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Comparison between Variable and Constant Refrigerant Flow Air Conditioning Systems in Arid Climate: Life Cycle Cost Analysis and Energy Savings

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Abstract: All over the world, there is a call to encourage sustainable energy thinking and implementation. There is an urgent need to consider sustainable solutions in any design projects that are able to reduce energy consumption. In the heating, ventilation, and air conditioning field, the rise of the variable refrigerant flow systems has made big progress. This study presents a life cycle cost analysis to evaluate the economic feasibility of constant refrigerant flow (CRF), and in particular, the conventional ducted unit air conditioning system and the variable refrigerant flow (VRF) system by using detailed cooling load profiles, as well as initial, operating, and maintenance costs. Two operating hours scenarios are utilized and the present worth value technique for life cycle cost analysis is applied to an existing office building located in Qatar, which can be conditioned by CRF and VRF systems. The results indicate that, although the initial cost of the VRF system is higher than that of the CRF system by 23%, the present worth cost of the VRF system is much lower than that of the CRF system at the end of the lifetime due to lower operating costs. There is also a significant energy saving of 27% by using VRF compared to the CRF. The implementation of these results on a national scale will promote the use of sustainable energy technologies such as the VRF system.

Keywords: energy efficiency indicators; HVAC systems; energy savings; life cycle cost; building energy

Citation: Atallah, G.; Tarlochan, F. Comparison between Variable and Constant Refrigerant Flow Air Conditioning Systems in Arid Climate: Life Cycle Cost Analysis and Energy Savings. *Sustainability* **2021**, *13*, 10374. https://doi.org/10.3390/su131810374

Academic Editor: Giacomo Salvadori

Received: 1 September 2021
Accepted: 10 September 2021
Published: 17 September 2021

1. Introduction

Designing and selecting air conditioning systems involves many factors to be considered and these factors differ depending on the type of application. The primary goal in designing air conditioning systems is to provide thermal comfort with good indoor air quality while ensuring low energy consumption [1]. In a study published by the U.S. Department of Energy [2], it is mentioned that the buildings sector accounts for about 76% of the overall electricity consumption in the U.S. From this, the major energy consumption in these buildings is for heating, ventilating, and air conditioning, which accounts for 35% of the total building energy [2]. In arid countries, such as those in the Gulf Cooperation Council (GCC), most of the energy in the building (commercial and residential) is used for cooling due to the extreme high temperature climate during summer, which typically lasts around 8 months. Typical temperatures in the summer are in the high 40 °Cs to low 50 °Cs. Besides this, in the last two decades, countries in the GCC such as Qatar are experiencing a large expansion of commercial and residential buildings due to an increase in population and economic activities. This increases the electrical energy consumption per capita are shown in Figure 1 and reported in the literature [3]. In Qatar, the air conditioning accounts for around 60–70% of Qatar's total electricity demand [4]. In view of the high demand for electricity for cooling, it is important to increase the efficiency of building systems and technologies in order to reduce the overall demand for energy [2]. It is essential to select the most appropriate air conditioning system so that it can be used efficiently during its life cycle, keeping in mind that the energy sources are becoming scarcer around the world. One of the approaches that is worth considering is the usage of variable refrigerant flow systems (VRF) [5].

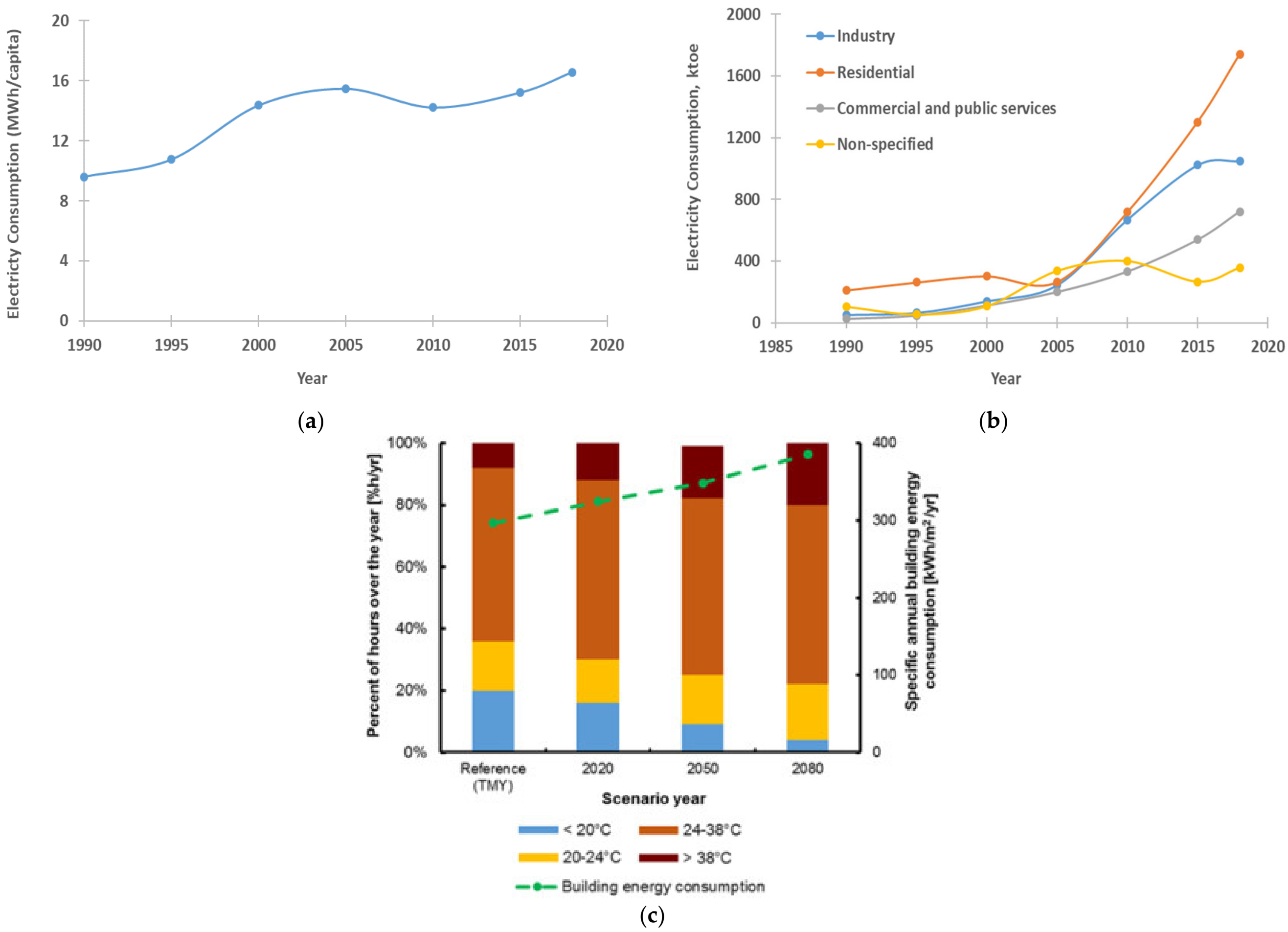

Figure 1. Electricity consumption in Qatar (**a**) per capita and (**b**) by sector; (**c**) climate and building energy demand modeling (image source: Andric et al., The results from climate and building energy demand modelling (30 August 2021), used under CC BY 4.0).

The indoor units of the air conditioning system in Qatar consists of constant air volume (CAV) and variable air volume (VAV). In CAV, the machine supplies the same quantity of air to the conditioned area (single-zone application), whereas in VAV, the tenants can control the temperature inside the room by reducing or increasing the air volume accordingly (multi-zone application where there are constant changing loads). Both systems can be used in ducted units and in package units and both systems are used in commercial and residential buildings in Qatar. The current work in this paper is looking from the refrigerant side of the cooling system, thus comparing the constant refrigerant flow (CRF) unit against the variable refrigerant flow (VRF) unit.

The VRF system can be best explained by using Figure 2. The system consists of multiple indoor units (IU), an outdoor unit (OU), and a variable speed controller. The electronic expansion valve (EEV) controls the mass flow rate in each of the indoor units. The electronic expansion valve (EEV) plays an important role in regulating the refrigerant flow rate through the heat exchanger of the indoor unit, while the inverter-driven variable speed compressors allow for a larger modulation capacity considering part load factors in the VRF systems. The VRF system allows each IU to be controlled independently and does not lose too much energy through ductwork like conventional systems [5]. Such VRF systems have been used widely in Japan since the 1980s and in the U.S. since 2002 [5]. An initial review on

VRF systems was done by Aynur [6], who looked at the VRF system from the experimental and modeling perspective. It was reported that the VRF system has a high initial cost compared to the common air conditioning systems; however, due to the energy saving potential, the estimated payback period of the VRF system compared to conventional chiller system in a generic commercial building could be about 1.5 years. In another study, Patel et al. [7] reported that VRF could fetch energy savings between 10% and 40%. Regarding VRF system responsiveness, Herdendez [8] reported that responsiveness and sensitivity are related to the quantity of indoor evaporators that are connected to the system. A lot of other works have been done with the VRF system in terms of the system architecture [9–11], modeling and simulation [12–18], and experimental work and field testing [6,19–23]. The work surrounding VRF system architecture has looked at performance improvement and integrated system design. It was found that one of the significant benefits of this system is its flexibility. Future work on VRF architecture needs to focus on efficient ventilation methods. In the area of modeling and simulation, research areas are centered on steady state and transient models, as well as empirical and component-based modeling. It was found that there is a need for more user-friendly dynamic models that are easy to be implemented, focusing on empirical dynamic models as the way forward. There is also a need to standardize the different simulation tools being used. Most of the experimental testing using VRF was conducted in Asia and was focusing on the cooling mode. This is because of the hot and humid weather in most of these Asian countries where the studies were conducted. There is still room to evaluate physical performance of VRF in terms of system stability and defrosting.

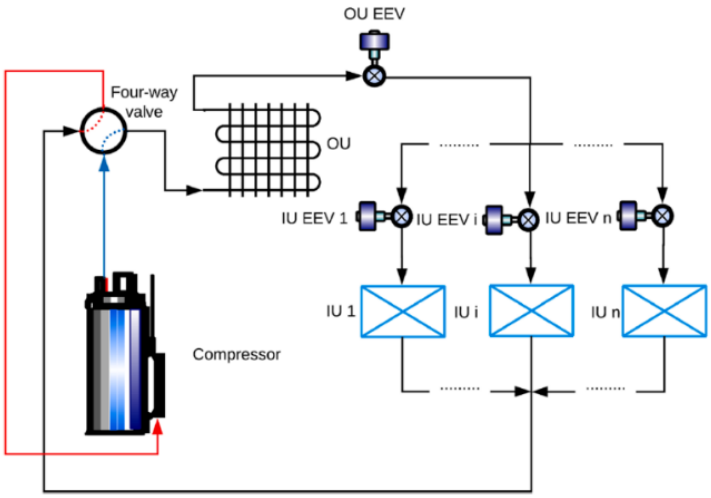

Figure 2. Simplified VRF diagram [5].

Most of the reported work pertaining to VRF is done in Asia (Japan and China in particular), Europe, and the U.S. To the best of authors knowledge, not much work in terms of VRF systems has been conducted in arid regions such as the GCC countries. In such hot climates, a lot of energy is consumed from conventional air conditioning systems and the usage of the latest technology is important to reduce the energy demand for cooling [24–26]. In view of this, and as an initial step in this direction, the objective of this study is to prove the economic feasibility of the VRF system over the conventional system in cooling mode only, especially for the countries with hot climates such as Qatar. The cooling process is very crucial for such countries while the heating demand is negligible. The paper is organized as follows: In Section 2, the current case is discussed in detail. The building characteristics are listed and the conventional CRF system using traditional ducted units is explained. Then, the VRF technology is explained, and a VRF system is modeled to the existing office building while the same indoor units' capacities are kept, so that the results remain accurate while comparing the energy consumption of the condensers between both systems. In Section 3, the discussion and the results are provided. In the final section, the conclusive remarks are stated.

2. Materials and Methods

For the purpose of conducting a comprehensive life cycle cost analysis based on CRF and VRF, an existing building in Qatar was selected. The name of the building is Al Muftah Plaza located in the city of Doha (Figure 3). This building has two basements, a ground floor and five floors above ground. The total built up area is 18,102 m^2 while the rentable area is 10,715 m^2. The ground floor consists of two car showrooms covering an area of 1475 m^2, while the upper floors consist of four offices each with an area of 1802 m^2. The height of the ground floor is 3.5 m from the finished floor level to the false ceiling level and 1.1 m from the false ceiling level to the upper slab level. In the five upper floors, the height is 3.2 m between the two slabs, out of which 0.5 m is between the false ceiling and the upper slab. The two basements provide a parking space for 125 cars without any cooling services except for the elevator lobbies, which are served by independent split units. The most widely used air conditioning system in commercial and residential buildings (below 10 floors) in Qatar is the traditional ducted unit system, which connects one outdoor unit to one indoor ducted unit.

Figure 3. Case study building (Al Muftah Plaza).

The operating principal of this air conditioning system is very simple, as shown in Figure 4. To cool the air inside a room, the compressor sucks low-temperature and low-pressure refrigerant gas, and with the help of a heat exchanger and a fan, it discharges high-temperature and high-pressure gas into the surrounding outdoor area and becomes high-pressure refrigerant liquid after transferring the latent heat. Then, a throttling element, usually an expansion valve, changes the high-pressure refrigerant liquid into low-temperature and low-pressure liquid and goes into the indoor heat exchanger. The internal fan helps the liquid evaporates and transforms into low-temperature and low-pressure refrigerant gas. The cycle continues to operate as long as there is a cooling demand. In this traditional system, there is a constant flow of refrigerant. It is an "on" and "off" mechanism so that when the compressor is performing its job, the entire refrigerant quantity is used in the process, whether the load is big or small, as long as there is a temperature difference and a need for cooling.

The VRF system allows us to connect multiple indoor units to a single outdoor unit or multiple ones if needed. The indoor units can vary between split, cassette, ducted, and other type of equipment [6]. In general, there are two piping configurations in a VRF system: the two-way and the three-way configuration. For this case study model, the cooling mode using only the two-way piping was studied, because the other configuration is generally used when there is a need for cooling and heating at the same time (Figure 5).

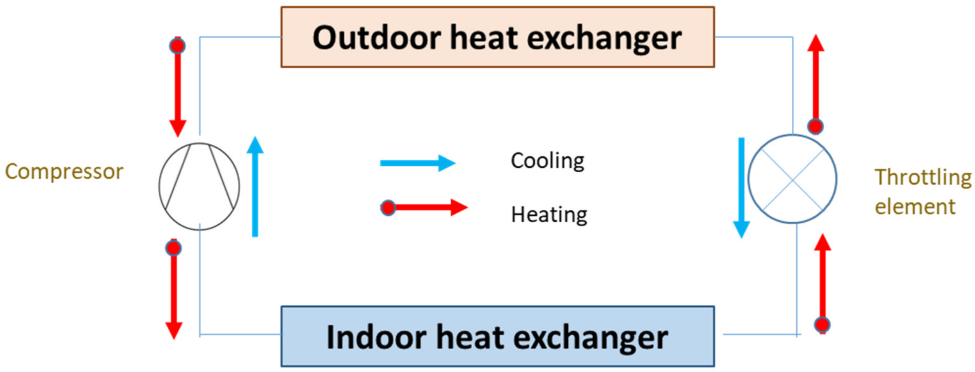

Figure 4. Conventional operating system.

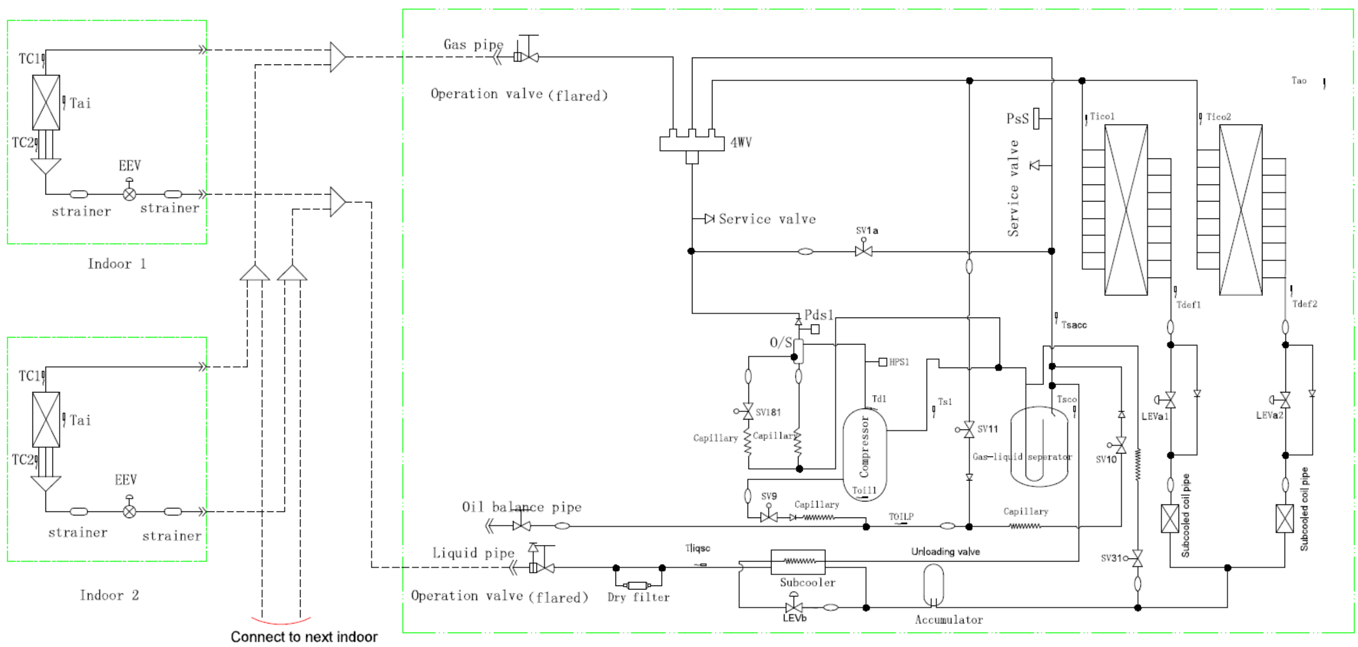

Figure 5. VRF system components.

In the model used here, a VRF system for each office is considered. It comprises outdoor units depending on the total cooling capacity needed and indoor units as per the office layout. The total cooling system of one system cannot exceed 50 tons of refrigeration (TR) as per the manufacturer's catalog. Two dedicated systems for all the common areas, such as corridors and elevator lobbies, were designed. Ducted indoor units were selected equal to CRF in order to focus the analysis on comparing the CRF and VRF outdoor units particularly in terms of energy savings, and generally in terms of life cycle cost analysis. In the following sections and after conducting a detailed heat load analysis, all the VRF system components were selected in detail. In this study, the ASHRAE Transfer Function Method (TFM) [27,28] was used for the calculation of the cooling load by using the well-known Hourly Analysis Program (HAP 4.9) [29–31] by Carrier (Carrier, Palm Beach Gardens, FL, USA), a company that provides solutions for air conditioning. The TFM method is a derivative of the Heat Balance Method and can predict the hourly cooling load of Al Muftah Plaza building. The heat transfer coefficients used in our study are listed in Table 1. For the cooling load estimation, it was assumed that the 'design day' is when there is relatively high humidity, little or no haze, and all internal loads are at their peak, which corresponds to the month of July. The HAP software utilizes the following input data before running the simulation: (1) climate data surrounding the building of interest; (2) information on the building material, such as that shown in Table 1; (3) the orientation of the building; (4) interior heat gain characteristics; (5) data on the HVAC system; (6) electricity tariff and energy source.

Table 1. Values of the heat transfer coefficient (U).

	Heat Gain Sources	U-Value (W/m^2·K)
1	Wall	7.271
2	Glass	18.96
3	Door	9.67
4	Roof	2.94
5	Partition	16.12

3. Results and Discussions

3.1. Cooling Loads

Hourly cooling loads of the sample building were calculated to determine the total cooling load required and to size the air conditioning system. After considering the external and internal heat parameters, the following total cooling load requirements were obtained, and they are divided into two groups: (a) rentable areas and (b) common areas. The cooling loads that were calculated are tabulated in Tables 2 and 3 for rentable areas and common areas, respectively. The maximum cooling load required for the building is 466 TR, having its peak in the month of July, and that is the basis of the design.

Table 2. Required cooling load (rentable areas).

Floor	Area	Calculated Capacity (TR)
Ground Floor	Showroom-01	19.9
	Showroom-02	27.9
First Floor	Office-1	23
	Office-2	7.2
	Office-3	24.1
	Office-4	16.7
Typical Floor—2nd to 4th Floor	Office-1	69
	Office-2	21.6
	Office-3	72.3
	Office-4	50.1
Fifth Floor	Office-1	23
	Office-2	7.2
	Office-3	24.1
	Office-4	16.7

Table 3. Required cooling load (common areas).

Floor	Area	Calculated Capacity (TR)
Ground Floor	Main Entrance Lobby	10.6
First Floor	Hallway With Male And Female W.C	10.4
Second Floor	Hallway With Male And Female W.C	10.4
Third Floor	Hallway With Male And Female W.C	10.4
Fourth Floor	Hallway With Male And Female W.C	10.4
Fifth Floor	Hallway With Male And Female W.C	10.4

Since this is an existing building, the installed units were checked and the data from the manufacturer was taken and is combined in Tables 4 and 5 to compare against the calculated heat load in HAP (Tables 2 and 3) and to be able to calculate the electrical cost of operations during our study. The total cooling load selected with the ducted units is 4% higher than the calculated load, which is acceptable and considered as a safety factor.

Table 4. Existing ducted units (rentable areas).

Floor	Area	QTY	Selected Capacity (TR)	Total Capacity (TR)
Ground Floor	Showroom-01	6	3.31	19.86
	Showroom-02	7 1	3.96 1.31	27.72 1.31
First Floor	Office-1	4 3	3.96 2.99	15.84 8.97
	Office-2	2	3.96	7.92
	Office-3	6 1	3.96 1.94	23.76 1.94
	Office-4	5	3.31	16.55
Typical Floor—2nd to 4th Floor	Office-1	12 9	3.96 2.99	47.52 26.91
	Office-2	6	3.96	23.76
	Office-3	18	3.96	71.28

Table 5. Existing ducted units (common areas).

Floor	Area	QTY	Selected Capacity (TR)	Total Capacity (TR)
Ground Floor	Main Entrance Lobby	2	1.63	3.26
		1	3.31	3.31
First Floor	Hallway With Male And Female W.C	1	3.96	3.96
		2	3.31	6.62
Second Floor	Hallway With Male And Female W.C	1	3.96	3.96
		2	3.31	6.62
Third Floor	Hallway With Male And Female W.C	1	3.96	3.96
		2	3.31	6.62
Fourth Floor	Hallway With Male And Female W.C	1	3.96	3.96
		2	3.31	6.62
Fifth Floor	Hallway With Male And Female W.C	1	3.96	3.96
		2	3.31	6.62

For the purpose of this study, the data sheets provided from York products from Johnson Controls were used for the VRF units, and the selection is shown in Tables 6 and 7 along with the cooling capacities for both indoor units, which are matching with the ducted units and the outdoor units. It is clear that for multiple indoor units there is an outdoor VRF unit, and the combination ratio was kept as close as possible to 100% for the sake of having a fair comparison between the two systems. However, in real life, the VRF systems can allow for a combination ratio up to 130% depending on the projects' requirements and the manufacturer's recommendations. This will increase the energy savings of the system.

Table 6. VRF selection (rentable areas).

Floor	Area	Quantity VRF Indoor Units	Capacity (TR)	Total Capacity (TR)	Quantity VRF Outdoor Units	Cooling Capacity (TR)	Total Capacity (TR)	Ratio (%)
Ground Floor	Showroom-01	6	3.33	19.98	1	19.36	19.36	101.2
	Showroom-02	7 1	3.75 1.73	26.25 1.73	1	26.3	26.3	101.8
First Floor	Office-1	4 3	3.75 2.81	15 8.43	1	23.88	23.88	98.8
	Office-2	2	3.75	7.5	1	8.19	8.19	90.8
	Office-3	6 1	3.75 1.9	22.5 1.9	1	24.51	24.51	99.8
	Office-4	5	3.33	16.65	1	17.06	17.06	99.5
Typical Floor—2nd to 4th Floor	Office-1	12 9	3.75 2.81	45 25.29	3	23.88	71.64	98.8
	Office-2	6	3.75	22.5	3	8.19	24.57	90.8
	Office-3	18 3	3.75 1.9	67.5 5.7	3	24.51	73.53	99.8
	Office-4	15	3.33	49.95	3	17.06	51.18	99.5
Fifth Floor	Office-1	4 3	3.75 2.81	15 8.43	1	23.88	23.88	98.8
	Office-2	2	3.75	7.5	1	8.19	8.19	90.8
	Office-3	6 1	3.75 1.9	22.5 1.9	1	24.51	24.51	99.8
	Office-4	5	3.33	16.65	1	17.06	17.06	99.5

Table 7. VRF selection (common areas).

Floor	Area	Quantity VRF Indoor Units	Capacity (TR)	Total Capacity (TR)	Quantity VRF Outdoor Units	Cooling Capacity (TR)	Total Capacity (TR)	Ratio (%)
Ground Floor	Main Entrance Lobby	2 1	3.75 3.33	7.5 3.33				
First Floor	Hallway With Male And Female W.C	1 2	3.75 3.33	3.75 6.66	1	31.61	31.61	99
Second Floor	Hallway With Male And Female W.C	1 2	3.75 3.33	3.75 6.66				
Third Floor	Hallway With Male And Female W.C	1 2	3.75 3.33	3.75 6.66				
Fourth Floor	Hallway With Male And Female W.C	1 2	3.75 3.33	3.75 6.66	1	31.61	31.61	97.7
Fifth Floor	Hallway With Male And Female W.C	1 2	3.75 3.33	3.75 6.66				

3.2. Life Cycle Cost Analysis

The life cycle cost (LCC) analysis adopted in this paper is very similar to that reported in the literature [32–37]. The net present value (NPV) is adopted in this paper to determine the LCC for both refrigeration systems. In order to have an accurate and fair comparison between the two air conditioning systems, a lifetime of 15 years was considered, and all the costs were taken into account, including initial, operating, and maintenance costs. The initial investment cost covers the main equipment of both systems such as the CRF and VRF units. Additionally, it covers the ducting, piping, insulation, dampers, grills and diffusers, and other accessories. The summary of the initial investment cost is tabulated in Table 8. The cost of diffusers and ducting works are the same since the same indoor unit quantities and capacities were selected in both systems. The VRF system is 23% more expensive than the traditional CRF system.

Table 8. Initial investment cost.

	CRF Cost (QAR)	**VRF Cost (QAR)**
CRF equipment	720,000	
VRF equipment		1,289,000
Ducting/dampers/insulation	902,000	902,000
Piping + insulation	373,000	350,000
Diffusers	387,000	387,000
Total	**2,382,000**	**2,928,000**

In this study, the outdoor units of both systems were compared and the indoor units were neglected since their electrical consumption is minimal compared to the outdoor units, and the same indoor units' capacities in both systems were kept. Hence, the variation in the fans' speed that is dependent on the cooling load is the same for the two type of systems and it was thus not considered in this study. First, the total power input required for the outdoor units of the CRF system was calculated to be 635 kW using the manufacturer's datasheets. These numbers correspond to 100% of the cooling load capacity, since it is a constant refrigeration flow system as explained earlier.

Then, the power input for the VRF outdoor units was calculated at 100%, 75%, 50%, and 25% of cooling capacity, as shown in Table 9. Linear interpolation was also used to obtain the needed power input at these precise percentages. Based on the Air-Conditioning, Heating, and Refrigeration Institute (AHRI), the VRF units run on 100% load for 2% of the time only, while for the 75%, 50%, and 25% loads, they run 61.7%, 23.8%, and 12.5% of the time, respectively [38]. Most of the weight exists within the 50% and 75% loads with 85.5% of running hours. This is the main benefit of the VRF technology is using the variable speed compressors.

Table 9. Power input for VRF outdoor units (kW).

Load	**100%**	**75%**	**50%**	**25%**
Power Input (kW)	581.82	402.17	234.84	49.93

For this study, two operational scenarios are considered. The first scenario covers 12 h of air conditioning while the second covers 24 h, which is the case in Qatar, especially in the long summer season. The buildings cannot be left without air conditioning even at nighttime because of the high temperature and humidity. The average tariff obtained from Kahramaa (local power company, Kahramaa, Doha, Qatar) is 0.18 QAR per kWh, and it was used to calculate the total operating cost of the CRF and VRF systems in both scenarios. The air conditioning machines function 12 months per year, 25 days per months, and 12 h per day for the first scenario, and 24 h per day for the second scenario. The running time of the ducted units is 70% considering that the compressor rests once it reaches the set temperature point and restarts again when the inside temperature rises [39]. The operating cost is calculated by using the following formula:

$$\text{Operating cost} = \text{sum of (weight} \times \text{running hours)} \times \text{Tariff} \tag{1}$$

The details of the operating cost for both scenarios are tabulated in Tables 10 and 11. The operating cost of the CRF is 38% higher than the VRF for both scenarios. Next, the maintenance cost is added and then the present worth value is used to determine the payback time over the years. The manpower needed to perform the maintenance works for both systems are almost identical because the number and capacities of indoor units are the same. Therefore, the cost of maintenance and spare parts used are the same except for the outdoor units, since the number of CRF outdoor units is 137 compared to 24 outdoor units for the VRF system. There is an additional cost of 18,000 QAR for the CRF system due to failing compressors per year [39].

Table 10. Operating cost (Scenario 1).

Scenario 1 (12 h)					Operating Cost (QAR)	
Loading	**Weightage**	**Running Hours per Year**	**kWh VRF**	**kWh CRF**	**VRF**	**CRF**
100%	2%	72	41,891	1,598,842	208,597	287,792
75%	61.70%	2221	893,300			
50%	23.80%	857	201,211			
25%	12.50%	450	22,469			
Total		**3,600**	**1,158,870**	**1,598,842**		

Table 11. Operating cost (Scenario 2).

Scenario 2 (24 h)					Operating Cost (QAR)	
Loading	**Weightage**	**Running Hours per Year**	**kWh VRF**	**kWh CRF**	**VRF**	**CRF**
100%	2%	96	55,855	2,131,789	278,129	383,722
75%	61.70%	2962	1,191,067			
50%	23.80%	1142	268,281			
25%	12.50%	600	29,958			
Total		**4800**	**1,545,161**	**2,131,789**		

The initial, operating, and maintenance costs for the two systems are developed in this study. A life cycle cost (LCC) analysis allows us to compare the CRF and VRF systems. The life of each system is considered to be 15 years. LCC analysis is based on the following interest and inflation rates, as depicted in Table 12. The present worth cost technique is used to compare the total costs (initial, operating, and maintenance) of the two alternative systems (CRF and VRF) taking into account the two operating scenarios (Scenarios 1 and 2) over the 15 years period.

Table 12. Sensitivity analysis of varying inflation and interest rates.

Analysis Type									
Rate Category	A1	A2	A3	A4	A5	A6	A7	A8	A9
Inflation (%)	0	3	6	0	3	6	0	3	6
Interest (%)	3	3	3	4.65	4.65	4.65	7	7	7

An example of variation of overall present worth costs for both systems is shown in Figures 6 and 7 for representation purposes. Based on Table 12, for Scenario 1 (12 h operation) the present worth cost for the VRF system is 7–15% lower if compared to the CRF system, and for Scenario 2 (24 h operation), the present worth cost for VRF system is 10–18% lower if compared to the CRF system. For longer operating hours, the VRF system shows a bigger advantage. The VRF cost is higher at the beginning, but after a certain number of years (approximately after 5 years) the VRF system becomes more economically efficient. The VRF system consumes less power input than the CRF system by 27% for both scenarios.

This reduction can have a significant impact on a national level when implementing green building techniques such as the VRF technology in the air conditioning industry. The impact of the reduction in energy consumption due to VRF technology implementation can be appreciated through visualizing it through CO_2 reduction [40]. In the equivalency calculator, the energy reduction can be converted to carbon dioxide-equivalent greenhouse gas emissions reduction. Details of this benefit are shown in Figure 8. In summary, by using VRF over CRF, an equivalent amount of 311,820 kg of CO_2 greenhouse gas can be reduced.

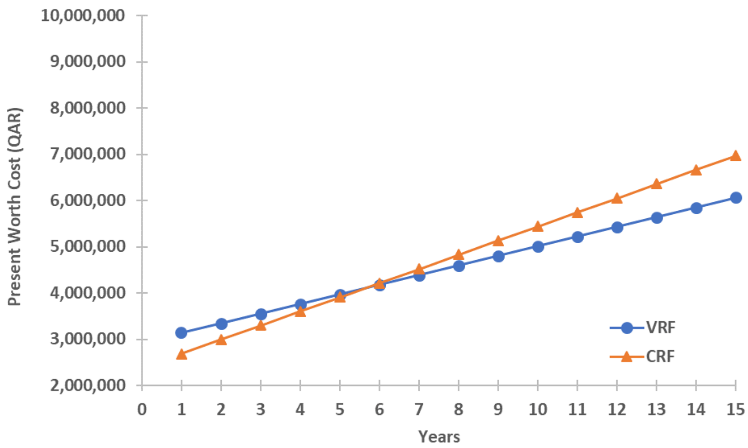

Figure 6. Present worth cost for Scenario 1—12 h running (interest rate 3%, inflation rate 3%).

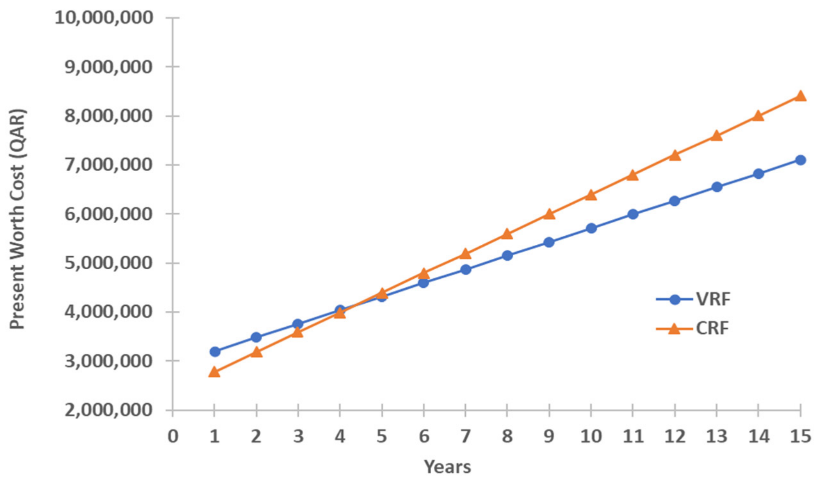

Figure 7. Present worth cost for Scenario 2—24 h running (interest rate 3%, inflation rate 3%).

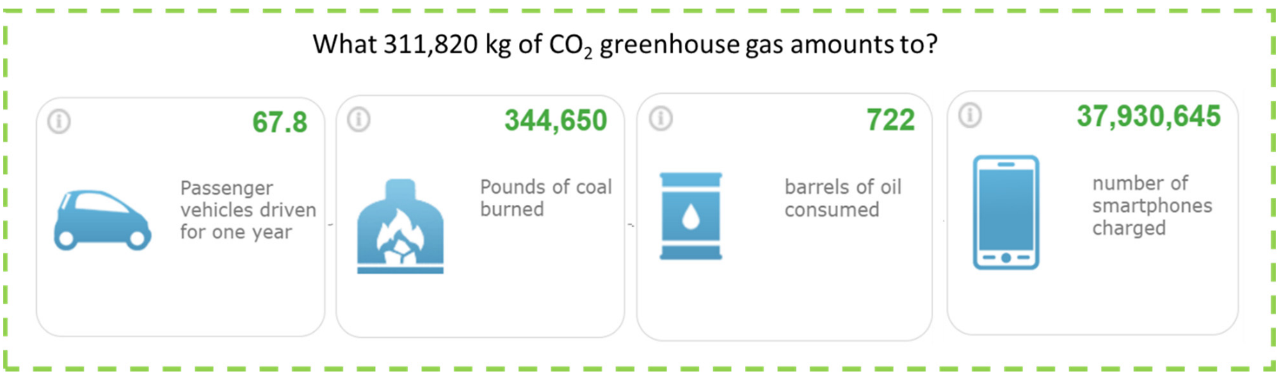

Figure 8. The amount of CO_2 reduction due to utilization of VRF technology in one building (case study).

4. Conclusions

When comparing the VRF and CRF systems in this study, the initial, operating, and maintenance costs were calculated for Al Muftah Plaza building in Qatar. The present worth cost method and the LCC analysis were used for two different scenarios. For Scenario 1 (12 h operation), the present worth cost for the VRF system is 7–15% lower if compared to the CRF system, and for Scenario 2 (24 h operation), the present worth cost for the VRF system is 10–18% lower if compared to the CRF system. For longer operating hours, the VRF system shows a bigger advantage. The VRF cost is higher at the beginning, but after a certain number of years (approximately after 5 years) the VRF system becomes more economically efficient. The power input needed for the VRF system is 27% lower than the CRF system, which can make a tremendous impact on a national level when sustainable energy methods are implemented such as the VRF technology. An equivalent amount of 311,820 kg of CO_2 greenhouse gas is reduced by changing from CRF to VRF technology. VRF technology provides energy savings because the system consists of (1) a variable speed air cooling compressor, (2) reduced fan energy due to reduced ductwork, and (3) dedicated outside air systems with energy recovery [41]. Such new technologies like VRF should be investigated further to identify potential barriers to the market. As such, the next step forward is to investigate the usage of VRF in residential buildings and to develop strategies for implementing VRF systems.

Author Contributions: G.A.: Method Investigation, Computation, Implementation, Writing—Original Draft and Drawing. F.T.: Conceptualization, Methodology, Writing—Original Draft and Revision, Supervision. Both authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge Al Muftah Contracting Company W.L.L. company (Doha, Qatar) for assisting this research in terms of providing useful field data and the usage of the transfer function method (TFM) through the software Hourly Analysis Program (HAP) by Carrier. The authors would also like to thank Qatar National Research Foundation (QNRF) (Doha, Qatar) for funding the open access fees for the publication of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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