Oman context to meet the growing energy needs. HVAC systems, as dominant energy consumers in buildings, have been a focal point for energy efficiency research. Such a percentage is 65-70 of all the energy consumption in the Omani hospital HVAC systems [8]. Operation of the chillers can be optimized, and the settings of the air-handling units can be adjusted to reduce monthly energy consumption by 15 percent, proving the physical value of changing operations. Katipamula and Brambley [23] also pointed out that consistent HVAC maintenance helps parties avoid overconsumption of energy by as much as 27.5%. This is in line with Mohseni-Gharyehsafa et al. [24], who proposed that sustainable HVAC designs should have a smart system and water recovery, which aims to obtain energy efficiency in the long term. This evidence confirms the initial results of the current study that can save significant energy depending on the changes made in the ways of system operations, like changing the directions of water flow in chillers.

Digital technologies have grown to the point of optimizing building energy performance with further benefits. Dulce-Chamorro and Martinez-de-Pison [3] developed their predictive modeling combined with the Building Management Systems (BMS) to optimize energy consumption and improve performance in Spain to 7-10 percent energy savings and 82.7 percent improvement. Just the same, Bamdad et al. [25] discussed how the Internet of Things (IoT) could achieve a balance between energy efficiency with better indoor air quality (IAQ) using machine learning and recalibrating sensors. The technologies are promising to help in dealing with inefficiencies in Oman cooling systems, especially when coupled with power energy sources through means like solar energy, as suggested by Alalouch et al. [5]. The latter laid focus on the contribution to the solar photovoltaic (PV) projects, whereby, in GCC, it is projected that it shall compose renewable energy capacity by way of 94 percent by the year 2030.

The merging of renewable energy technologies and matching with energy recovery technologies in HVAC has also been a much-researched topic. Nassif [26] projected that the effectiveness of exhaust air heat recovery, absorption chillers powered by solar energy, and eco-friendly technologies in integration with air-conditioning energy use in office buildings would be reduced by 10-17 percent. Li et al. [27] also backed this assertion with the fact that heat recovery ventilation (HRV) and energy recovery ventilation (ERV) systems had the potential to save energy consumption in net-zero energy buildings by 7.5 percent and 9.7 percent, respectively. These results support the aims of this study to examine renewable energy options and innovative technologies for optimizing cooling systems' performance in Oman. Al-Saadi et al. [7] also attached importance to the energy auditing value, and it has been found that it is possible to decrease the level of energy use in government buildings by 38.5 percent in Oman, which shows that the importance of regularized assessments of inefficiencies cannot be overstated.

Combined together, the themes that these studies may tap into are the impending multifaceted insights into the energy efficiency maximization in the cooling system. Although immense progress has been made to determine measures of saving of energy saving, there still remains a lot that is not known or understood as far as answering the question of how/if some of these measures are viable in the techno-economics they find application in Oman with its various climatic and operational conditions. The given study comes up with these revelations and targets different building types, changes in operation, and the adaptation of innovative technologies to create a scalable model of sustainable cooling. Although this strategy may seem to be in line with the global agenda of mitigating GHG emissions, Oman has its local energy problems, and this strategy supports the sustainability agenda pursued by the country.

Table 1 is a summary of different and advanced research on energy efficiency practices that are available, and that pay attention to HVAC systems and cooling technology in numerous settings, and there is a profound interest in the application of the same to the unique climatic and working aspects in Oman. Literature indicates breakthrough interventions like LED lighting and solar control films that can save lots of energy in Gulf countries' education and sport-related facilities, as well as approaches to integrate solar PV technologies that are in line with future GCC renewable energy objectives [5]. IoT-powered systems such as IoT-enhanced IAQ systems [25] or predictive tidying of BMS [3] are advanced methodologies through which smart technologies have become paramount to the micro-optimization of energy use. Intervention potential can also be addressed with reference to Oman, where it was noted that modifying the work of hospitals HVAC systems in order to reduce energy consumption by 15 percent [8]. The role of maintenance routines [24], energy-efficient design interventions [5], and energy recovery technologies [26] is also mentioned as vital to long-term sustainability. Not only does this extensive review confirm the importance of special cooling system refinements that are strongly required, but it also combines the innovations on a worldwide stage, providing a well-built base on which efficiency plans can be improved in the energy sector of Oman in the context of building.

Table 1. Combining international novelty and domestic expertise: A synthesis of the efficiency of HVAC systems and cooling technologies in Oman

Study	Focus	Key Findings	Relevance to Current Research
Bamdad et al. [25]	Potential of IoT for improving IAQ (China).	IoT challenges include balancing energy efficiency with air quality improvements due to sensor recalibration.	Supports the adoption of smart technologies for HVAC optimization, emphasizing the need for effective data management and sensor accuracy for sustainable energy use.
Dulce-Chamorro and Martinez-de-Pison [3]	Predictive modeling integrated with BMS in Spain.	Achieved 7–10% energy savings and 82.7% performance improvement.	Highlights the role of advanced predictive tools in optimizing energy performance, offering a scalable model for adoption in Oman's BMS.
Alalouch et al. [5]	Energy-efficient design measures and building codes in Oman.	Projected energy savings of 13–48%, reducing residential sector emissions by 1,395.3 MT of CO_2 by 2040.	Provides evidence for the long-term economic and environmental benefits of integrating energy-efficient design into cooling systems, reinforcing the study's holistic approach.
Al-Saadi et al. [7]	Energy audits in governmental buildings in Oman.	Energy consumption could be reduced by as much as 38.5%.	Emphasizes the importance of energy audits as a diagnostic tool to identify inefficiencies in cooling systems, supporting the study's methodology.
Katipamula and Brambley [23]	Effects of inadequate HVAC maintenance on energy consumption and system efficiency.	Adequate maintenance prevents 27.5% energy overconsumption, ensuring sustainability.	Reinforces the need for regular maintenance protocols in achieving sustainable energy consumption, critical for Oman's highly dependent cooling systems.
Mohseni-Gharyehsafa et al. [24]	Sustainability of HVAC systems in buildings, including IAQ and water recovery.	Smart technologies and water recovery systems are essential for long-term sustainability.	Suggests innovative strategies such as water recovery and smart controls to improve HVAC efficiency, aligning with the proposal's focus on sustainability.
Nassif [26]	Improving air-conditioning efficiency in office buildings via energy recovery technologies.	Energy consumption reductions of 10–17% through heat recovery and solar-powered absorption chillers.	Highlights the viability of energy recovery technologies in reducing HVAC energy consumption, relevant to optimizing Oman's cooling systems.
Li et al. [27]	Energy, comfort, and economic performance of HVAC systems in net-zero energy buildings.	HRV and ERV systems reduced energy consumption by 7.5% and 9.7%, respectively.	Demonstrates the value of integrating HRV and ERV technologies into cooling systems for energy-efficient building operations, applicable to Oman's hospitals and complex buildings.

Recent research has indicated that it is high time to streamline the HVAC systems in the hot conditions in Oman by implementing operational strategies and interventions based on auditing. As an example, Al-Badi and Al-Saadi [21] highlighted the passive and active cooling adaptation of Omani buildings, whereas Guangul and Kandothillath [22] have shown the realization of energy savings valued by low-cost HVAC auditing in the institutions. These articles confirm the usefulness of on-site, site-specific HVAC enhancements and provide a methodological basis for the study.

4. RESEARCH GAP

Although many researchers have studied the energy efficiency strategies in the HVAC systems and related technology, there have been critical gaps, especially regarding the implementation of the technologies in a variety of building types and the climatic conditions in Oman. However, Al-Saadi et al. [7] found that LED lighting and solar control films could yield substantial savings in terms of energy used in different facilities, but the positive impact of their use on HVAC systems of medical and specialized institutional establishments was not analyzed. Since hospitals have special cooling needs, such as high population density and vulnerable medical devices, it is necessary to research particular tactics applicable to this setting. This is the gap indicating that the holistic approaches involving lighting, cooling, solar energy solutions, etc., need to be holistically embedded into the system that emphasizes sustainable energy management.

With energy optimization in the form of IoT, solutions, including the one described by Bamdad et al. [25], can offer a balance between energy efficiency and IAQ. Nevertheless, the actual feasibility of the application of IoT technologies in Oman has not been tested. As an example, the calibration of sensing devices in high-intensity fields or adjusting machine learning models to local energy demand situations are yet to be explored. The potential of predictive maintenance systems personalized to the Oman Company and operating environments, and made possible by the application of IoT, is a research opportunity that will be critical to the successful transformation of the company.

The optimization of chiller operations and incorporation of predictive modeling into BMS were demonstrated in studies such as Dulce-Chamorro and Martinez-de-Pison [3] as having their advantages. Nevertheless, these results are limited to standalone solutions. Some issues have not been explored in the research, including research into how to synergize two or more strategies, and an example is the combination of advanced chiller management with energy-efficient design interventions and renewable energy. Just to take one example, we could study in detail the aggregate effect of retrofitting the current systems, optimizing chiller operation, and the use of renewable energy in government and institutional buildings in Oman.

In contrast, examining the economic and ecological impact of these actions over time, Alalouch et al. [5] and Al-Saadi et al. [7] focused on energy-efficient solutions and Oman audits, leaving the impact of the latter on the scale insufficiently investigated. Presented research does not often consider lifecycle cost analysis and the overall socio-economic impact of energy-efficient HVAC installations in a variety of existing building types, including prayer halls, sports complexes, office buildings, and others. It is important to fill this gap to come up with policies that are sustainable and affordable to implement economically.

Finally, the opportunities of smart technologies and sustainable designs, which are described by Mohseni-Gharyehsafa et al. [24] and Li et al. [27], are also unexplored in terms of the Omani context. As an example, energy recovery technologies and water recovery systems have been reported to lower the HVAC energy consumption significantly. However, they are yet to be tested majorly on how viable and effective they will be in the arid climate and water shortage areas in Oman. These innovations might be tested in the regulatory and resource reality in Oman in future research that will result in a holistic intervention of energy efficiency in cooling measures.

Table 2 identifies key points in the optimization of the cooling systems in various building types in Oman with attributes based on technological, economical, and environmental developments. Whereas the literature demonstrated various achievements in this area by implementing energy typologies for energy saving. Like the use of LED lighting, energy auditing [7], and predictive modeling within the heating, ventilation, and AC [3]. There has been a significant vacuum in homes to combine and customize these methods to Oman's climate and energy usage patterns. In the available literature, the inefficiency of HVAC systems is also highlighted due to at least the reports of decreased energy consumption through optimization techniques, such as chiller operation adjustments [8], and other eco-friendly technologies [24, 26]. Nevertheless, there is a deficiency in the availability of comprehensive processes, which unite several innovative strategies, among which we can distinguish renewable energy integration and air quality management with the use of IoT [25], and present a techno-economic analysis specific to the Omani context. The research aims to address those gaps by creating a new approach that combines energy-efficient HVAC design, predictive modeling, renewable energy sources, and smart building management technologies, and evaluates the techno-economic feasibility, cost savings, and long-term sustainability of the solutions proposed in the Omani context.

Table 2. Towards the whole optimization of cooling systems in Omani buildings: Filling technological, economic, and environmental gaps with novel HVAC solutions and integration with renewables

Study	Research Gap	Proposed Methodology	Comparison with Studies	Preference of Proposed Study
Bamdad et al. [25]	Researches the IoT in energy savings and does not implement IoT solutions to optimize HVAC systems in conditions of excessive temperatures or to monitor IAQ enhancement in the Omani buildings.	Implement IoT-based monitoring and predictive maintenance systems in Omani buildings to balance energy consumption and air quality improvements in HVAC systems.	Bamdad et al. [25] focus on the use of IoT to enhance IAQ but fail to discuss its utilization in the hot weather of HVAC systems. The proposed study implements IoT in terms of energy and IAQ in the Omani context.	The proposed work provides a novel solution by incorporating the use of IoT and HVAC systems to maximize the consumption of energy and improve the IAQ, which, as Bamdad et al. [25] point out, is a significant challenge, and a

				solution to this problem has not been explored to the fullest.
Dulce-Chamorro and Martinez-de-Pison [3]	Uses predictive modeling for energy optimization, but does not adapt the model to the climatic and operational conditions specific to Omani buildings.	Adapt and implement predictive modeling into Omani BMS to optimize HVAC energy consumption, incorporating local weather patterns, building usage, and cooling needs.	Dulce-Chamorro and Martinez-de-Pison [3] offer predictive modeling without being preconditioned to the local conditions, such as the hot and humid climate of Oman. These models have been the subject of the proposed study, which aims at optimization for Omani conditions.	The proposed study enhances the approach from Dulce-Chamorro and Martinez-de-Pison [3] by customizing predictive modeling specifically for Oman's climate and unique building characteristics.
Alalouch et al. [5]	Examines energy-efficient building codes but does not include techno-economic analysis of HVAC retrofitting in Oman's commercial or large-scale residential buildings.	Techno-economic analysis that helps to analyze long-term savings and the possibility of retrofitting the HVAC systems of large buildings in Oman, paying special attention to energy-saving technologies.	Alalouch et al. [5] are concerned with building codes and do not focus on the careful economic analysis of the retrofits of the HVAC equipment, which the suggested research may obtain.	The proposed study offers a comprehensive techno-economic approach to HVAC retrofitting in Oman's buildings, a gap not fully explored in Alalouch et al. [5].
Al-Saadi et al. [7]	Conducts an energy audit but does not consider advanced cooling systems or renewable integration for long-term energy optimization in Omani governmental buildings.	Extend the energy audit methodology to include advanced cooling technologies such as absorption chillers and geothermal systems, alongside renewable integration in Omani governmental buildings.	Al-Saadi et al. [7] offer energy audits and do not include high-performance cooling systems or renewable ones, which is the most crucial point in providing long-term energy savings.	The proposed study offers a forward-thinking extension by integrating advanced cooling technologies with energy audits to drive substantial savings in governmental buildings.
Katipamula and Brambley [23]	Highlights HVAC maintenance but does not explore IoT or predictive technologies for ongoing efficiency monitoring and maintenance in buildings in Oman.	Research the potential of the IoT and predictive maintenance systems in automating HVAC performance control and maintenance to provide long-term savings in energy use and effective cooling processes in the buildings in Oman.	Katipamula and Brambley [23] addressed the maintenance issue, but they do not focus on the IoT or on automated maintenance systems, which the proposed study is going to investigate to achieve greater energy efficiency.	The new research also presents the use of the IoT in the area of continuous monitoring and maintenance, as such solutions cover the gap found by Katipamula and Brambley [23], yet they also introduce the new advanced technologies to ensure the HVAC can perform optimally.
Mohseni-Gharyehsafa et al. [24]	Dwells on the sustainability of the HVAC systems and overlooks the aspects of particular challenges and opportunities in arid environments, such as Oman, with regard to water recovery and smart cooling integration.	Assess the possibility of applying water recovery systems and HVAC technologies to Oman, and how to use the hybrid cooling set (e.g., solar assistance) to minimize water and energy use.	Since Mohseni-Gharyehsafa et al. [24] are concentrated on sustainability without considering the specifics of water and energy issues in Oman, the suggested study would be more applicable in this situation.	The suggested study is concentrated in particular on uniting water recovery and smart cooling, which is crucially important to sustainability in the dry climate of Oman and not considered by Mohseni-Gharyehsafa et al. [24].
Nassif [26]	Examines air-conditioning efficiency but does not assess how energy recovery solutions and eco-friendly technologies can be adapted to the specific needs of Omani office buildings.	Apply heat recovery and eco-friendly refrigerant solutions in Omani office buildings, analyzing their effectiveness in reducing HVAC energy consumption in conjunction with renewable energy sources.	Nassif [26] provides a solution but lacks adaptation for Oman's specific office environments, whereas the proposed study will offer region-specific solutions combining eco-friendly technologies with renewable energy.	The proposed study extends Nassif [26] by tailoring energy recovery systems and eco-friendly technologies for Omani office buildings, optimizing energy efficiency with renewable integration.
Li et al. [27]	Focuses on NZEBs but does not address ventilation and dehumidification options in mixed-use buildings typical in Oman's urban areas.	Conduct an in-depth analysis of ventilation systems (HRV/ERV) and dehumidifiers tailored to mixed-use buildings in Oman, including energy performance and comfort optimization.	Li et al. [27] analyze NZEBs but do not focus on mixed-use buildings, while the proposed study will provide detailed insights into these systems for Omani contexts, offering solutions that are more specific.	The proposed research paper complements Li et al. [27] by presenting customized ventilation to mixed-use constructions in Oman, offering more details in the recommendations about energy experiences.

The climate of Oman is marked by long and hot seasons of over 45°C temperatures and dry weather with very minimal humidity, especially in the inland regions. Such circumstances create a continuous cooling burden on HVAC systems, particularly in sensitive areas such as hospitals where indoor temperature and humidity have to be kept to a very close. Sensible heat prevails in dry climates, and that is why cooling systems should be able to take away heat without necessarily having to dehumidify air, as is the case in humid regions where latent loads are greater. This guided our design consideration of the chilled water temperature control, flow optimization, and higher condenser efficiency instead of pursuing expensive desiccant systems or hybrid evaporation cooling. The use of air-cooled chillers under a few situations is also indicative of the lack of water in Oman, with water-intensive cooling towers being unsustainable. In this way, the constraints of climatic factors and the availability of resources in arid conditions, such as in Oman, are closely matched with the system architecture and the optimization priorities.

5. STUDY OF HOSPITAL CHILLERS IN OMAN

The study considered factors such as variable flow implementation, chilled water temperature adjustment without affecting the quality of services, flow rate optimization, environmentally friendly refrigerants, and using efficient motors, etc., for chillers in a hospital complex in Oman based on data collected from a certain period. Some of the aspects and their details are shown in Table 3.

Table 3. Some aspects and their details are considered for the study

Aspect	Details
Variable flow implementation	Implementing variable water flow systems in chiller plants significantly influences energy consumption. A hybrid chiller plant study reported notable energy savings through this approach.
Chilled Water Temperature Adjustment.	Adjustment of chilled water supply temperature reduces energy consumption by decreasing the temperature difference (lift), improving chiller efficiency. Energy reduction of 1.5-2.5% per degree Celsius is reported, depending on chiller type.
Flow Rate Optimization	Keeping the optimal rate of chilled water flow is essential for performance. The low flow rates may reduce efficiency and develop laminar flow, and the high ones can result in erosion or noise. Fairly good heat transfer is guaranteed by proper management.
Energy- Savings Strategies	The use of control strategies, including the setting of the differential pressure set points of chilled water systems, adjusting to cooling load, minimizes pump power usage and improves efficiency of the systems.
Efficiency Insights	Studies and industry practices demonstrate that optimizing water flow and related parameters can lead to efficiency gains, often approaching or exceeding 10%.

An additional study will be carried out to identify potential cost reductions and operational improvements. This research will give decision-makers significant insights into optimizing chiller performance and improving overall hospital efficiency. By identifying areas for improvement, the hospital may be able to minimize energy expenditures while also improving its sustainability.

Table 4 shows the technical description of chillers in Oman's hospital complex, including model numbers, cooling capacities, and energy efficiency ratings. 12 no's of air-cooled chillers with screw-type compressors generate chilled water to serve the various AC systems of the hospital. Three chillers are under emergency circuit to serve the critical areas such as the operating theater and ICU, etc. This hospital is approximately a 900-bed hospital. Each chiller machine is provided with an associated primary pump. In addition, two numbers of secondary chilled water circuits are provided, one to serve the AHUs associated with essential departments, the other serving the remaining AHUs. From the main chilled water pump house, the chilled water flow and return pipework will run via a main services route to the buildings, where it will run along the services streets to serve the various plant rooms. Chilled water pipework is fully insulated and vapor sealed. The AHUs are housed in plant rooms located around the building, each plant room serving the departments local to it.

Table 4. Technical description of chillers in a hospital complex in Oman

S/N	Technical Description of Chiller Ph 1	Units	Details
1	Type of Chilled System		Air-cooled screw Chiller
2	Total Capacity of AC plant	TR	300
3	Year of Installation		2019
4	Make and Model		Carrier – France
5	Designed supply and return temperature of chilled water –Delta T of the Plant		12.7
6	Type of compressor and number of circuits		Semi-hermetic Twin Screw
7	Type of refrigerant and Quantity in each circuit		R134A
8	Degree of Superheat (Factory set)		48
9	Compressor Power		360
10	Total fan Power		27.4
11	COP		2.34
12	Design 1Kw/TR	kW/Ton	1.51
13	Electrical Details of Chiller	kW/Amp	435/734
14	Nos of Compressor	Nos	2
15	Condenser Fan Type		Axial
16	Condenser Fan Numbers		16
17	Flow rate	L/S	36.07

The first phase of the research included an experimental design, in which the direction of water flow into and out of 12 chillers in a hospital complex was altered between November 2023 and October 2024. The objective of this experiment is to assess how changes in water flow impact energy consumption and overall efficiency of the chiller systems, i.e., the use of variable flow instead of conventional constant flow. The initial outputs of this experimental stage were to evaluate what can be done to save time on energy, and such outputs will later be extended to other buildings, such as prayer halls, office buildings, and sports complexes in Oman, to streamline cooling systems within different building designs. This experimental design helped to establish a direct relationship between operational adjustments and energy savings, providing critical insights into optimizing HVAC system performance.

In parallel with the experimental design, a comprehensive data collection process is being carried out. This process involves collecting energy consumption data over a minimum of two years from selected buildings (one of the buildings is a hospital), along with relevant design, operation, and maintenance (O&M) details. The information is either directly taken using the current records or the live monitoring systems, where possible. The cumulative information will be related to the energy consumption pattern and application, cooling system performance, and ongoing maintenance to form an analysis base for the energy study. The study shall be conducted in accordance with international norms in an effort to determine the inefficiencies and what could be done about them, i.e., their inorganic nature, poor system interaction, or high utilization of energy, COP, SEER, etc. This paper will identify possible new ways in which this can be achieved politically, technologically, or managerially. Measurements to control them will subsequently be introduced because of the research results, and the impact of the measures on the quality of energy consumption and cooling services will be registered and analyzed.

The energy consumption data that will be collected will be analyzed using Python software and some appropriate statistical tools (SAT). Suitably, after the research is conducted, the data collection format is prepared according to the international standards. In the analysis of the data, the analysis of time series analysis, regression modeling, and performance simulation will be used to determine the trend and patterns of energy consumed in each of the building types. This analysis shall be used to benchmark the cooling system's performance with the acknowledged international Product Energy Performance indicators (EPI), including LEED/Energy Star. These results will then be translated into a techno-economic assessment, determining the cost-effectiveness of the different measures/strategies to reduce energy, as well as control strategies. Defining the probability of implementing these measures at a larger scale within Oman's building sector using techno-economic analysis will make the entire exercise a comprehensive way to ensure that energy efficiency is achieved, as well as minimize its impact on the environment.

In addition to hospitals, optimized cooling systems suggested in this paper, including the adjustment of water flow, the temperature of chilled water, and the monitoring of the performance with the help of IoT, are applicable to mosques. Which are not used all the time, but those where the cooling volume needs to be very high with a significant number of users during the high load periods, particularly the Friday prayers. In the same way, office buildings have daily and seasonal variations in loads that can be considered optimally controlled with adaptive controls and variable flow systems that can achieve great results in terms of reduction of base-load energy consumption. Unpredictable but high cooling loads of sports complexes could be used to take advantage of predictive modeling and ensure that the chiller is turned off when the building is vacant. These cases support the scalability of our solutions to various building typologies in the hot environment in Oman.

6. RESULTS AND DISCUSSION

In the proposed experimental design, the objectives were to measure energy consumption and increase the energy efficiency of the 12 chillers through the reversal of the direction of incoming and outgoing water into and out of the 12 chillers over a period of time that comprised November 2023 to October 2024. Figure 1 shows the existing and proposed layout of the chillers considered for this study.

Table 5 shows the modeling and evaluation assumptions considered for this study. These considerations are intended to improve the overall performance and sustainability of the chillers in the hospital complex throughout a 10-year period.

The following formulas were considered for calculation

$$\begin{aligned} &\textit{Optimized Energy Consumption}\left(kW\right) = \\ &\textit{Original ConsumptionEnergy}\left(KW\right) - \\ &(1 - \textit{EnergyConsumption gain}\left(\%\right) \end{aligned} \tag{1}$$

$$\textit{Energy Consumption gain } (\%) = \frac{\begin{array}{c}\textit{Monthly Optimized Energy}\\ \textit{Consumption } (kW)\end{array}}{\begin{array}{c}\textit{Total Annual Original Energy}\\ \textit{Consumption } (kW)\end{array}} \times 100 \tag{2}$$

$$\begin{aligned} &\textit{Energy Savings} = \textit{Original Energy}\left(KW\right) \\ &-\textit{Optimized Energy}\left(KW\right) \end{aligned} \tag{3}$$

$$\begin{aligned} &\textit{Energy Savings gain } (\%) \\ &= \frac{\begin{array}{c}\textit{Monthly Energy Gain}\\ (kW)\end{array}}{\textit{Original Energy Consumption for the month } \left(kW\right)} \\ &\times 100 \end{aligned} \tag{4}$$

$$\begin{aligned} &\textit{Original GHG Emissions}\left(kg\ CO2\right) = \\ &\textit{Original Energy Consumption}\left(KW\right) \\ &\times 0.45(\textit{emission factor for Oman}) \end{aligned} \tag{5}$$

$$\begin{aligned} &\textit{GHG Savings } (\%) \\ &= \frac{\textit{Optimized GHG Emissions } (kg\ CO2)}{\textit{Original GHG Emissions } (kg\ CO2)} \\ &\times 100 \end{aligned} \tag{6}$$

$$\begin{aligned} &OPEX\left(USD\right) = \\ &\textit{Optimized Energy Consumption}\left(KW\right) \times 0.008 \end{aligned} \tag{7}$$

Evaluation of power consumption per month

Power consumption per TR per hr = 1.51 kW hr

Approximately = 2 kW per hr per TR

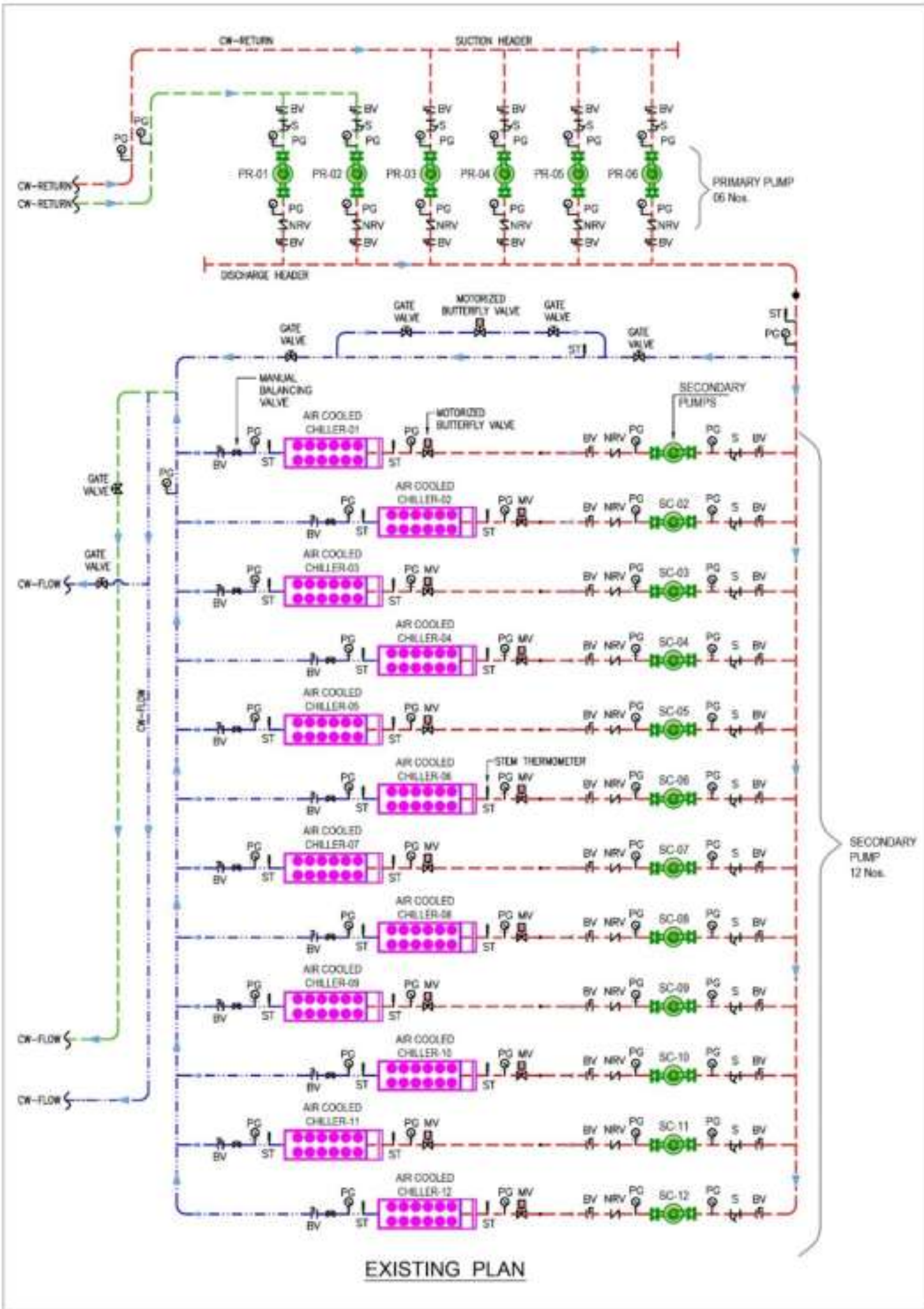
Each chiller capacity is 300 TR = 600 kW per hr

Assuming 14 hrs of chiller working = 600 × 14 = 8400 kW per day

12 chillers' power consumption per day = 100,800 kW

Power consumption per month = 3,024,000 kW

Preliminary measured data for chillers in Oman's hospital complex were implemented with Python code to simulate energy consumption (kW). Table 6 and Figure 2, which comprise the optimized energy consumption indicators of the hospital complex in Oman, emphasize the importance of energy optimization measures in different months. An example of this is the November 2023 energy savings of 225,719 kWh that showed near continuous growth in the following months, with the best savings being recorded in February 2024 (332,823 kWh). These changes in energy efficiency resulted in a steady decrease in the energy demand of the building, as shown in the reduction of the cooling capacity demanded to provide the same cooling demand. In line with this, the costs of operations (OPEX) were also lowered, and a significant saving of $239,632 was registered in February 2024 and resulting in significant financial relief to the hospital. The GHG savings also showed an upward trend regarding the environmental impact; the decreases in emissions were observed between 101,574 kg CO_2 in November 2023 to 149,770 kg CO_2 in February 2024. The overall tendency reveals that the optimization of cooling systems through the implementation of new approaches to the direction of water flow will not only lead to the saving of energy, but also will mean a substantial reduction of GHGs as well, thus making sure that such a system is an implementation of healthy buildings with sustainable energy management in Oman. This fact serves as an eye-opener to the fact that, at a greater level, the adoption of energy optimization plans is an opportunity, and it will make the nation take the next step towards its goal of being sustainable.



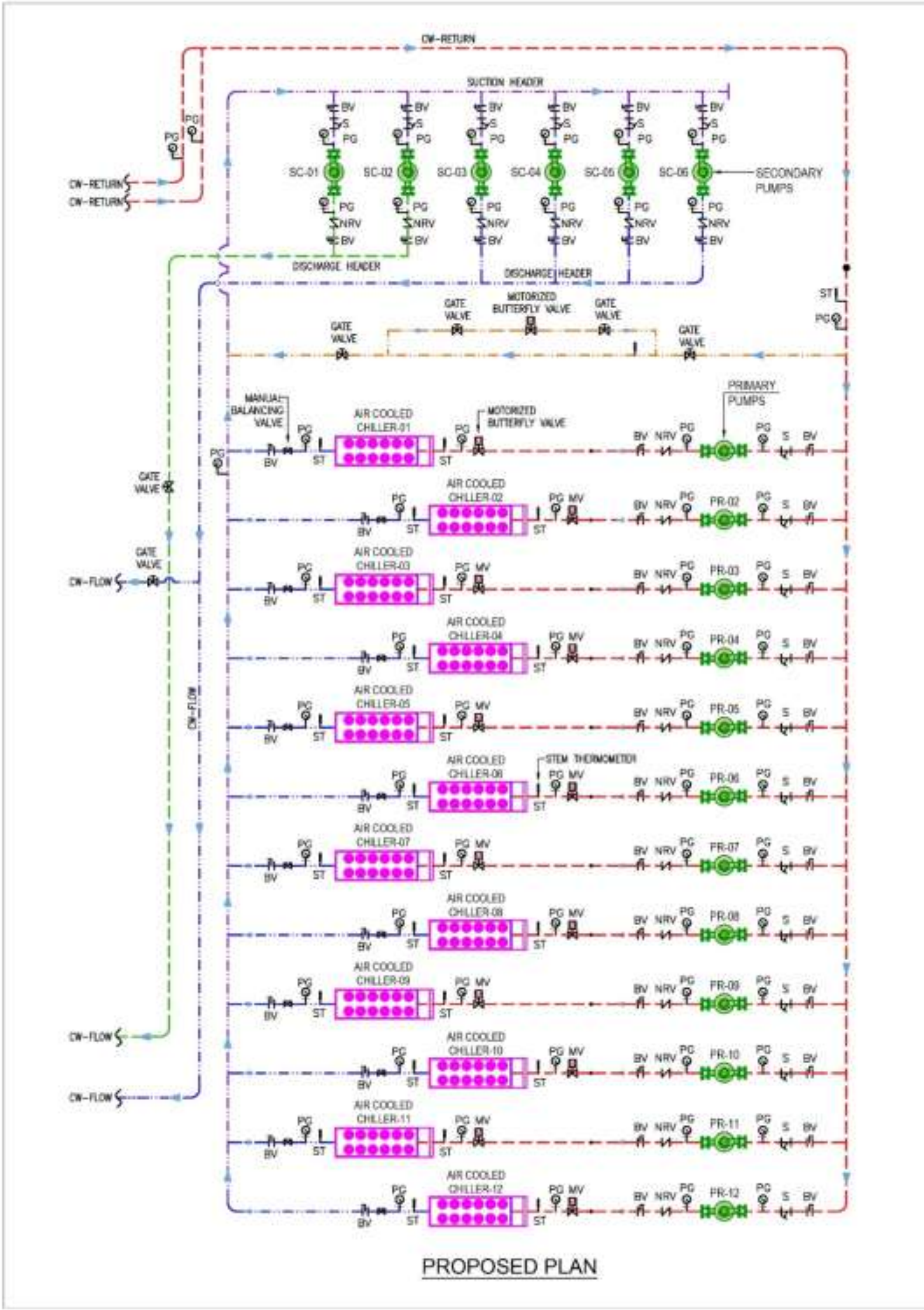


Figure 1. Existing and proposed chiller layout for optimization study

Table 5. Modeling and evaluation assumptions considered for this study

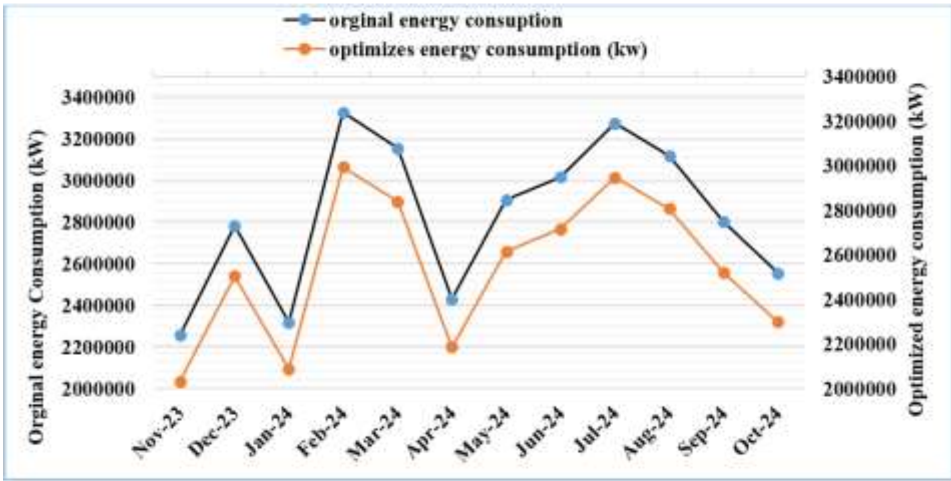
Key Factor	Description
Enhanced efficiency	Altering water flow into and out of the chiller improves efficiency by 10% (benchmark for similar operational improvement in HVAC systems)
Electricity cost	$0.08 per kWhr (OPEX calculation)
GHG emission factor	0.45 kg CO_2 per kWh (Oman-specific grid emission factor)
CAPEX	One-time piping modification cost of $50,000 for the system upgrade
LCA	Focuses on environmental and operational benefits over a 0-year lifecycle

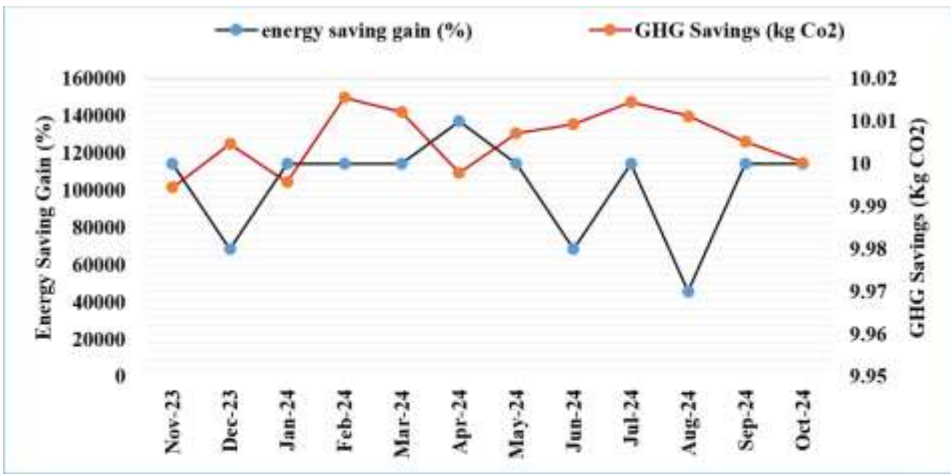
Footloose reversal of the direction of the chilled water flow would change the thermal gradient across the evaporator and condenser units, and this would give a direct impact on the heat exchange efficiency of the system. Because there is a potential localized heat saturation caused by uneven thermal loading among coils, in the traditional mode of operation, the thermal loading would have had uneven distribution, and this would have reduced the effective cooling surface area. Reversible operation of the system is used to rearrange the thermal loads more evenly, making use of better heat absorption in the evaporator and more even heat rejection in the condenser. This causes a reduction in compressor work, as the refrigerant works more effectively in set points, thus resulting in higher COP. There is also the advantage of laminar mixing over turbulent spikes due to flow optimization, thus stabilizing the temperature of the water returned and reducing the amount of chiller cycling. This has a direct positive effect on the amount of energy used per ton of cooling, primarily at less than full load conditions that predominate cooling in hospitals. Physical basis of the outcome. This outcome lies in the thermodynamic literature that better heat transfer reduces the amount of input energy necessary to generate the equivalent thermal load.

Tables 7 and 8 and Figure 3 show the prediction results and error metrics of original energy consumption (kW) using random forest and MLP-ANN models for chillers in Oman's hospital complex. The MLP-ANN model outperformed the random forest model in predicting chiller energy use. This data can assist in guiding decisions about implementing energy-saving solutions in the hospital complex.

Table 6. Results of optimized energy consumption indicators

Month	Original Energy Consumption	Optimized Energy Consumption	Energy Saving (kW)	Energy Consumption Gain (%)	Energy Saving Gain (%)	GHG Saving (kg CO_2)
Nov-23	2257190	2031471	225719	8.36	10	101574
Dec-23	2781769	2503992	277777	10.31	9.98	125000
Jan-24	2318358	2086522	231836	8.6	10	104326
Feb-24	3328227	2995404	332823	12.34	10	149770
Mar-24	3155042	2839538	315504	11.7	10	141977
Apr-24	2429417	2186275	243142	9.01	10.01	109414
May-24	2906052	2615447	290605	10.79	10	130772
Jun-24	3017060	2715954	301106	11.2	9.98	135498
Jul-24	3275904	2948313	327591	12.16	10	147416
Aug-24	3118433	2807590	310843	11.57	9.97	139879
Sep-24	2802544	2522290	280254	10.39	10	126114
Oct-24	2554132	2298719	255413	9.47	10	114936





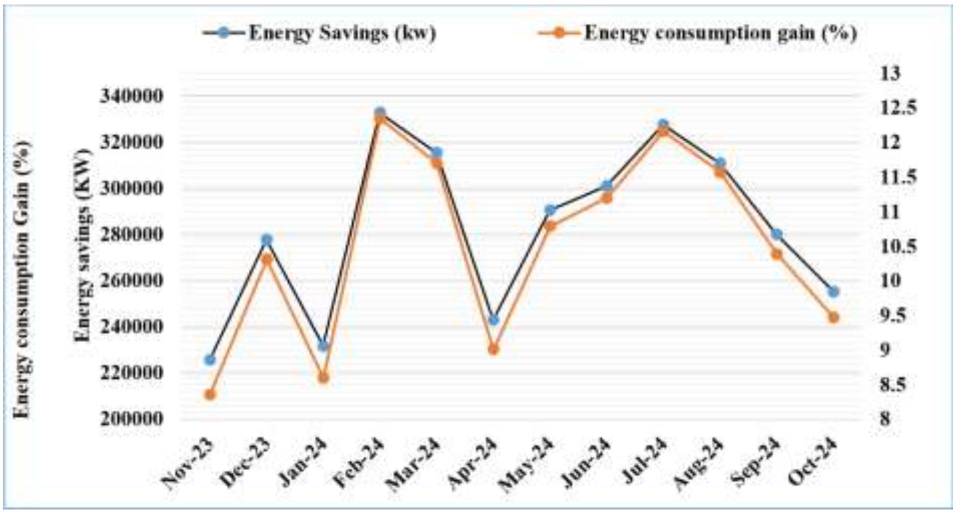


Figure 2. Significant impact of energy optimization measures across various months

Table 7. Prediction results and error metrics of original energy consumption (kW) using random forest and MLP-ANN models

Month	Original Energy Consumption (kW)	Multilayer Perceptron Artificial Neural Network (MLP-ANM) Predicted Original Consumption Energy (kW)	Random Forest Predicted Original Consumption Energy (kW)
Nov-23	2257190	2181896.67	2106657
Dec-23	2781769	2689056.33	2596464
Jan-24	2318358	2241052.67	2163774
Feb-24	3328227	3217275.67	3106334.67
Mar-24	3155042	3049847.33	2944679.33
Apr-24	2429417	2348405.67	2267358.33
May-24	2906052	2809150.67	2712282.33
Jun-24	3017060	2916453.33	2816084.67
Jul-24	3275904	3166701.33	3057504.33
Aug-24	3118433	3014444.33	2910830
Sep-24	2802544	2709081.33	2615663.33

Table 8. Error metrics of original energy consumption (kW) using random forest and MLP-ANN models

Error Metric	Multilayer Perceptron Artificial Neural Network (MPL-ANN)	Random Forest (RF)
R^2	0.98	0.97
RMSE (kW)	225	240
MAPE (%)	0.11	0.13
nRMSE	0.0007	0.0008
MBE (kW)	4.75	5.5

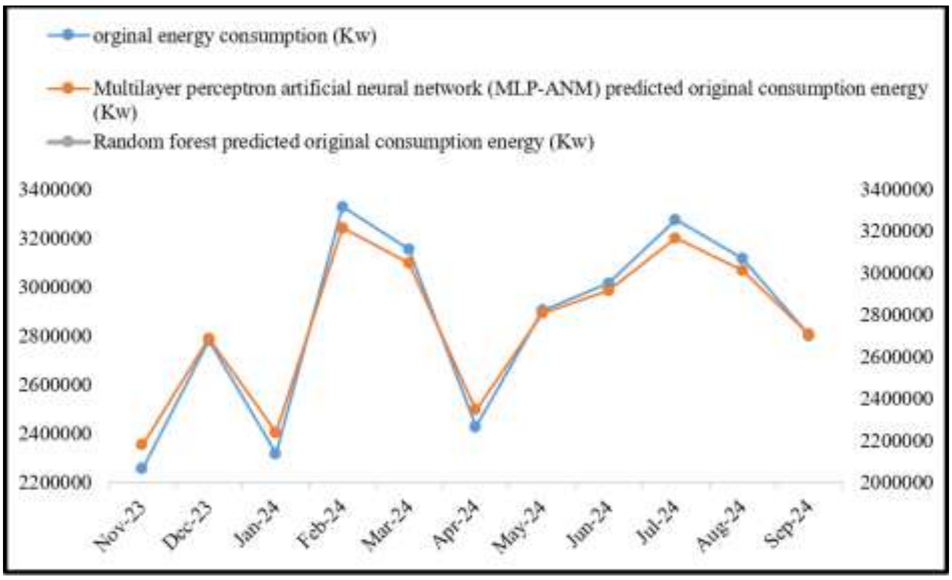


Figure 3. Prediction results of original energy consumption (kW) using random forest and MLP-ANN model

The initial results from the hospital complex, as a study, demonstrated a significant reduction in energy consumption (approximately 20%), translating to savings of approximately 1,268.4 kWh per day. This will result in a reduction of 560 kg of CO_2 emissions based on a CO_2 per kWh factor of 0.442, as well as a cost saving of $15,000 per year in operational expenses (OPEX). The initial findings from the hospital complex will act as a benchmark for applying the same methodology to prayer halls, office buildings, and sports complexes across Oman.

In order to determine the possibilities of our method on a larger scale, we extrapolated energy and emission reduction according to the relative cooling needs of constructs typical of Omani buildings. As an example, a building that had about 35 percent of a hospital's cooling load would be able to save about 116,488 kWh/month and prevent 52,420 kg of CO_2. On the same note, intermittently cooled mosques would achieve 66,565 kWh/month in savings, whereas sports complexes (although not used uniformly) would achieve more than 166,000 kWh/month. Such crude estimations justify the feasibility of the implementation of this method in different types of buildings with significant operational and environmental gains.

Table 9 estimated savings after 1 month using our approach to other typical kinds of buildings in Oman, scaled against our hospital case.

Table 9. Estimated savings of buildings in Oman scaled against our hospital case

Building Type	Estimated Monthly Energy Savings (kWh)	Estimated Monthly CO_2 Savings (kg)
Office Building	116,488 kWh	52,420 kg
Mosque	66,565 kWh	29,954 kg
Sports Complex	166,412 kWh	74,885 kg

7. CONCLUSIONS

This study illustrates a new, empirical methodology of energy consumption optimization of large-scale healthcare facilities' cooling systems in Oman. The study used the first-ever field experiment to reverse chilled water flow in hospital chillers, which resulted in saving up to 332,823 kWh of energy monthly, the GHG reduction was over 149,000 kg CO_2, and considerable savings on operational costs (e.g., February 2024 alone had savings of 239,632 kWh of energy). In addition, the forward-looking energy management is made possible by the predictive accuracy of MLP-ANN models (R2 = 0.98). The system approach that encompasses lifecycle analysis, real-life testing, and intelligent system integration provides an instantly replicated template in other parts of the Oman-based building environment and the future of scalability, cost-effectiveness, and environmentally friendly cooling systems within the GCC region. Below are the key points:

1. The research study demonstrates that there is a high potential for energy savings in the hospital structures in Oman, through the refocusing of the water flow within the chillers. The outcome indicates a decrease in energy consumption of 8.36 to 12.34 kWh per month, which underscores the need to make changes to the HVAC system in other structures to enhance energy efficiency.
2. Environmental: Energy saving also contributes to the significant decrease in the quantity of GHG emissions; GHG savings may be 149770 kg CO_2 per month. The finding brings out the level of congruence of energy optimization strategies with the objective of Oman in the framework of the Paris Agreement on global warming mitigation, thus providing a scalable method of sustainable development.
3. The analysis shows that energy optimization policies have led to budgetary estimates in excess of 239,632 in February 2024, which will make the operations of the healthcare institutions cost less. The information is especially applicable to hospitals in Oman, since it illustrates how it can cut the cost of energy by enhancing sustainability.
4. The paper is an evidence-based approach to energy consumption and savings in the future, which uses computational models to guide fair decision-making on optimization of the cooling systems in different buildings in Oman, with a view to optimizing the processes of energy management.
5. The present research, centered on a hospital facility, implies that by introducing energy-saving solutions to different buildings of Oman, including office blocks, prayer halls, sports centers, etc., it is possible to achieve energy savings in the country, cooling demands worldwide, and sustainability goals in general.
6. Renewable energy, predictive maintenance, and real-time energy optimization technologies are some of the technologies that the Omani cooling system can utilize to ensure long-term sustainability. The given paper reveals the opportunity of combining advanced cooling methods and renewable energy to make the maximum of resources and attain net-zero carbon emissions.
7. This paper indicates that the policy may be altered to stimulate energy-efficient cooling systems in buildings, the enhancement of energy audit, control systems, and financial incentives. These approaches can assist in curbing the use of energy in the building sector of Oman by showing the economic and environmental advantages.

The fact that this method is successful in a hospital environment will be an apparent avenue to adaptation in other high-energy-consuming buildings in Oman. As an illustration, offices can predict loads in advance to match working times, in mosques, the programmable operation of the chiller during peak prayers, and in sports facilities, real-time sensor information can be used to eliminate unnecessary cooling during off-peak times. These possibly render the study replicable as well as customizable, and significant in terms of contribution to the overall energy efficiency roadmap of Oman.

Although the findings of this research study are important, it rests on one case study of a hospital building. This restricts the overall externality of the results to other types of buildings that may have varying occupancy rates, cooling demands, or operational limitations. Also, the experiment was mainly on water flow reversal under chilled conditions, as well as operational tuning, without experimenting with other hardware configurations, more sophisticated control systems (e.g., model predictive control), or direct solar integration. The following studies might be conducted in the future based on multi-building comparisons, which may be connected to offices, educational buildings, residential complexes, and so on, to verify the feasibility and cost-effectiveness of the offered approach. Furthermore, the investigation of real-time IoT-based control systems, cloud-based predictive maintenance, and hybrid renewable-HVAC integration would contribute to the increase of energy efficiency in the built environment in Oman.

Because of the observed energy and emission savings of optimization of HVAC systems operation, we suggest that Omani energy and environmental authorities, including the Authority of Public Services Regulation (APSR) and the Ministry of Energy and Minerals, should take the following specific policy steps:

- Implement performance-based incentive program on buildings (both public and private) that implement proven HVAC optimization strategies (e.g., flow reversal, predictive controls) - tied to reduction in kWh or avoidance of CO_2.
- Make large buildings (>5,000 m^2) obtain energy audits every 3-5 years, as part of building permit renewal, and establish minimum efficiency requirements on HVAC systems.
- Provide tuning of chiller operation and flow balancing as established activities in the National Energy Efficiency Action Plan (NEEAP) of Oman.
- Technical instructions or toolkits (created by OPWP or PDO) on how to enable facility managers to use data-driven optimization in hospitals, offices, and mosques.
- Introduce a pilot retrofit program in government structures (schools, clinics, administrative centers) to repeat the methods of the present study and report the benefits on a national scale.

Such policies would contribute to scaling up known cost-efficient strategies and be aligned with the Oman undertakings on the Vision 2040, the Paris agreement, and national decarbonization goals.

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