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Derleme

Yalin ve Keklikcioglu 04:02 (2026) 1-13

Net Sıfır Enerji Binalarda Bina Enerji Performansı Açısından Su Kaynaklı VRF Sistemlerinin Değerlendirilmesi

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Öne Çıkanlar:

-Su soğutmalı VRF sistemleri, hava soğutmalı muadillerinin performansını iki kata kadar aşarak yüksek COP değerlerine ulaşmaktadır.

-Su kaynaklı soğutma teknolojisinin uygulanması, bina enerji tüketimini %30 ila %50 oranında büyük ölçüde azaltarak, bina enerji performansını artırmaktadır.

-Deniz suyu ve göl suyu kaynaklı sistemler, Net Sıfır Enerjili Bina (NZEB) statüsüne ulaşmak için önem arz etmektedir.

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Amaç:

Bu çalışmada, Akdeniz kıyı bölgeleri gibi doğal su kaynaklarına erişimi olan yüksek kapasiteli tesislerde, su soğutmalı VRF sistemleri, neredeyse Sıfır Enerji Binaların (nZEB) tasarımında ve genel bina enerji performansının iyileştirilmesindeki rolü incelenmiştir.

Metot:

Bu derleme çalışması; performans katsayısı (COP), enerji tasarrufu potansiyeli ve sistem konfigürasyonları gibi temel performans göstergelerini inceleyerek su soğutmalı VRF sistemlerinin Net Sıfır Enerji Binalardaki (NZEB) uygulanabilirliğini değerlendirmektedir. 2009 ile 2026 yılları arasında yayımlanan ilgili çalışmalar, sistematik bir şekilde taranmıştır.

Sonuç:

Hava soğutmalı VRF sistemleri için rapor edilen COP değerleri genel olarak 3,5 ile 5 arasında değişirken, su soğutmalı VRF sistemleri teorik olarak 12 gibi yüksek COP değerlerine ulaşmaktadır. Ayrıca, su soğutmalı VRF sistemlerinin enerji tasarrufu potansiyelinin %30 ile %50 arasında değiştiği tespit edilmiştir. Bu avantajlara rağmen literatür, doğrudan NZEB uygulamalarını ele alan çalışmaların su soğutmalı VRF sistemlerini nadiren değerlendirdiğini ve bu alanda önemli bir araştırma boşluğu olduğunu göstermektedir. Genel olarak bu çalışma, su soğutmalı VRF sistemlerinin enerji verimliliğini artırma ve sürdürülebilir bina tasarımını destekleme konusundaki önemli potansiyelini vurgulamaktadır. Sonuçlar, NZEB uygulamalarında su soğutmalı VRF sistemlerinin dikkatle değerlendirilmesinin önemli ölçüde enerji tasarrufu sağlayabileceğini; bunun da ulusal ve küresel ölçekte bina enerji tüketimini azaltmayı hedefleyen mühendisler ve tasarımcılar için bu sistemleri değerli bir seçenek haline getirdiğini göstermektedir.

Anahtar Kelimeler: Net Sıfır Enerji Binalar; Değişken Debili Soğutucu Akışkan, Performans Katsayısı.

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Review

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Assessment of Water-Source VRF Systems for Building Energy Performance in Net-Zero Energy Buildings

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Highlights

- Water-cooled VRF systems achieve high COP values, outperforming air-cooled counterparts by up to twofold
- The application of water-source cooling technologies significantly reduces building energy consumption by approximately 30–50%, thereby enhancing overall energy performance.
- Seawater- and lake-water-source systems play a crucial role in achieving Net Zero Energy Building (NZEB) targets.
- The application of water-cooled VRF technology in NZEBs remains limited, and existing studies in this area are scarce.

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Abstract: To reduce electricity consumption in buildings, engineering applications should prioritize cooling technologies with high energy performance. Within this context, water-cooled Variable Refrigerant Flow (VRF) systems emerge as a promising alternative to conventional air-cooled VRF systems. In high-capacity facilities with access to natural water sources, such as coastal regions along the Mediterranean, water-cooled VRF systems can play a critical role in the design of Net Zero-Energy Buildings (NZEBs) and in improving overall building energy performance. This review study evaluates the applicability of water-cooled VRF systems in NZEBs by examining key performance indicators, including coefficient of performance (COP), energy-saving potential, and system configurations. Relevant studies published between 2009 and 2026 were systematically reviewed using major scientific databases. The review clearly demonstrates the performance advantages of water-cooled VRF systems over air-cooled counterparts. While the reported COP values of air-cooled VRF systems generally range between 3.5 and 5, water-cooled VRF systems achieve COP values as high as theoretically 12. Furthermore, the energy-saving potential of water-cooled VRF systems was found to range from 30% to 50%. Despite these advantages, the literature reveals a notable research gap, as studies directly addressing NZEB applications rarely evaluate water-cooled VRF systems. Overall, this study highlights the significant potential of water-cooled VRF systems to enhance energy efficiency and support sustainable building design. The results indicate that careful consideration of water-cooled VRF systems in NZEB applications can lead to substantial energy savings, making them a valuable option for engineers and designers aiming to reduce building energy consumption at both national and global scales.

Keywords: Net-Zero Energy Buildings; Variable Refrigerant Flow; Coefficient of Performance

Nomenclature

Symbols

Q_L Heat extracted from the cooled space [W]

Q_H Heat supplied to the heated space [W]

$W_{net,in}$ Required network input [W]

U Overall heat transfer coefficient $[\frac{W}{m^2K}]$

Performance Parameters

COP Coefficient of Performance

COP_R Coefficient of Performance of the Refrigeration System

COP_{HP} Coefficient of Performance of the Heat Pump

Abbreviations

NZEB Net-Zero Energy Buildings

VRF Variable Refrigerant Flow

HVAC Heating, Ventilation, and Air Conditioning

HAP Hourly Analysis Program

1. Introduction

Within the scope of this study, the existing literature on water-cooled Variable Refrigerant Flow (VRF) systems reviewed and evaluated in terms of building energy performance and their applicability to net-zero energy buildings. Globally, air-conditioning and HVAC systems constitute a substantial share of electricity consumption. As illustrated in Figure 1, global electricity consumption has shown a continuous increase over the years [1]. Considering that buildings worldwide account for approximately 40% of total global energy consumption [2], the design of newly constructed buildings as net-zero energy buildings has become an essential requirement rather than an option.

Air conditioning and HVAC systems account for a significant share of total global electricity consumption. Figure 2 presents the amount of electricity consumed worldwide by air-conditioning and cooling-related applications [3].

An analysis of global electricity consumption for air-conditioning reveals that it accounts for approximately 8% of the total electricity consumption capacity worldwide. For this reason, the efficiency of designed HVAC systems must be carefully considered, and applications with high building energy performance should be prioritized. Given the substantial share of air-conditioning in overall electricity consumption, the construction of net-zero energy buildings and buildings with high energy performance is of critical importance, with building energy demand in design calculations being minimized and ideally approaching zero. This review clearly identifies the advantages of using water-cooled VRF systems in NZEBs when evaluated in comparison with existing studies in literature. By focusing on the COP values of VRF systems, it explains the performance differences and highlights the added value of water-cooled VRF systems when applied in NZEBs.

1.1. Net-Zero Energy Buildings

The design and planning of net-zero energy buildings are of great importance in enabling cities to achieve sustainable environmental conditions and controlled energy consumption levels. In parallel, the reduction of urban carbon footprints plays a critical role in the management and long-term development of such cities. Another key aspect of NZEBs that should be considered by design engineers is their contribution to providing a comfortable living environment for occupants and society as a whole [4].

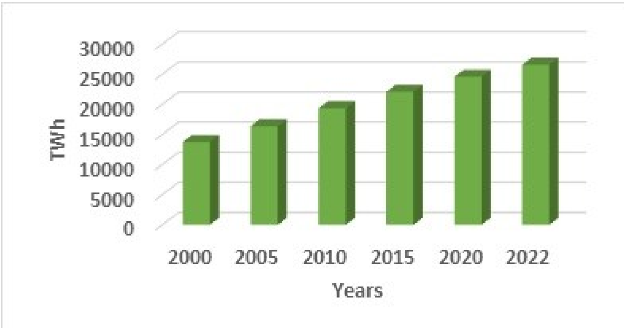

Figure 1. Global electricity consumption between 2000 and 2022 [1].

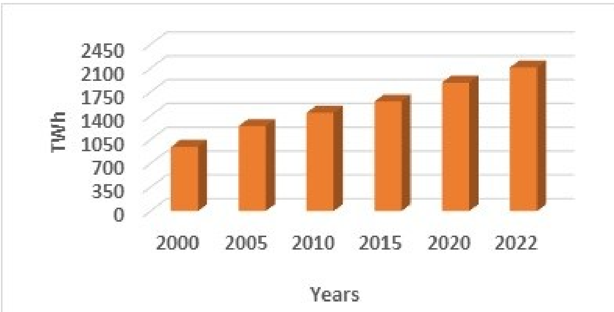

Figure 2. Global electricity consumption for air conditioning between 2000 and 2022 [3].

The main parameters to be addressed during the design phase include the calculation of the overall heat transfer coefficient (U-value) of building walls and roofs, determination of building orientation, design of thermal energy storage systems, integration of renewable energy sources, and, importantly, the reduction of building cooling demand [5]. In this context, water-cooled VRF systems occupy a significant position due to their high efficiency in reducing building cooling requirements.

1.2. Heat Pump

Heat pumps offer significantly higher efficiency than direct electric heating systems in NZEB design and in terms of their contribution to building energy performance. During winter conditions, heat pump applications operate by transferring heat extracted from the ambient environment to indoor spaces.

In addition, heat pumps can be used for cooling purposes under summer conditions by operating as refrigeration systems. The most important performance indicator of heat pumps is the Coefficient of Performance (COP). Heat pumps can be considered a typical application of the vapor-compression refrigeration cycle [6].

Heat pumps can be categorized as air-cooled, water-cooled, and ground-cooled systems based on the environmental conditions and available energy sources at the installation site. In air-cooled heat pumps, the outdoor air is utilized as an energy source. Compared to water- and ground-cooled systems, air-cooled heat pumps have lower initial investment costs and are therefore widely used in HVAC applications. Although water-cooled heat pumps involve higher initial and maintenance costs, their high efficiency leads to lower operating costs, allowing the initial investment to be recovered over the long term. Ground-cooled heat pumps are the least commonly used type due to their high initial investment costs and maintenance challenges [7].

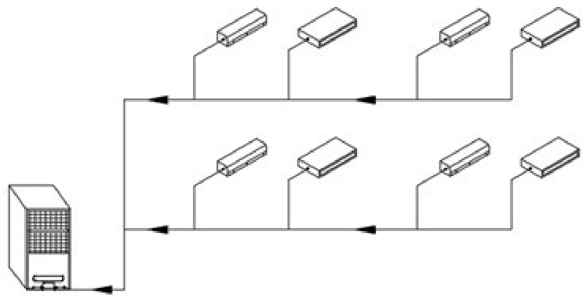

Figure 3. Air-cooled VRF systems [8].

1.3. Air-Cooled VRF Systems

Air-cooled VRF systems operate based on a vapor-compression refrigeration cycle formed by indoor and outdoor units. During cooling mode in summer, heat is extracted from the indoor environment and rejected to the outdoor air, whereas in heating mode during winter, heat absorbed from the ambient air is transferred to the indoor space. One of the most important features of these systems is their ability to operate with multiple indoor units of different types connected to a single outdoor unit.

In addition, thanks to variable refrigerant flow technology, conditioning can be reduced or completely suspended during periods or in spaces where air conditioning is not required. Air-cooled VRF systems are particularly advantageous in applications where architectural aesthetics are a priority, such as ceiling-concealed installations commonly used in construction sites. Figure 3 illustrates a representative example of an air-cooled VRF system [8].

1.4. Water-Cooled VRF Systems

Water-cooled VRF systems are more efficient than air-cooled VRF systems due to the lower temperature of the water and its superior heat transfer characteristics. Although their application is environmentally restricted in regions where potable water is used, facilities located near alternative water such as streams, rivers, canals, and seawater offer viable implementation options for design engineers. In particular, the construction of intake and discharge wells in coastal areas with access to seawater, such as bays and cliffs, can facilitate practical system integration.

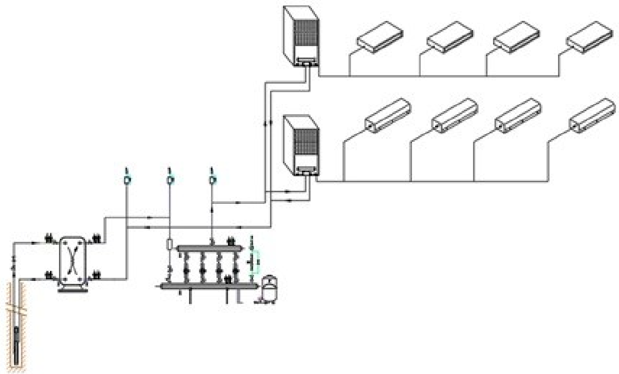

Figure 4. An example of a water-cooled VRF system.

For large-scale facilities such as hotels, restaurants, and business centers, a comprehensive assessment of available water should be conducted prior to the design phase. In air-cooled systems, heat extracted by the indoor units is rejected to the atmosphere through the outdoor unit, whereas in water-cooled systems, heat is transferred from the outdoor unit to the water instead of the ambient air. Water-cooled VRF systems also operate more quietly than their air-cooled counterparts. Another significant advantage is that outdoor units are not required to be installed in open atmospheric conditions and can therefore be in underutilized indoor spaces such as storage rooms within the building. This feature provides an important benefit in terms of architectural design flexibility. Figure 4 presents an example of a water-cooled VRF system.

1.5. Building Energy Performance and Coefficient of Performance (COP)

Building energy performance in Türkiye is regulated by the Regulation on Energy Performance of Buildings issued by the Ministry of Environment, Urbanization, and Climate Change. The regulation aims to ensure that newly constructed buildings are environmentally friendly, energy-efficient, and sustainable. In addition, it seeks to assign energy identity certificates to buildings and to certify those with high energy performance levels [9]. The most widely used method for calculating building energy performance is the BEP-TR1 software. Through this approach, buildings are issued an Energy Performance Certificate, enabling the classification and assessment of their overall energy performance [10].

In heat pumps and refrigeration systems, the most critical performance parameter is the Coefficient of Performance (COP). From an energy efficiency perspective, achieving the highest possible COP value is desired.

For a refrigeration system, the Coefficient of Performance (COP) is defined as:

$$COP_R = \frac{Q_L}{W_{net,in}} \quad (1)$$

Here, Q_L represents the heat extracted from the conditioned space, and $W_{net,in}$ denotes the required net – work input.

For a heat pump, the Coefficient of Performance (COP) is defined as:

$$COP_{HP} = \frac{Q_H}{W_{net,in}} \quad (2)$$

Here,Q_H represents the heat supplied to the heated space, and $W_{net,in}$ denotes the required net – work input.

COP values of refrigeration systems can reach levels as high as 6–7, indicating the amount of cooling provided per unit of electrical energy consumed. In other words, a higher COP corresponds to greater cooling capacity for the same electrical input. For this reason, HVAC system designs prioritize technologies with the highest possible COP values in order to enhance overall building energy performance [11].

1.6. Net-Zero Energy Building Design with a Water-Cooled VRF System

During the design process, the first parameter to be determined is the city and specific location where the project is situated. One of the most critical factors in classifying a building as a net-zero energy building is meeting the cooling demand using highly efficient systems. In this way, a significant reduction in overall building energy consumption can be achieved. Due to their high COP values, water-cooled VRF systems should be carefully considered in net-zero energy building design.

The initial step in designing a water-cooled VRF system is the identification of a suitable water. In cases where no appropriate water is available in the vicinity of the building, air-cooled VRF systems or cooling-tower-based systems may be considered as alternative solutions. Heating and cooling load calculations are then performed based on the outdoor design temperatures of the city in which the building is located. Upon completion of these calculations, the total HVAC loads of the building are determined, and the system design is carried out accordingly. At this stage, the conditioned zones are defined and the types of indoor units to be used in these spaces are selected. These indoor units may include wall-mounted, cassette-type, or ducted units. Following the selection of indoor unit types, the copper piping design is completed.

In water-cooled VRF systems, outdoor units can be installed in suitable indoor spaces such as storage areas or mechanical rooms. Water extracted from the source is delivered to the outdoor units through pumping systems. An important consideration at this point is the corrosive nature of the water source; if seawater or other corrosive fluids are used, materials resistant to corrosion must be selected. Owing to their high COP values, water-cooled VRF systems clearly enhance building energy performance. In addition to meeting cooling demands with minimal energy consumption, the ability to locate outdoor units in underutilized indoor spaces contributes to the development of environmentally friendly net-zero energy buildings.

2. Material and Method

It should be emphasized that Net-Zero Energy Buildings (NZEBs) do not represent specific technology or a single standardized design approach. Rather, NZEB is a performance-based concept whose definition varies significantly across regions, regulatory frameworks, and assessment methodologies. While some definitions focus on site energy balance, others adopt source energy, carbon emissions, or primary energy metrics. Furthermore, a building that merely generates energy without first minimizing consumption cannot be considered a true NZEB [32]. In this study, NZEB was evaluated as a building that produces as much energy as it consumes.

In the present review, various water-based options including seawater-source, ground water-source, lake-water-source, and cooling-tower-assisted systems are collectively addressed under the general category of water-cooled systems. This approach is adopted to enable a broad comparative assessment of water-cooled and air-cooled VRF technologies based on reported performance indicators such as COP and energy-saving potential.

A review of the literature on net-zero energy buildings and water-cooled VRF systems reveals that existing studies have been conducted using both experimental and theoretical approaches. The share of buildings in global energy consumption has been increasing significantly, making net-zero energy building design an emerging necessity [2]. Studies on net-zero energy buildings emphasize the importance of renewable energy integration and high-efficiency engineering solutions [12]. Key elements in NZEB design include building insulation, efficient and optimized HVAC systems, energy storage, and the use of renewable energy technologies [13].

In one study, HVAC systems in NZEBs were examined to assess their impact on overall building design, with particular emphasis placed on the role of heat-recovery HVAC systems [14]. Other studies in the literature highlight that the integration of optimization techniques with VRF systems can significantly enhance energy savings [15].

In addition, a study conducted in Antalya investigated a water-cooled VRF system installed in a shopping center comprising four-story retail and fast-food areas. The system was evaluated experimentally under real operating conditions for both summer and winter modes. Although the building was not originally designed as a net-zero energy building, the results indicated that it could be more easily adapted to NZEB standards in the future [6]. In another study carried out in Antalya, a seawater-cooled VRF system installed in a 360-room hotel located in the Alanya district was analyzed. The total cooling load of the hotel was reported as 2200 kW, and the seawater-cooled VRF system was thermodynamically evaluated as an alternative to conventional cooling systems for such large-scale facilities [16].

In several theoretical studies, the efficiencies of air-cooled and water-cooled VRF systems have been compared, and the advantages and disadvantages of VRF systems have been highlighted. In particular, the superior energy efficiency of water-cooled VRF systems has been emphasized [17]. In a study conducted on a sample building with a floor area of 11,000 m² in Istanbul, five different HVAC system designs were compared. The systems were modeled three-dimensionally using the Revit software, and heating and cooling load calculations were performed using the Hourly Analysis Program (HAP). By including VRF systems among the compared alternatives, their advantages relative to other HVAC systems were systematically evaluated [18].

In another study, the applicability and system design criteria of water-cooled heat pump systems were investigated. Energy and exergy analyses were carried out for both summer and winter operating conditions. In addition, COP values were calculated for heating and cooling modes, and the factors influencing COP variation were examined [19].

A review of international journal publications indicates that studies on water-cooled VRF systems are predominantly focused on configurations integrated with cooling towers and chiller-based systems. Research in which the water source is directly utilized by the VRF outdoor unit remains relatively limited. In this context, international journals present significant potential for further studies on water-cooled VRF systems.

In a different study, the performance of a 2.4 MW capacity system installed in the French village of Brando was investigated. The experimentally conducted study compared COP values with those of conventional air-cooled systems. In addition, the carbon emission performance of the system was analyzed, highlighting its positive environmental impacts [20].

3. Results and Discussion

An examination of Table 1 indicates that the COP values of water-cooled VRF systems reach up to theoretically 7 and, in some studies, even attain levels theoretically 7–12. In contrast, air-cooled VRF systems, which serve as an alternative to water-cooled systems, exhibit COP values in the range of 3.5–5.5. The operation of the condenser in air-cooled VRF systems dependent on outdoor air temperature represents a disadvantage compared to water-cooled systems and leads to a reduction in COP values [21, 22].

In terms of energy-saving rates, air-cooled VRF systems generally provide savings in the range of 5–15%. Although these systems offer advantages over conventional HVAC solutions, they are often insufficient on their own to meet NZEB targets [23, 24]. In contrast, studies conducted on different building types (hotels, offices, and commercial buildings) have shown that water-cooled VRF systems can achieve energy savings in the range of 30–50%. It can therefore be stated that water-cooled systems have a strong potential to significantly reduce total annual energy consumption. Accordingly, the application of water-cooled VRF systems in NZEBs has been identified as a major advantage [25 – 27].

When Table 1 is analyzed in terms of building type, VRF cooling systems are observed to provide greater benefits in office and hotel buildings, while similar performance improvements are also reported for mixed-use buildings. Therefore, building types should be carefully considered in the selection of cooling systems. Another notable finding from the table is that, in studies directly related to NZEBs, the contribution of water-cooled VRF systems has been evaluated only in a limited number of studies. In this respect, the experimental and numerical investigation of water-cooled VRF systems in NZEBs can be considered an important research gap.

In NZEB technology, the selection of HVAC systems compatible with local climatic conditions is of critical importance. For instance, in regions where water-cooled VRF systems can be implemented, air-cooled systems should not be preferred [2].

Table 1. Indicator Values of Cooling Systems in Net Zero-Energy Building (NZEB) Applications

Ref	Year	Building Type	System Type	Capacity (kW)	Reported COP	Energy Saving (%)	NZEB Relevance
[6]	2009	Hotel	Water-Cooled VRF Air-Cooled VRF	881.469	8.39 3.42	50	Indirect
[16]	2019	Hotel	Seawater-Sourced Water-Cooled VRF	2200	4.9	34	Indirect
[17]	2013	-	Water-Cooled VRF	-	5.0	-	Indirect
[18]	2017	Mall	Water-Cooled VRF	759	7.0	10	Indirect
[19]	2023	-	Water-Cooled Heat Pump	25	6	4.4	Indirect
[20]	2023	Hotel	Sea Water Air Conditioning	18.000	12	-	Indirect
[28]	2023	-	Water-Cooled System	-	-	7	Indirect
[25]	2020	Commercial Building	Water-Cooled System	30	6.2	15	Indirect
[29]	2018	Multifamily Building	Water-Cooled System	-	6.7	11	Indirect
[23]	2016	Office Building	VRF heat pump	160	-	18	Indirect
[26]	2021	Office Building	Water-Cooled VRF	150	7.48	35	Indirect
[27]	2020	Research and Development Center	Water-Cooled VRF	350	5.0	30	Indirect
[13]	2025	Industrial poultry houses	Optimization of HVAC	-	-	9.62	Explicit NZEB
[14]	2026	Multifamily Building	Heat-recovery HVAC Systems Combined with Artificial Intelligence	-	-	25	Explicit NZEB
[15]	2025	Smart Buildings	VRF Systems and Optimization	-	-	30	Explicit NZEB
[30]	2022	-	Heat Pumps	-	-	30	Explicit NZEB
[21]	2022	Office Building	Air-Cooled VRF	10000	-	35	Explicit NZEB
[22]	2024	Residential Building	Air-Cooled VRF	12	-	5	Explicit NZEB
[24]	2021	Office Building	Air-Cooled HVAC System	-	-	5	Explicit NZEB
[31]	2025	University Buildings	Air-Cooled VRF	-	5.34	17	Explicit NZEB

In NZEB design, efficiency optimization of HVAC systems can influence overall building energy performance by up to 9.62% [13]. Furthermore, the use of heat-recovery HVAC systems combined with artificial intelligence–based optimization strategies can result in energy savings of up to 25% [14]. Therefore, in order to reduce energy consumption and carbon emissions, it is essential for countries to establish effective short- and long-term policies focusing on HVAC optimization, installation of high-efficiency air-conditioning systems, building insulation, renewable energy integration, and energy storage technologies [15].A study emphasizing the superior electrical energy performance of water-cooled VRF systems compared to air-cooled systems [6] evaluated summer operation by comparing electricity consumption relative to the cooling load met in August. According to the reported results, the water-cooled VRF system consumed 131,024 kWh of electricity to deliver 881,469.20 kWh of cooling energy during August. In contrast, an air-cooled VRF system was estimated to consume 265,290.74 kWh of electricity to meet the same cooling demand.

Based on these findings, it can be stated that the water-cooled VRF system is approximately twice as efficient as the air-cooled VRF system. Consequently, the investigated building can be inferred to exhibit significantly higher energy performance compared to conventional air-cooled systems.

Another notable advantage of water-cooled VRF systems is their ability, during winter operation, to transfer heat extracted from zones requiring cooling, such as fast-food areas—to spaces with heating demand. When this capability is considered, it can be concluded that although the building may not initially fall within the NZEB category, it could be relatively easily upgraded to NZEB status through the integration of appropriate renewable energy systems.

In a study parallel to the present work [16], a seawater-cooled VRF system installed in the Alanya district of Antalya was experimentally investigated, and the overall exergy efficiency of the system was evaluated. The results indicated that the highest exergy destruction occurred in the seawater heat exchanger, Bernoulli filter, and secondary circuit circulation pumps, whereas the lowest exergy destruction was observed in the VRF units. The total exergy efficiency of the seawater-cooled VRF system was calculated as 66.5%. These findings demonstrate that the building energy performance achieved by the seawater-cooled VRF system is superior to that of conventional air-cooled systems. Owing to the implementation of the water-cooled VRF system, it is expected that upgrading the building to net-zero energy building (NZEB) status can be achieved at more attainable costs [16].

In another study, it was reported that the COP values of water-cooled VRF systems can reach up to 5, and that their maintenance, repair, and operating costs are lower compared to systems such as fan-coil units. Furthermore, the system was described as having a long economic lifetime, low carbon emissions, and environmentally friendly characteristics, although its initial investment cost was noted to be relatively high [17].

A separate study focusing on investment costs concluded that although the initial investment cost of water-cooled VRF systems is higher than that of alternative systems, considering a fifteen-year payback period, the operating costs effectively decrease to near zero, resulting in a more efficient overall system [18]. From an NZEB perspective, achieving net-zero energy performance generally requires higher initial investment costs. However, for industrial and high-energy-demand buildings such as hotels, achieving the net-zero energy target can offset the initial investment over the long term, providing significant advantages in terms of operating costs.

In a study examining the COP characteristics of such systems, COP values were analyzed for both summer and winter operating conditions. Under winter operation, an increase in condenser temperature was found to result in a decrease in COP and an increase in exergy destruction. Conversely, during summer operation, an increase in evaporator temperature led to higher COP values and reduced exergy destruction. These findings emphasize that careful consideration of optimal operating temperatures is essential when utilizing water-cooled heat pump systems [19].

In a study conducted in Brando, a village in France, the use of deep ocean water for cooling applications in a representative facility was investigated, and it was emphasized that the installed cooling system achieved a COP value as high as theoretically 12. Such a high COP clearly demonstrates the potential of water-cooled cooling systems to reach exceptionally high efficiency levels. Although the system was not a direct application of a water-cooled VRF configuration, the findings underline the critical importance of utilizing water sources in HVAC systems. It should be noted that when deep-water sources are used, both water quality and temperature levels tend to be more favorable.

From an environmental perspective, the study reported that the water-cooled system resulted in annual carbon emissions of approximately 225 tons, whereas conventional systems produced around 860 tons of carbon emissions [20]. Given that many studies in the literature emphasize carbon emission reductions and consider the positive impact of net-zero energy buildings (NZEBs) on carbon mitigation, the present findings further highlight the importance of high-energy-performance buildings and HVAC systems, in line with the existing literature.

In another study investigating the potential of lake-water-cooled heating and cooling systems in Europe, it was reported that this potential corresponds to approximately 7% of the total heating and cooling capacity. Moreover, the carbon emission reduction benefits of lake-water-cooled systems were also emphasized [28].

Based on the holistic analysis of the data obtained from the studies presented in Table 1, water-cooled VRF systems represent a highly promising solution for NZEB design due to their high COP values and energy-saving potential of up to 30–50%. Considering the contribution of NZEBs to environmentally friendly and sustainable living, the application of water-cooled VRF systems in such buildings is regarded as a significant and advantageous approach.

Although several studies report exceptionally high COP values for water-cooled systems—occasionally reaching values in the range of theoretically 10–12—such results should be interpreted with caution. From a thermodynamic perspective, sustained COP values exceedingly approximately 6 are generally not achievable under standard operating conditions for heat pump and VRF systems. Reported extreme COP values are often associated with specific and idealized conditions, such as short-term measurements, partial-load operation, narrow system boundaries or highly favorable temperature differences between heat source and sink. Therefore, these values should be regarded as theoretical or case-specific upper limits rather than representative indicators of long-term or seasonal system performance. In practical applications, the realistic seasonal COP of high efficiency water-cooled VRF systems is typically expected to remain within a more limited range like 5-6 values.

Limitations of Water-Cooled VRF Systems

Despite their superior thermal performance, water-cooled VRF systems also present notable limitations that must be carefully considered, particularly in regions experiencing water stress. In arid and semi-arid climates, the availability of freshwater resources is increasingly limited, and the use of water for HVAC applications may conflict with domestic, agricultural, or industrial demands. Open-loop and cooling-tower-based systems are associated with continuous water losses due to evaporation and blowdown, which can significantly increase water consumption and operational complexity. In contrast, closed-loop systems mitigate water loss but require higher initial investment costs due to the need for heat exchangers, pumping systems, and water treatment infrastructure. Consequently, the environmental and economic feasibility of water-cooled VRF systems is strongly site-dependent, and their application may be constrained in regions where water conservation is a critical concern.

4. Conclusion

In this review study, water-cooled and air-cooled VRF systems used in NZEB applications were comparatively evaluated in terms of COP values, energy-saving rates, and system configurations. An examination of studies published between 2009 and 2026 indicates that water-cooled VRF systems offer significantly superior energy performance compared to air-cooled systems.

The findings of this review study demonstrate that reducing energy consumption requires minimizing energy use in buildings and prioritizing the design of self-sufficient, high-energy-performance net-zero energy buildings.

Accordingly, the present evaluation indicates that HVAC systems must be designed and engineered with a stronger emphasis on efficiency. In this context, the water-cooled VRF systems examined in this study generally exhibit COP values of approximately and theoretically 7-12. Based on these results, buildings equipped with water-cooled VRF systems can be expected to achieve high levels of energy performance. When compared to conventional air-cooled systems, which typically exhibit COP values in the range of 3.5–5.5, water-cooled VRF systems clearly offer significant advantages in terms of electrical energy consumption and operating costs.

Therefore, it was concluded that replacing air-cooled systems with water-cooled VRF systems in the design of nearly zero-energy buildings (NZEBs) would be highly beneficial. In addition, the use of water-cooled VRF systems can provide significant energy savings in facilities with high cooling energy demand.

As a result of this study, it was determined that design engineers should carefully evaluate the implementation of water-cooled VRF systems, particularly in buildings targeting NZEB status, due to their substantial energy-saving potential of up to 30–50% and the significant advantages they offer in terms of energy performance and environmental sustainability.

5. References

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