QATAR UNIVERSITY

COLLEGE OF ENGINEERING

POSSIBLE USAGE OF VARIABLE REFRIGERANT FLOW IN ARID CLIMATE:

TECHNICAL AND MANAGEMENT PERSPECTIVE

BY

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ABSTRACT

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Title: <u>Possible Usage of Variable Refrigerant Flow in Arid Climate: Technical and Management Perspective</u>

Supervisor of Thesis: Faris, Tarlochan.

All over the world, there is a call to encourage sustainable energy thinking and implementation. In the heating, ventilation and air conditioning field, the rise of the variable refrigerant flow systems has made a big progress throughout the years. This study presents a life-cycle cost analysis to evaluate the economic feasibility of constant refrigerant flow (CRF) in particular the conventional ducted unit air conditioning system that is widely used in Qatar and the variable refrigerant flow (VRF) system. Detailed cooling load profiles will be used for the existing units and the new VRF model in addition to initial, operating, and maintenance costs.

Two operating hours scenarios are utilized to consider 12 and 24 operating hours 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, the present-worth cost of the VRF system is lower than that of the CRF system at the end of the lifetime due to lower operating costs.

The implementation of these results on a national scale will promote the use of sustainable energy technologies such as the variable refrigerant flow system to reduce the energy consumption in Qatar and to improve the national power grid utilization, efficiency, and expansion in the coming years.

DEDICATION

This paper is dedicated to my life partner, Edith, who has been a constant source of encouragement during the challenges of life, work, and graduate school during the Covid-19 pandemic. This work is also dedicated to my parents who have always loved me unconditionally and to my office colleagues for their continuous support.

ACKNOWLEDGMENTS

I would like to acknowledge the support of Qatar University for providing all the needs to achieve the requirements of this study.

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CHAPTER 1 – INTRODUCTION

1.1 Background of the Study

Designing and selecting air-conditioning systems involves a lot of factors to be considered and these factors differ depending on the type of application. Some projects require external maintenance works only so the air conditioning system to be used can be the packaged unit type. Others impose a restriction in terms of outdoor surface area so the suggested system can be the water chiller type or the variable refrigerant flow type as part of the direct expansion units.

These are the major categories of air conditioning systems that can be utilized:

a- Chilled water type such as chillers and fan coil units

b- Direct expansion type:

- Split units
- Ducted units
- Package units
- Variable refrigerant flow units

The most important goal in designing air-conditioning systems is to deliver thermal comfort with decent indoor air quality in terms of air flow, temperature, humidity and noise while ensuring low energy consumption [1]. Many opportunities for improvement can be made and the most important five basic categories are shown below:

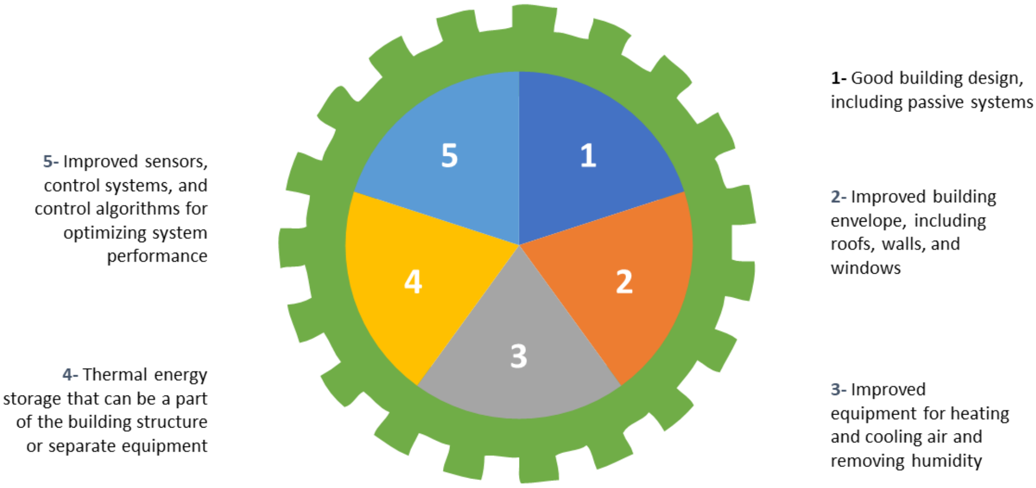

Figure 1 Five basic categories for thermal comfort improvement

In a study published by the Department of Energy, USA [2], it is mentioned that the buildings sector constitutes about 76% of overall electricity consumption in USA. From this, the major energy consumption in these buildings is for heating, ventilation, and air conditioning which accounts for 35% of overall building energy [2].

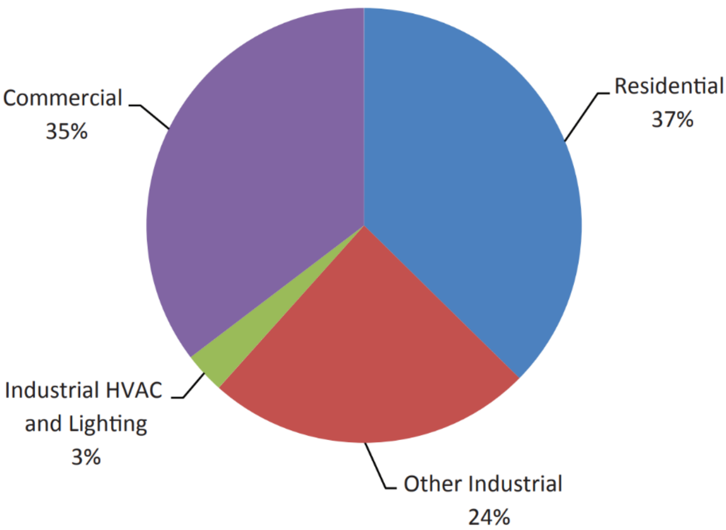

Figure 2 Electricity sale for buildings in the USA (2014) [2]

In our study, we are going to investigate constant refrigerant flow systems

(CRF) such as the ducted unit type and variable refrigerant flow systems (VRF) in Qatar.

1.2 CRF System

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 is 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.

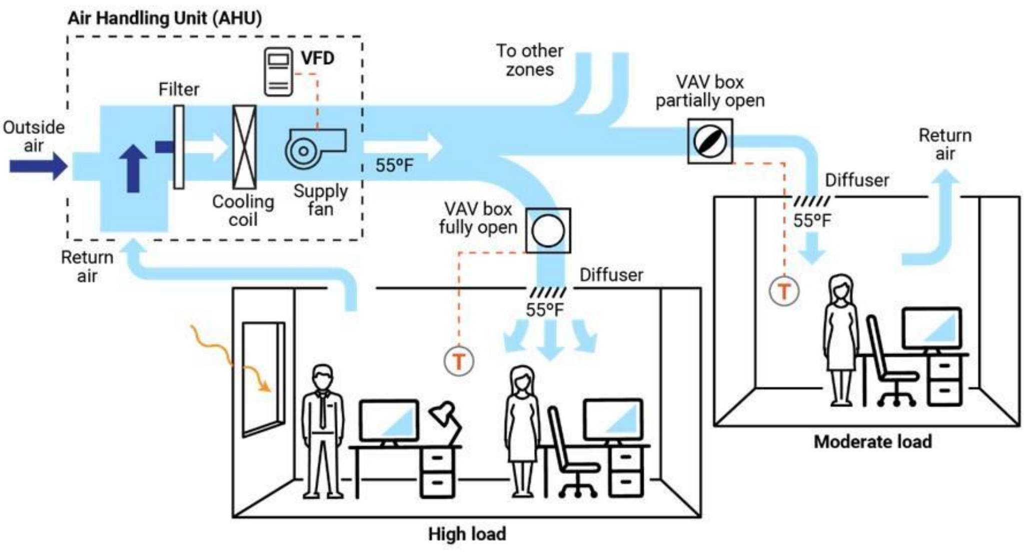

Figure 3 Typical VAV-based distribution system [25]

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 variable refrigerant flow unit (VRF).

The most frequently installed air conditioning system in residential and commercial buildings (below 10 floors) in Qatar is the traditional ducted unit system which joins one outdoor unit to one indoor ducted unit as shown in Fig.4.

Figure 4 Ducted system components [25]

The operating principal of this air conditioning system is very simple as shown in Fig.5. 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 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.

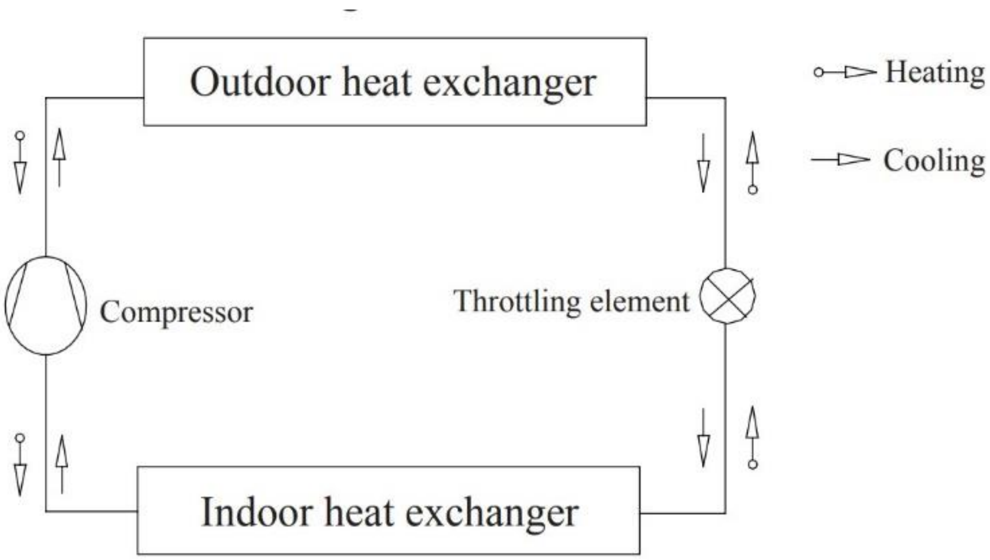

Figure 5 Conventional operating system [25]

1.3 VRF System

The VRF system can be best explained by using Fig. 6. The system comprises several 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 IU. The electronic expansion valve EEV is crucial in regulating the flow rate of the refrigerant through the heat exchanger of the indoor unit while the inverter driven variable speed compressors allow a larger variation capacity considering part load factors in the variable refrigerant flow systems. VRF system allows each IU to be controlled independently and does not consume considerable energy within the ductwork as the traditional systems [5].

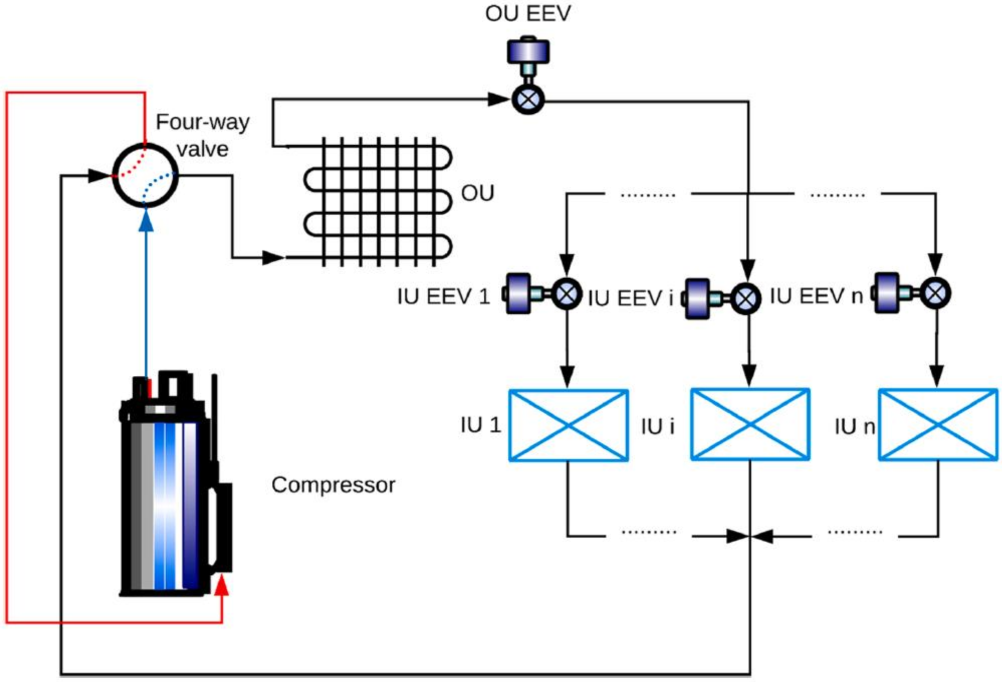

Figure 6 Simplified VRF diagram [25]

The VRF system as shown in Fig.7 allows us to connect several 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. For this case study model, the cooling mode only using the two-way piping is studied while the other configuration is used when there is a need for heating and cooling simultaneously (Fig.8). The quantitative study will be based on the cost incurred by using the two-way piping system only.

Figure 7 VRF system components [25]

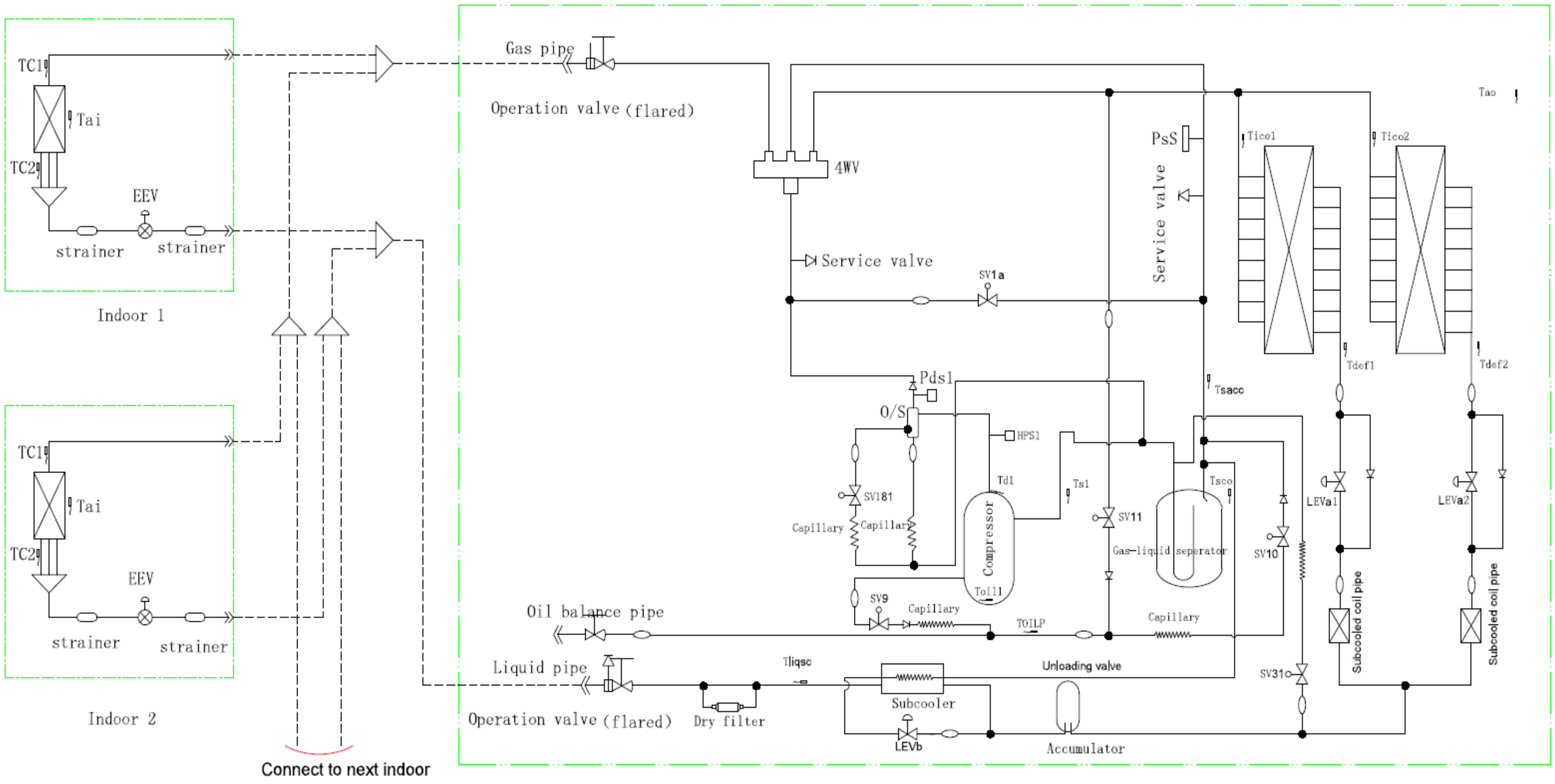

Figure 8 Two way piping diagram [25]

1.4 Problem Statement

In arid countries such as countries 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 in summer which typically last 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 GCC such as Qatar is experiencing a large expansion of commercial and residential buildings due to increase in population and economic activities. This increases the electrical energy consumption per capita as shown in Fig.1 and as reported in literature [3]. In Qatar, the air conditioning accounts for around 60 - 70 % of the Qatar's total electricity demand [4].

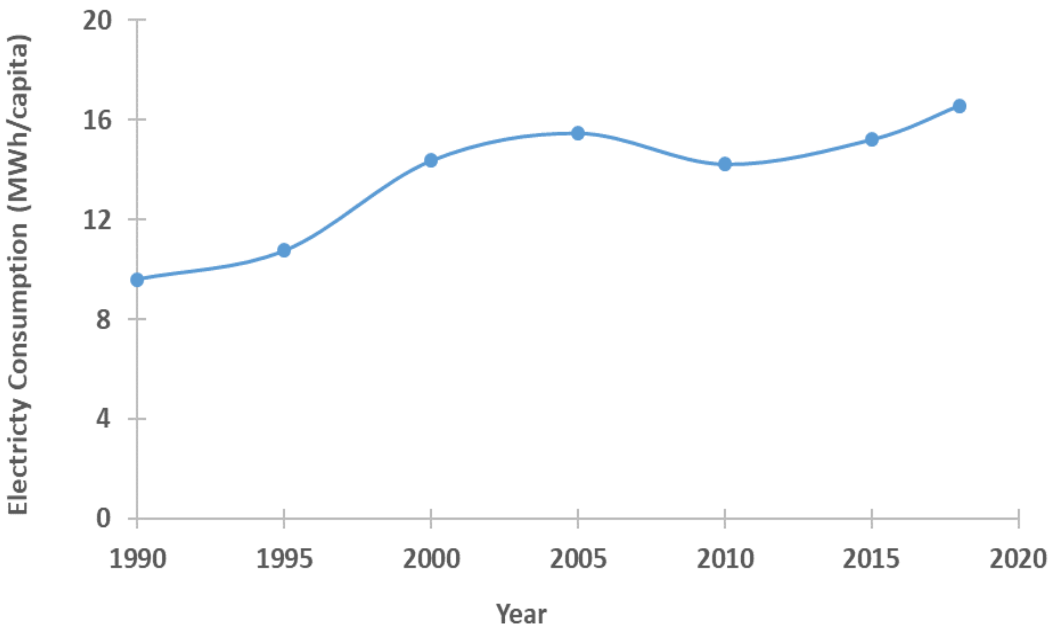

Figure 9 Electricity consumption in Qatar per capita [3]

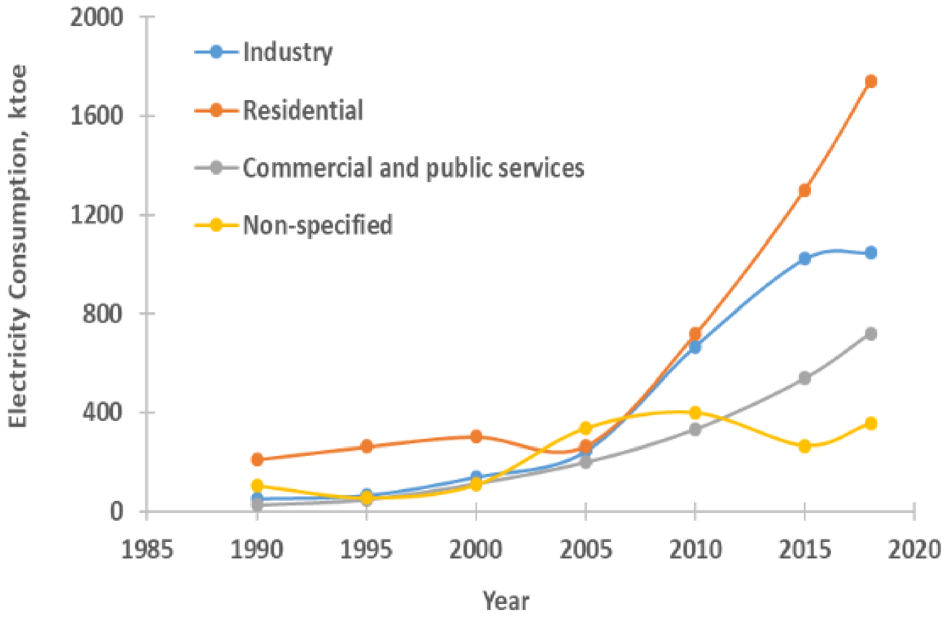

Figure 10 Electricity consumption in Qatar per sector [3]

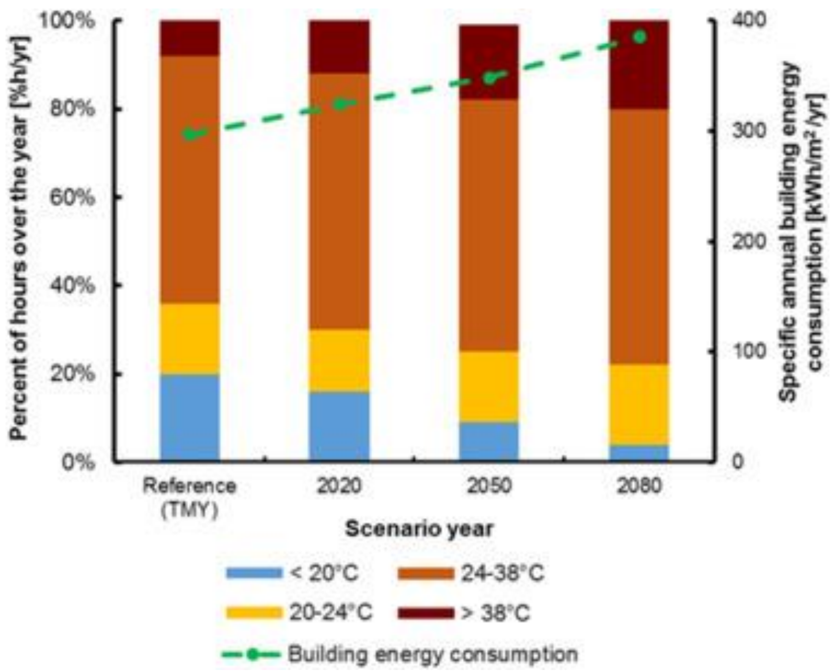

Figure 11 Climate and building energy demand [3]

1.5 Aims and Objectives

In view of high demand in electricity for cooling, it is important to increase the efficiency of building systems and technologies with the objective of reducing the overall demand for energy [2]. It is essential to opt for the most suitable 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].

Most of the reported work pertaining to VRF is done in Asia (Japan, China in particular), Europe and USA. To the best of the authors' knowledge, not much work on VRF systems was conducted in arid regions such as the GCC countries.

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 variable refrigerant flow system over the conventional system in cooling mode only especially for the countries with hot climate such as Qatar. The cooling process is very crucial for such countries while the heating demand is negligible.

1.6 Significance of the Study

Identifying and applying sustainable energy sources for the cooling purpose is very crucial towards achieving Qatar's vision 2030. Such practices have a great impact on the environmental level as well as on the national budget related to the power grid infra structure. Another significant importance is the lack of studies on VRF systems in the GCC area in general and in Qatar in particular. Hence, this thesis will become a reference for the stakeholders who are linked to the energy sector such as governments, owners, design firms and contractors.

1.7 Scope of the Study

The thesis will focus on:

a- Identifying a case study building in Qatar

b- Calculating the design cooling loads

c- Modeling a VRF system

d- Conducting a life cycle cost analysis

e- Comparing the outcomes between CRF and VRF systems

1.8 Organization of the Thesis

The thesis is organized as follows. In chapter 1, the background of this study is introduced in addition to a brief description about CRF and VRF systems. In Chapter 2, the VRF literature review is presented in addition to the Transfer Function Method (TFM) and the Life Cycle Cost (LCC) Analysis. Chapter 3 highlights the methodologies used and the case study building characteristics are listed while the results, analysis, and discussion are reflected in Chapter 4. Finally, the conclusion, the recommendations, and the future work is presented in Chapter 5.

CHAPTER 2 – LITERATURE REVIEW

2.1 History of VRF

VRF systems have been used widely in Japan since 1980s and in the US since 2002 [5]. Initial review on VRF systems was done by Aynur [6] who looked at the VRF system from the experimental and modelling perspective. It was reported that the variable refrigerant flow system is more expensive compared to the conventional air conditioning systems, but since the VRF system offers high energy saving potential in a generic commercial building, the assessed payback period of the variable refrigerant flow system compared to conventional chiller system could be about 1.5 year.

In another study, Patel et al. [7] reported that VRF could fetch energy savings between 10 – 40%. Regarding VRF system responsiveness, Herdendez [8] reported that the quantity of indoor units that are linked to the system are directly related to responsiveness and sensitivity. A lot of other works have been done with the variable refrigerant flow system in terms of the system architecture [9 -11], modeling and simulation [12-18] and experimental work and field testing [6, 19-23].

2.2 Background Theory

2.2.1 VRF and VAV

In air conditioning systems, air can be supplied in two different ways: constant air volume (CAV) and variable air volume (VAV). Back in the 1970s, VAV systems were significantly utilized in the United States market especially in commercial buildings [6]. VAV systems offer many advantages when compared to CAV systems:

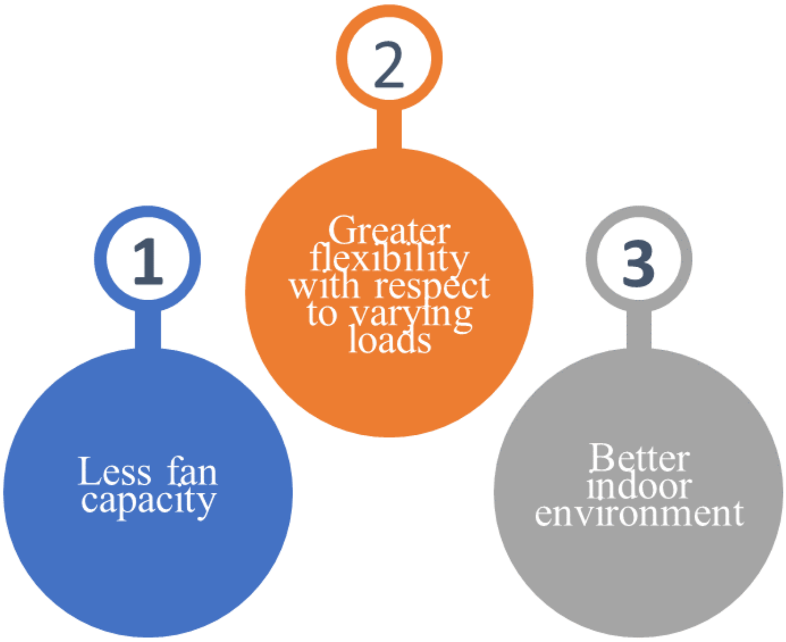

Figure 12 VAV advantages

Dongsu Kim et al. evaluated the operation of a variable refrigerant flow system and a roof top unit variable air volume system (RTU-VAV) in a simulation environment utilizing a whole building energy modeling software, EnergyPlus and under diverse climate situations. Sixteen US climate locations were used to determine the potential energy and cost savings [26].

Three basic parts were obtained using the simulation model that was built in EnergyPlus:

- a simulation manager

- a heat and mass balance simulation module
- a building systems simulation module.

The HVAC input particulars for the RTU-VAV and the variable refrigerant flow systems are presented in the below table:

Table 1 EnergyPlus HVAC model for RTU-VAV versus VRF HP systems

HVAC system component	RTU-VAV system	VRF HP system
Heating	Gas furnace inside the packaged air conditioning unit	VRF DX heating coil
Cooling	Unitary DX inside the packaged air conditioning unit	VRF DX cooling coil
Distribution and terminal units	VAV terminal box with damper and electric reheating coil (minimum supply air at 30% of the design peak supply air)	Variable refrigerant flow (VRF) DX cooling and heating coils (air-to-air heat pump)
Total cooling capacity	Auto-sized to design day	Auto-sized to design day
Total heating capacity	Auto-sized to design day	Auto-sized to design day
Cooling COP	3.39	3.23
Heating COP	0.8 (heating gas burner efficiency)	3.20
Thermostat set-point (occupied hours)	24 °C for cooling/21.1 °C for heating	24 °C for cooling/21.1 °C for heating
Thermostat set-back (unoccupied hours)	26.6 °C for cooling/15.5 °C for heating	26.6 °C for cooling/15.5 °C for heating
Supply fan type	Fan: variable volume	Fan: on/off
Indoor supply fan efficiency (%)	60%–62% depending on the fan motor size	0.7
Outdoor ventilation air	0.000431773 $m^3/s - m^2$ (0.0085 cfm/ft^2)	0.000431773 $m^3/s - m^2$ (0.0085 cfm/ft^2)
Supply air set-point manager	Outdoor air reset set-point (differential dry bulb in economizer control type): 15.6 °C if outdoor air is lower than 10 °C and 12.8 °C if outdoor air is higher than 21.1 °C Constant supply air set-point (differential enthalpy in economizer control type): 12.8 °C for cooling and heating operation	N/A
Supplementary heater type	N/A	Zonal baseboard convective elec. heater (natural convection unit)
Supplementary heater heating capacity	N/A	Auto-sized to design day
Supplementary heater efficiency	N/A	0.97

The VRF system distributes the refrigerant to each indoor unit as per the design zones. The electronic expansion valve with the assistance of the variable speed compressor allows for a variable flow rate of refrigerant. The heat pump (HP) type of VRF systems allows only cooling or heating mode while the heat recovery (HR) type allows simultaneous heating and cooling during the same operation.

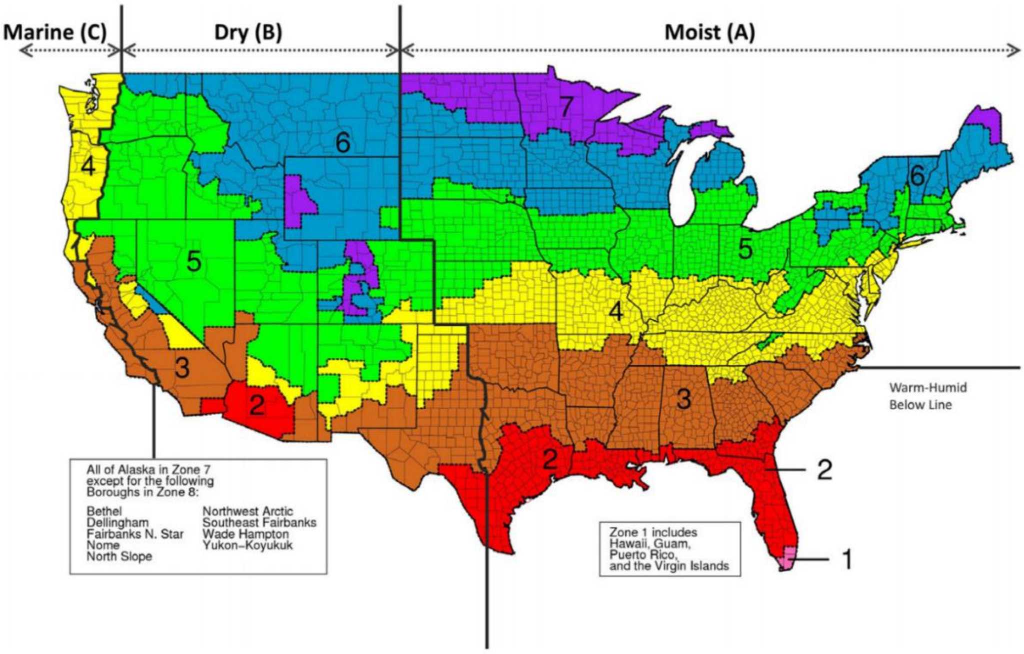

Figure 13 ASHRAE cliamte zones in the United States [26]

A comparison based on all annual HVAC energy consumption was made between the simulation results of the RTU-VAV and VRF systems. Because of the heating energy requirement, hot and mild climate locations showed more HVAC energy consumption compared to cold climate locations when the simulation was made for both VRF HP and RTU-VAV systems. The VRF HP system showed an important HVAC energy savings that is between 14% to 39% per year in sixteen US climate places. Every year, 2% to 32% of HVAC source energy savings were projected for the VRF HP systems after changing to source energy use.

Due to the variations in gas and electricity expenditure, better HVAC cost savings were shown in the VRF HP models in hot and mild climate areas than the RTU-VAV systems which use less HVAC energy cost in various cold environment zones [26].

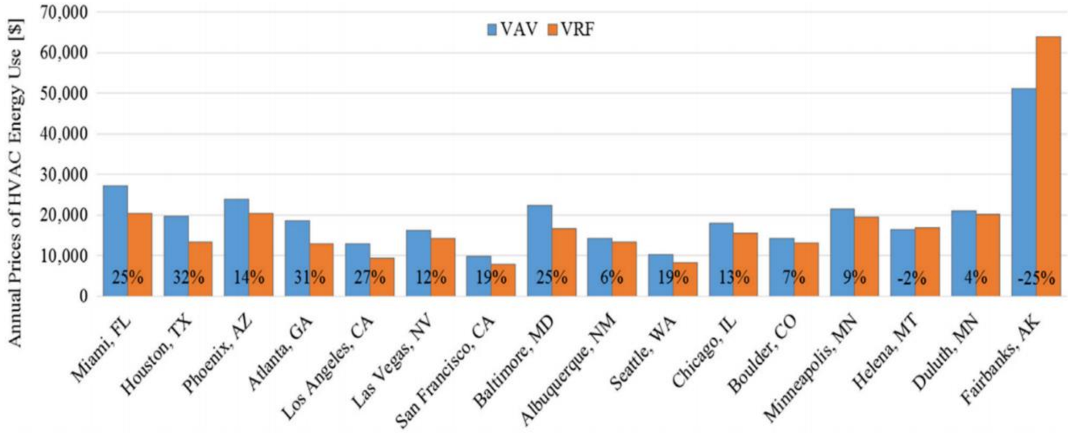

Figure 14 VRF models calculated annual HVAC energy cost savings potential [26]

2.2.2 Water-cooled VRF and Conventional Chiller Systems

Having in mind the same target of minimizing the energy utilization in the HVAC systems, studies were made to investigate and compare the VRF-HP connected to a direct expansion air handling unit (DX-AHU) and a chiller based conventional AHU system. The VRF-HP system was water cooled and the targeted building was a research and development building in Seoul, South Korea [27].

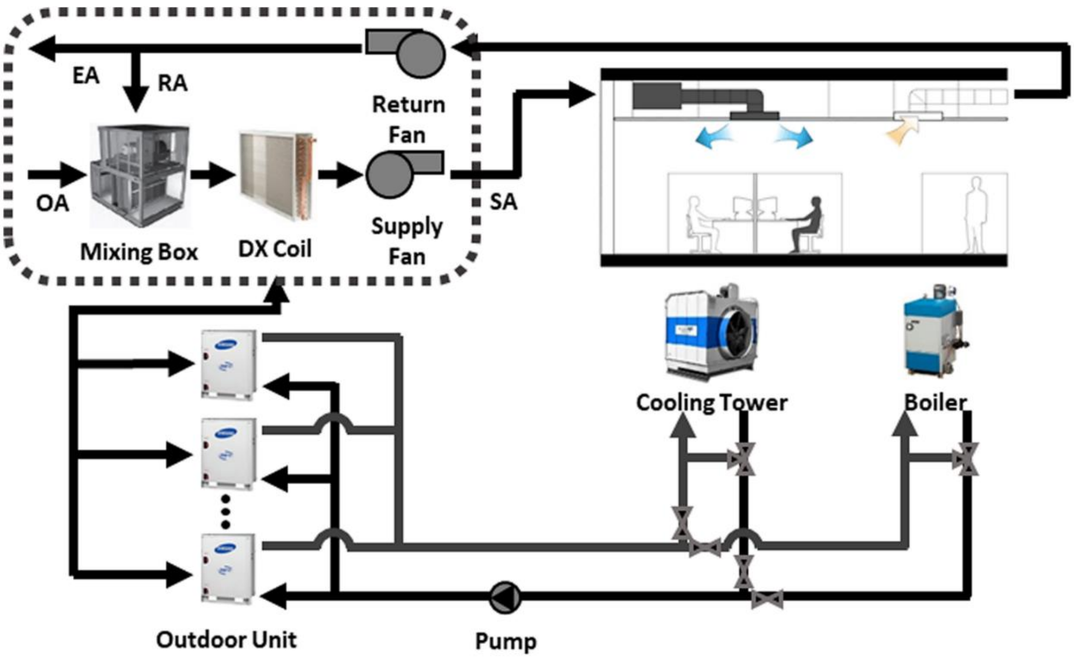

Figure 15 Schematic diagram of a water-cooled VRF-HP system [27]

EnergyPlus was the program used to perform the simulation and it is created by the United States Department of Energy. The performance curve of the variable refrigerant flow system has been already demonstrated in preceding papers [28]. Data exchange was needed between EnergyPlus and Matlab as per the below table:

Table 2 EnergyPlus and Matlab data exchange list

EnergyPlus to MATLAB	MATLAB to EnergyPlus
Outdoor Air Dry-Bulb Temperature	Outlet Water Temperature from Cooling Tower
Outdoor Air Humidity Ratio	Cooling Tower Water Flow Rate
DX Cooling Coil Electric Energy	Cooling Tower Energy Consumption
DX Cooling Coil Total Cooling Rate	AHU Supply Air Temperature
Zone Mean Air Temperature	Pump Energy Consumption
Fan Electric Energy	
DX Cooling Coil Part-Load Ratio	

To obtain the total annual cooling energy consumption in both systems, all the components were taken into consideration such as the chiller/VRF outdoor units, the AHU fan, the pump and the cooling tower fan.

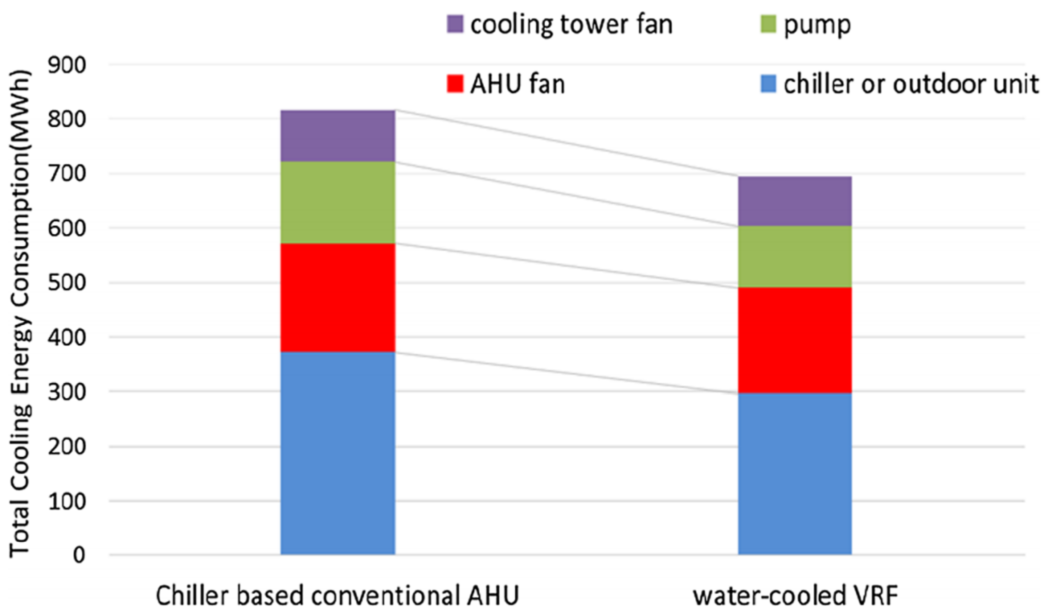

Figure 16 Comparison of annual total cooling energy consumption [27]

The results obtained on annual basis show that the VRF-HP system that is water-cooled can save:

- twenty percent of chiller energy
- three percent in Air Handling Unit fans
- twenty five percent in pumps
- three percent in the cooling tower

Hence, when comparing the total annual cooling energy, the water-cooled VRF-HP system is 15% better compared to a chiller based conventional Air Handling Unit system [27].

2.2.3 Life Cycle Cost Analysis for CAV and VAV

VRF systems were studied in terms of [6]:

- Field performance test
- System component simulation
- System fault detection and diagnosis
- Control strategy optimization

Additional studies were made to study the performance of the cooling process of multi-split variable refrigerant flow system with microchannel condenser under part load conditions [10] and to develop an energy diagnosis method for VRF systems based on data mining techniques and statistical quality control approaches. This way, the energy utilization can be anticipated based on significant factors. Different techniques and approaches were used to develop the model such as the Pearson's correlation analysis, the density-based special clustering of applications with noise method (DBSCAN), the support vector regression (SVR) algorithm and the exponentially-weighted moving average (EWMA) [29]. Life cycle cost analysis were also performed on CAV and VAV air conditioning systems and that is very relevant to our study.

2.2.3.1 Life Cycle Cost Analysis

In 1969, Coca-Cola sponsored a study that was conducted by Harry Teasley and is thought to be the starting point of the life cycle assessment (LCA). This study was carried out by the United States Midwest research institute, and it evaluated numerous containers of beverages with the purpose of finding those that developed less natural resource consumption and smaller number of environmental problems [30].

Life Cycle Assessment is a holistic methodology, and its background is general systems theory [31]. Most researchers have accepted the Life Cycle Costing (LCC) analysis. LCC is referred to total life cycle costing (TLCC) and it is the addition of all sorts of costs incurred over the lifespan of a project discounted to the present. The purpose of the LCC analysis is to select the most cost-effective tactic among several options to attain the lowest long-term cost of ownership. Companies are using LCC to better understand their projects or products in their life cycles because costs and profits are highly affected by not only sales but also the life cycle of a building for example [32].

Green buildings in specific use the LCC technique of joining both capital and operating costs to define the net economic impact of a certain project. All costs are calculated to a certain year that is considered to be the Present Value (PV). This way the criterion is unified in terms of time and dollars.

Healthy buildings are gaining more attention because they can decrease the overall illness of the workers and this cost can also be part of the LCC analysis. A Guide to Building life Cycle Assessment in Practice was published by The American Institute of Architects (AIA) and it shows the tactics and tools of evaluating and maximizing the combination of the benefits and expenses of systems and material selection. This is established on material and resource utilization and contamination from construction, operations, and the deconstruction of a project [32].

The initial cost or capital investment cost is related to the acquisition of the land, building the project, or renovating and for the tools and materials needed for the operation of the project. During the execution phase, special care should be given in order not to confuse between cost savings and quality compromise. This could impact the performance of a green building, so it must be incorporated in the first design stage and it is part of the initial investment.

The following steps are considered to be very important while performing a proper life cycle cost analysis:

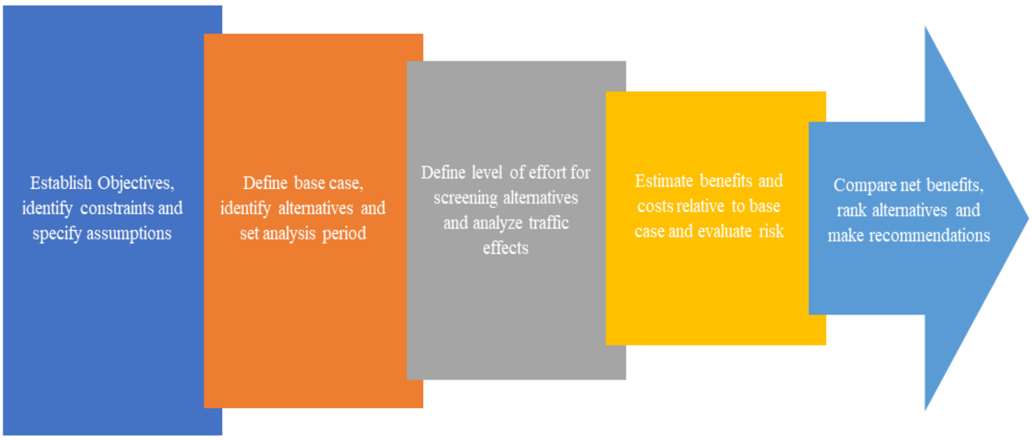

Figure 17 LCC major steps

Unfortunately, many buildings stakeholders concentrate on direct costs only or on short time frame payback periods. They pay more attention to construction of buildings with the perspective of their own utilization, and they disregard the operating costs. So, the LCC analysis has a primary goal of calculating the whole costs of a building options and to select the design that guarantees the lowest cost of ownership throughout the lifetime of the project [32].

2.2.3.2 Present Value Analysis

The present value analysis (PVA) is created on the simple idea that the value of a dollar profit today is bigger than the value of a dollar profit next year [32].
The upcoming cash flow is discounted to its present value by the application of time value of money.

The current market return will determine the discounting rate that is needed for the present value. A pre-specified rate (discount rate) and a number of years are used to discount the future cash flow and to obtain the present value formula.

Formula For Present Value is shown below:

$$\text{Present Value} = CF / (1 + r)^t \qquad (1)$$

Where,

- PV = Present Value
- CF = Future Cash Flow
- r = Discount Rate
- t = Number of Years

whenever there is multiple compounding per year (denoted by n), the formula for Present Value can be modified as,

$PV = CF / (1 + r/n)^{t*n}$ (2)

To calculate the present worth value of annual payments, we use the following:

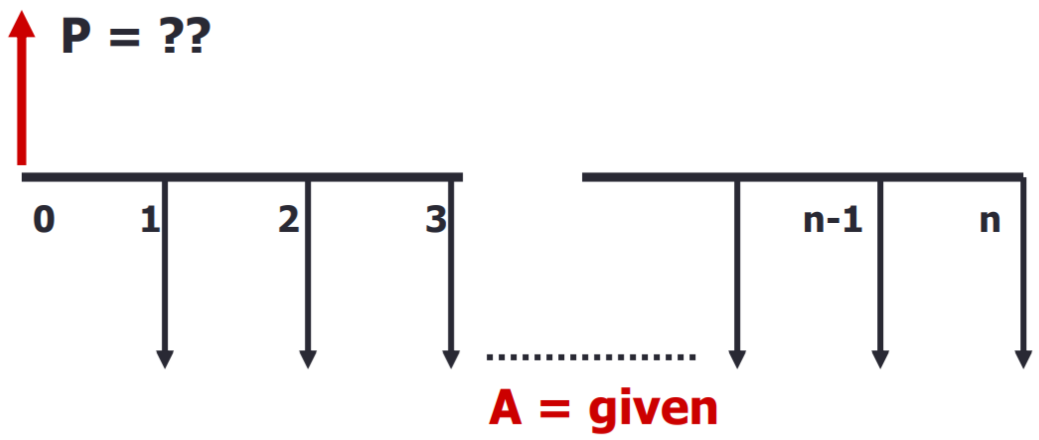

Figure 18 Present value of annual payments illustration

$PV = A\,[(1+R)^n - 1] / [R(1+R)^n]$ (3)

Where PV is the present value

A is the annual total cost incurred for each system

R is the real interest rate

n is the number of years

In order to calculate the real interest rate R, the following formula was used:

$i = (1+R)(1+h) - 1$ (4)

where i is the nominal interest rate

R is the real interest rate

h is the inflation rate

So $R = (i+1)/(h+1) - 1$ (5)

Therefore, cash flows have to be made time-equivalent so that they can be added and compared since they are incurred at distinct periods throughout the life cycle of a building. To achieve this, the life cycle cost method allows us to convert everything to present values by bringing them back altogether to a common point in time, which is referred to as a baseline date.

From this baseline date, the period of the study begins and that is the date where all cash flows are discounted. The major phases that are included in the study period are:

- planning
- construction
- execution
- operational period

The study cycle stays unaffected for all of the considered options [32].

Sieglinde Fuller stated that, “It is particularly suitable for the evaluation of building design alternatives that satisfy a required level of building performance but may have different initial investment costs, different operating and maintenance and repair costs, and possibly different lives.” However, life cycle cost analysis can be utilized where there is a capital investment decision that includes high initial cost and many upcoming cost commitments.

Sieglinde states that the life cycle cost analysis is a method that offers an improved evaluation of the long-period relationship between effectiveness and cost of a project than different economic techniques that mostly emphasize initial costs or operating costs in the short term. Moreover, Sieglinde states that life cycle cost analysis can be used at different stages of complication, and in this case the analysis will shift from a “back-of the envelope” analysis to a detailed one. This scenario requires more investigated input data, additional assessments of economic valuation, complicated uncertainty review, and wide documentation.

One of the important features of the LCCA is that it can be done in either case of current or constant dollars. The calculations made in both ways will generate the same PV. In the case of constant dollar analysis, the rate of inflation is not included so it is an advantage of not getting into an estimate of the inflation rate during the study life period. In federal projects, except for those paid by the private sector like the energy savings performance contracting (ESPC) and the utility energy services contract (UESC), the current dollar analysis is recommended, and it incorporates the general inflation rate in all dollar values, price escalation rates and discount rates [32].

If the goal is to compare the actual yearly operational or energy cost savings with the contract payments, one can use different financing studies that are normally calculated using the current dollars [32].

2.2.3.3 Break-even analysis

The moment when a project starts to generate a profit after covering all of its costs is called a break-even point. The analysis of this point is very powerful technique in the building projects. When starting a business, it is very crucial to determine how much sales should be done, and at which profit margin in order to cover the initial costs so that the business can run in a positive manner.

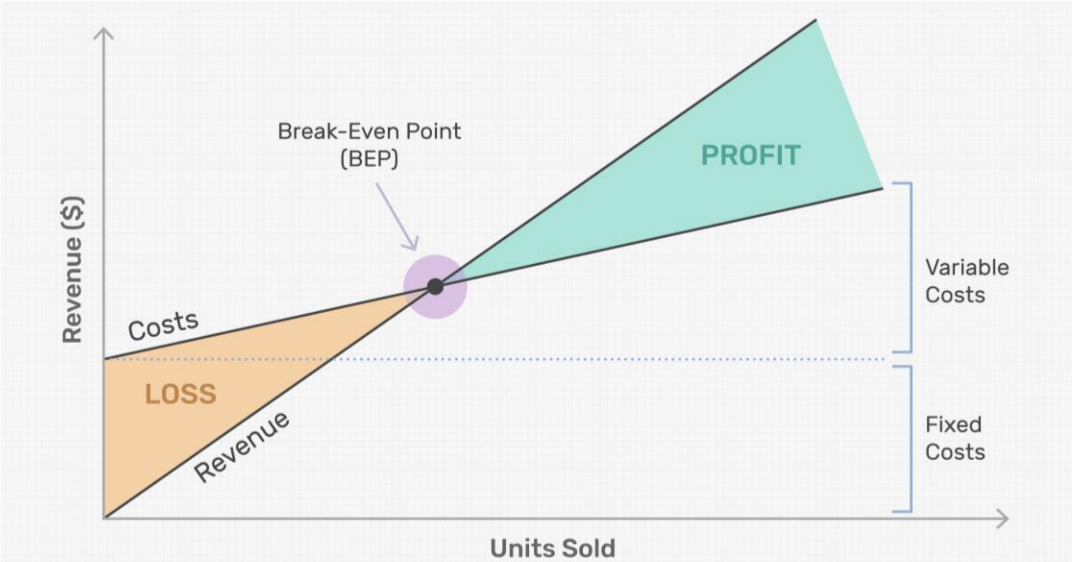

Figure 19 Break-even analysis

So, the cash flow of a business is monitored through the break-even analysis. Two types of costs, variable and fixed, and the profit are interconnected while using this type of analysis. Stakeholders and managers utilize this analysis to determine the break-even of a project knowing the maximum cost of an input, or contrarywise, to determine the least benefit that the project has to achieve in order to pay for the investment cost.

The break-even analysis can be solved mathematically by setting equal both costs and benefits and by specifying all variables. All noncash expenses such as depreciation are removed from the operating expenses because actual and real cash flow are being studied.

To execute a break-even analysis, the following variables must be defined:

- Gross profit margin
- Operational expenditures
- Debt service per year

2.2.3.4 LCC for CAV and VAV

The transmission of the cooling and the heating between the conditioned buildings and the central plants will determine the categories of the AC systems. There are four fundamental system types: all-air systems, air- and water-systems, all-water systems and packaged unitary equipment systems [33].

All-air systems have been broadly utilized in air-conditioning system projects. In these systems, the energy is mainly used by moving the air between different points with different criteria. Two primary air-distribution systems linked with all-air air-conditioning systems are constant-air-volume (CAV) and variable-air-volume (VAV) systems. Various categories of these two systems exist, such as single-duct, dual-duct, reheat and multi-zone systems. Constant air volume systems were initially used in the air-conditioning field while the variable air volume systems have been introduced back in the 1960s. Multiple industrial and commercial projects are using the VAV system in an effort to achieve more energy savings. With the VAV system, the quantity of air varies depending on the total cooling demand in the air-conditioned area [34,35].

In Adana, a comparison was made between CAV and VAV systems and all initial and operating costs were accounted for [33]. The project consisted of two different buildings, one is a school and the second is an office building. Also, two scenarios were taken into consideration in terms of occupancy and operating time. In the first scenario, the AC system ran from 8 am to 5 pm and from 8 am to 12 midnight in scenario 2. Cooling load profiles were performed in detail, all the costs were considered so that the life cycle cost analysis could be completed in an attempt to compare between the CAV and the VAV systems. The total cost was evaluated by using the present worth method for the life cycle cost. Two ecosets were used while defining the economic measures of the inflation rate and the interest rate. The first ecoset is for the developed economy and the second ecoset is for the developing economy such as the case study in that research [33].

The computed cooling loads for both office and school buildings are shown in Figs. 20 and 21, respectively. It is obvious, from the graphs, that August holds the maximum cooling load of the studied building. Hence, the design of the air conditioning system should cover the results related to the month of August. The upper limit cooling load for the school and the office center is 131.1 and 117.7 kW at 1 pm, respectively. The sensible heat ratio is the ratio of sensible to total cooling load. At the maximum load, the sensible-heat ratio for the office building is 0.94 while it is 0.89 for the school building. The number of occupants varies drastically depending on the working hours and this is why the cooling load changes accordingly showing a sharp increase at 8 am and a decrease at 12 midnight.

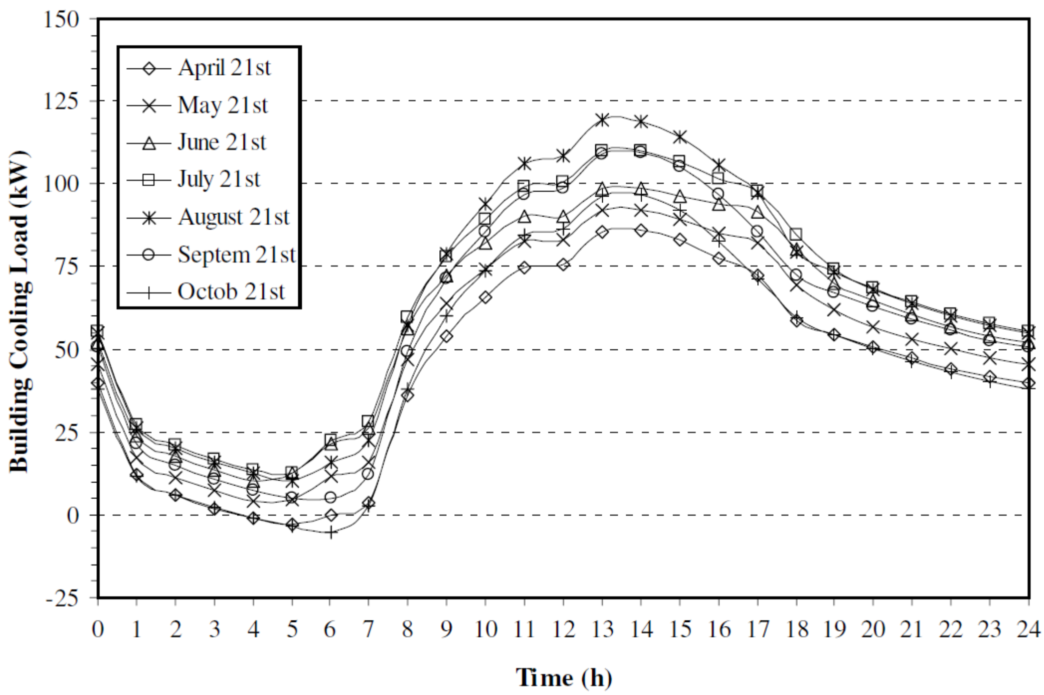

Figure 20 Building cooling load profile of the office center for scenario 2 (operating hours from 8:00 to 24:00) [33]

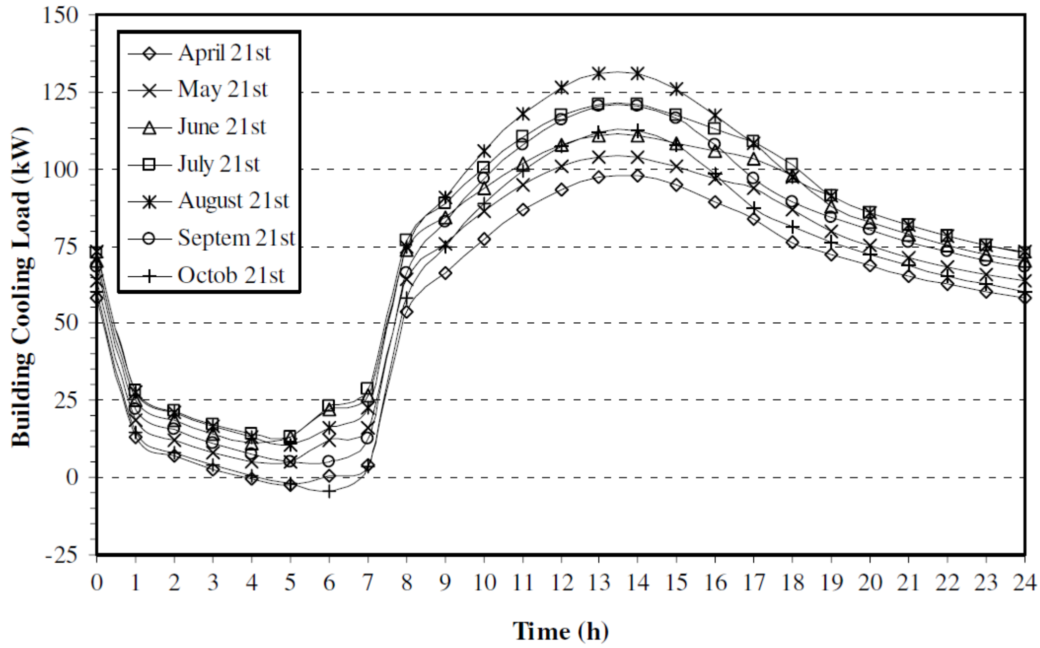

Figure 21 Building cooling load profile of the school building for scenario 2 (operating hours from 8:00 to 24:00) [33]

The cost of the air handling units, chiller system, ducts, insulation, and control accessories constitute the initial cost of both, CAV and VAV systems. The anticipated initial costs of the CAV and VAV systems are given in Table 3. For the school project, the VAV initial cost is higher by 21% than the CAV system and for the office building project, the VAV initial cost is higher by 23% than the CAV system [33].

Table 3 Comparison of the initial costs of the VAV and CAV systems [33]

Unit	Initial cost ($)			
	School building		Office building	
	CAV	VAV	CAV	VAV
AHU	20,355	20,355	20,355	20,355
Duct	20,000	20,000	20,000	20,000
Chiller	47,495	47,495	40,710	40,710
Automation	6785	11,696	6785	11,649
VSD	0	4150	0	4150
VAV Box	0	10,877	0	10,754
Total	94,635	11,4573	87,850	10,7618
Extra investment for the VAV	–	19,938	–	19,768

Employee salaries, material supply, water and electricity form the operating costs in the project. The electrical consumption of the supply and return fans of the air handling units and chillers constitutes the electrical operating costs and that is why the electrical costs of the chiller, supply and return fans were calculated independently for both systems. Maintenance costs were not taken into consideration because they vary with many constraints, such as skill, local labor rates, the system initial commissioning date, duration of operation. This is an addition to the complication of the AC system and the accessibility issues which play a significant role on the maintenance cost [36].

This CAV and VAV study did not cover the maintenance scope because a proper estimation with detailed analysis was required. Therefore, the cost related to maintenance for the CAV and the VAV systems can be considered nearly the same. In the computations, consequently, maintenance costs and other operating costs such as employee salaries, materials, etc., were ignored.

Table 4 Annual operating costs of the fans for the school building [33]

Scenario[a]	System	Operating time	Power (kW)	Electric consumption (kWh/year)	Operating cost ($/year)
I	VAV	08:00–09:00	2.59	475.98	52
		09:00–10:00	5.12	942.75	104
		10:00–11:00	8.34	1535.41	169
		11:00–12:00	11.72	2156.62	237
		12:00–13:00	14.71	2706.39	298
		13:00–14:00	16.78	3087.82	340
		14:00–15:00	16.77	3085.19	339
		15:00–16:00	14.85	2733.10	301
		16:00–17:00	12.33	2268.29	250
		Total operating cost of the fans ($/year)=			2089
	CAV	08:00–17:00	26	43056	4736
		Total operating cost of the fans ($/year)=			4736
II	VAV	08:00–09:00	2.59	475.98	52
		09:00–10:00	5.12	942.75	104
		10:00–11:00	8.34	1535.41	169
		11:00–12:00	11.72	2156.62	237
		12:00–13:00	14.71	2706.39	298
		13:00–14:00	16.78	3087.82	340
		14:00–15:00	16.77	3085.19	339
		15:00–16:00	14.85	2733.10	301
		16:00–17:00	12.33	2268.29	250
		17:00–18:00	10.04	1846.70	203
		18:00–19:00	7.65	1407.53	155
		19:00–20:00	5.71	1049.99	115
		20:00–21:00	4.59	844.48	93
		21:00–22:00	3.80	699.56	77
		22:00–23:00	3.26	600.52	66
		23:00–24:00	2.85	523.66	58
		Total operating cost of the fans ($/year)=			2856
	CAV	08:00–24:00	26	76544	8420
		Total operating cost of the fans ($/year)=			8420

[a] Operating time of the air-conditioning system is between 8:00 and 17:00 for scenario 1 and between 8:00 and 24:00 for scenario 2.

Table 5 Annual operating cost of the chiller unit for the school building [33]

Scenario[a]	System	Operating time	Power (kW)	Electric consumption (kWh/year)	Operating cost ($/year)
I	CAV and VAV	08:00-09:00	24.58	4522.72	497
		09:00–10:00	37.00	6808.00	749
		10:00–11:00	38.12	7014.08	772
		11:00–12:00	39.13	7199.92	792
		12:00–13:00	54.59	10044.56	1105
		13:00–14:00	55.34	10182.56	1120
		14:00–15:00	55.81	10269.04	1130
		15:00–16:00	55.65	10239.60	1126
		16:00–17:00	40.20	7396.80	814
		Total operating cost of the chiller ($/year)=			8105
II	CAV and VAV	08:00–09:00	24.58	4522.72	497
		09:00–10:00	37.00	6808.00	749
		10:00–11:00	38.12	7014.08	772
		11:00–12:00	39.13	7199.92	792
		12:00–13:00	54.59	10044.56	1105
		13:00–14:00	55.34	10182.56	1120
		14:00–15:00	55.81	10269.04	1130
		15:00–16:00	55.65	10239.60	1126
		16:00–17:00	40.20	7396.80	814
		17:00–18:00	42.13	7751.92	853
		18:00–19:00	42.73	7862.32	865
		19:00–20:00	43.32	7970.88	877
		20:00–21:00	43.91	8079.44	889
		21:00–22:00	44.51	8189.84	901
		22:00–23:00	30.62	5634.08	620
		23:00–24:00	31.01	5705.84	628
		Total operating cost of the chiller ($/year)=			13736

[a] Operating time of the air-conditioning system is between 8:00 and 17:00 for scenario 1 and between 8:00 and 24:00 for scenario 2.

Table 6 Summary of the results obtained from the operating-cost analysis [33]

Building	Scenario[a]	System		Operating cost ($/year)		
				Chiller	Fans	Total
School building	I	CAV		8105	4736	12,841
		VAV			2089	10,194
		Saving	$/years	0	2647	2647
			%		56	21
	II	CAV		13,736	8420	22,156
		VAV			2856	16,592
		Saving	$/year	0	5564	5564
			%		66	25
Office center	I	CAV		6824	4736	11,560
		VAV			1998	8821
		Saving	$/year	0	2738	2738
			%		58	24
	II	CAV		10,603	8420	19,023
		VAV			2650	13,253
		Saving	$/year	0	5770	5770
			%		69	30

[a] Operating time of the air-conditioning system is between 8:00 and 17:00 for scenario 1 and between 8:00 and 24:00 for scenario 2.

The below table shows the break-even point of the VAV system over the years and that is for both ecosets 1 and 2. Scenario 1 covers the occupancy and the operating time from 8 am to 5 pm while scenario 2 covers from 8 am to 12 midnight. Different interest and inflation rates were used over the year such 6% interest rate and 0% inflation rate for ecoset 1 and 22% interest rate and 12% inflation rate for ecoset 2.

Table 7 Life-cycle analysis results for ecosets 1 and 2 [33]

Building	Scenario[a]	Ecoset[b]	System	PWC at the end of lifetime	Payback period of VAV (years)
School building	I	I	VAV	$213576	10.32
			CAV	$219347	
		II	VAV	295612 YTL	13.06
			CAV	297841 YTL	
	II	I	VAV	$275718	4.15
			CAV	$309817	
		II	VAV	373305 YTL	4.51
			CAV	410949 YTL	
Office center	I	I	VAV	$193292	9.74
			CAV	$200120	
		II	VAV	268577 YTL	12.10
			CAV	272123 YTL	
	II	I	VAV	$236330	3.95
			CAV	$272602	
		II	VAV	322328 YTL	4.27
			CAV	362731 YTL	

At the end of the life cycle, VAV systems showed lower present worth value than the CAV system for all the scenarios. The VAV system is more economically feasible with longer operating hours and the additional investment in the VAV system in that case will reach the break even point within four years. On the other side, for shorter operating hours, the break even point or the payback period is more than ten years.

CHAPTER 3 – METHODOLOGY

3.1 General Approach

In order to conduct a life cycle cost analysis between the CRF and the VRF systems in Qatar, the following methodology was used:

- Different research papers related to the VRF systems and the life cycle cost analysis were studied so that we can understand the gaps pertaining to this field in our application in Qatar.
- A case study building was selected with existing conventional CRF units.
- Quantitative study was conducted by collecting data from the manufacturer's catalogs, designing the needed cooling loads using Hourly Analysis Program (HAP), modelling a VRF system, calculating the power consumption and all the related costs.

3.2 Research Process Flow Chart

The process flow chart for our research is shown below:

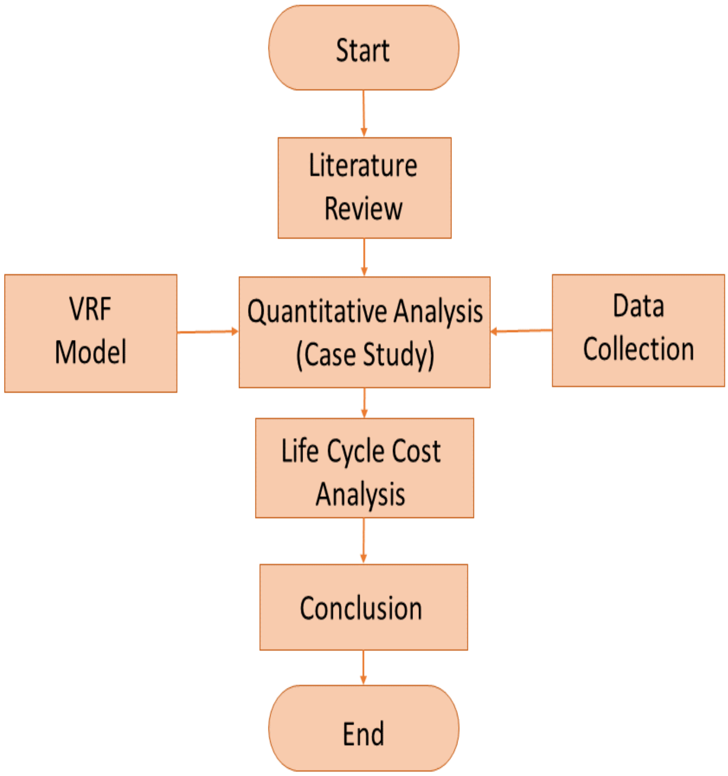

Figure 22 Process flow chart

3.3 Case Study

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 23 Al Muftah Plaza Building [25]

This building has two basements, a ground floor and five floors above ground. The total built up area is 18,102 m2 while the rentable area is 10,715 m2 only. The ground floor consists of two car showrooms covering an area of 1,475 m2 while the upper floors consist of 4 offices each with an area of 1,802 m2. The height of the ground floor is 3.5 m from the finished floor level to the false ceiling level and 1.1m 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.

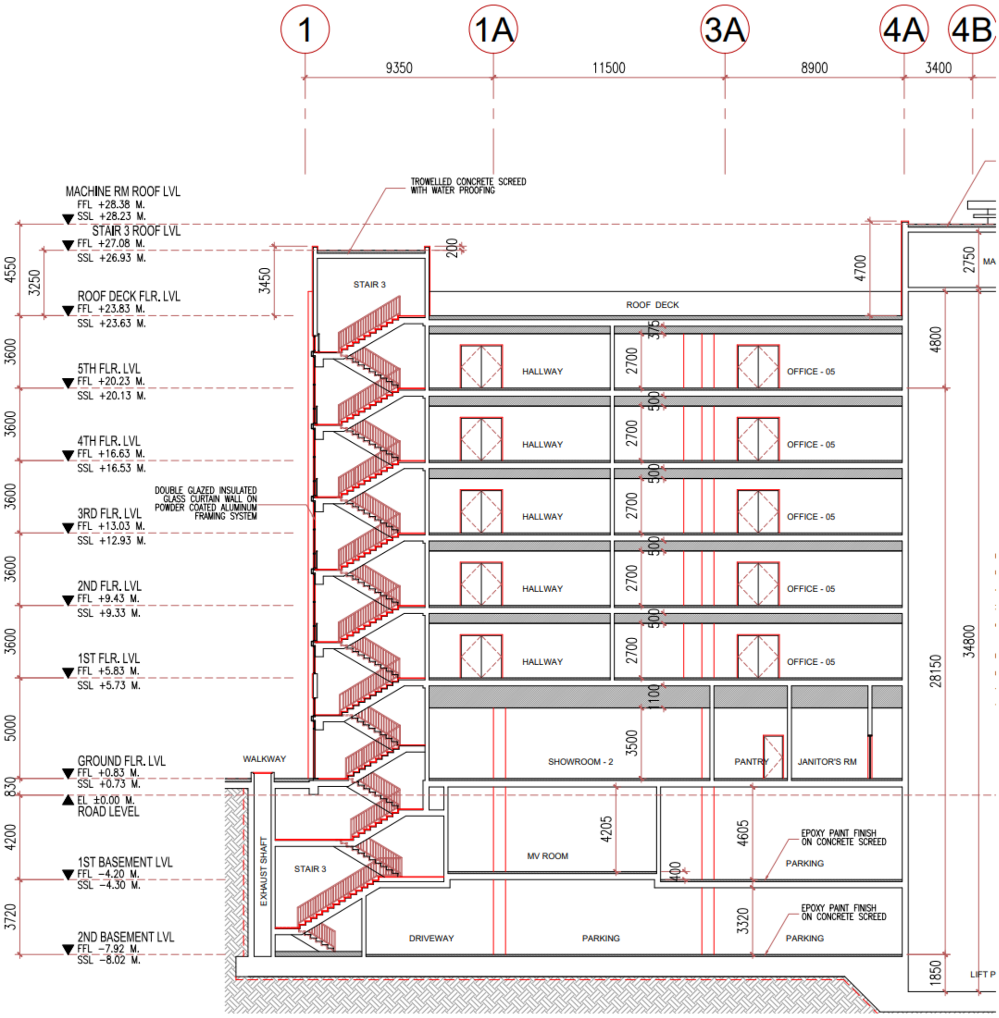

Figure 24 Al Muftah Plaza sectional view [25]

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.

3.4 HAP

In this study, the transfer function method (TFM) was used for the calculation of the cooling load by using the well-known Hourly Analysis Program (HAP) by

Carrier, a company that provides solutions for air conditioning. The TFM method is a derivative of the Heat Balance Method and will 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.

Table 8 Values of the heat transfer coefficient (U)

	Heat Gain Sources	U-Value (BTU/hr/ft2/F°)
1	Wall	1.28
2	Glass	3.339
3	Door	1.703
4	Roof	0.518
5	Partition	2.839

3.5 VRF Model

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 ton of refrigeration (TR) as per the manufacturer's catalog. Two dedicated systems for all the common areas such as corridors and elevators' lobbies are designed. Ducted indoor units are selected equal to CRF in order to focus the analysis on comparing the CRF and VRF outdoor units in terms of energy savings in particular and life cycle cost analysis in general.

3.6 Data Collection

For the purpose of this thesis, we have collected the data from York products from Johnson Controls USA where Al Muftah Contracting is the local distributor in Qatar. The data was crucial in determining the power consumption in the existing CRF units as well as in the VRF units where extrapolation was needed to obtain the needed percentages. We also conducted an online interview with one of the well-known designers in Qatar to determine that the CRF ducted units are the most used in existing residential and commercial buildings.

Since there is no data pertaining to the actual consumption of the existing CRF units until the time of this study, we conducted a technical meeting with multiple experienced engineers and technicians with more than 10 years of experience in the field to determine the actual usage of the ducted CRF units during the year taking into consideration all operational conditions.

Kahramaa consumption unit rates were also used in our cost calculation.

3.7 Present Value

Several steps are needed to calculate the present worth value of each system.

First, the formula of the present value (PV) is described as below:

$$PV = A\,[(1+R)^n - 1] / [R(1+R)^n] \qquad (6)$$

Where PV is the present value

A is the annual total cost incurred for each system

R is the real interest rate

n is the number of years

In order to calculate the real interest rate R, the following formula was used:

$$i = (1+R)(1+h) - 1 \qquad (7)$$

where i is the nominal interest rate

R is the real interest rate

h is the inflation rate

$$\text{So } R = (i+1)/(h+1) - 1 \qquad (8)$$

The life of each system is considered to be 15 years so n is equal to 15. LCC analysis is based on the following interest and inflation rates as depicted in Table 9. The present worth cost technique is used to compare the total costs (initial, operating and maintenance) of the two alternative systems (CRF and VRF) considering the two operating scenarios (scenario 1 and 2) over the 15 years period.

Table 9 Varying interest and inflation 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

3.8 Cost Breakdown

To calculate A, the total annual cost of the CRF and VRF systems, we divided it into three main categories:

a- Initial cost: this is the cost of the supply and installation of the system and it includes the equipment, the ducts, the dampers, the pipes, the insulation and the diffusers. We only listed the main items while the cost included all others that are part of the initial cost.

b- Operating cost: this is the cost of operating the system and that is mainly related to the power consumption. In our research, we selected the same indoor units for both systems so that we can compare the outdoor units for a better understanding. The study is focusing on the VRF and CRF outdoor units only.

c- Maintenance cost: this is the cost of maintaining the system in a good condition throughout the year. In our research, we calculated the difference between the maintenance of the two systems and we added it to the CRF system since it needed more maintenance than the VRF system.

CHAPTER 4 – RESULTS, ANALYSIS, AND DISCUSSION

4.1 Cooling Loads

4.1.1 Design 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 are obtained and they are divided into two groups: (a) rentable areas and (b) common areas. The cooling load calculated are tabulated in Tables 10 and 11 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 will be the basis of the design.

Table 10 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 11 Required cooling load (common areas)

FLOOR	AREA	Calculated Capacity (TR)
GROUND	MAIN ENTRANCE	10.6
FIRST	HALLWAY WITH	10.4
SECOND	HALLWAY WITH	10.4
THIRD	HALLWAY WITH	10.4
FOURTH	HALLWAY WITH	10.4
FIFTH	HALLWAY WITH	10.4

4.1.2 Existing Units

Since this is an existing building, the installed units are checked, the data from the manufacturer is taken and combined in Tables 12 and 13 to compare against the calculated heat load in HAP (Tables 10 and 11) 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 12 Existing ducted units (rentable areas)

FLOOR	AREA	DSAC Model	QTY	SELECTED CAPACITY (TR)	Total Capacity (TR)
GROUND FLOOR	SHOWROOM-01 SHOWROOM-02	YGFN48BXNWUVH1 + YUFN48BYMNUVH1	6	3.31	19.86
		YGFN60BZMWUVH1 + YUFN60BYMNUVH1	7	3.96	27.72
		YEFN18BXNWUVH1 + YUFN18BYNNUVH1	1	1.31	1.31
FIRST FLOOR	OFFICE-1	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	4	3.96	15.84
		YGFN42BXNWUVH1 + YUFN42BYNNUVH1	3	2.99	8.97
	OFFICE-2	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	2	3.96	7.92
	OFFICE-3	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	6	3.96	23.76
		YGFN30BXNWUVH1 + YUFN30BYNNUVH1	1	1.94	1.94
	OFFICE-4	YGFN48BXNWUVH1 + YUFN48BYMNUVH1	5	3.31	16.55
TYPICAL FLOOR - 2nd to 4th FLOOR	OFFICE-1	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	12	3.96	47.52
		YGFN42BXNWUVH1 + YUFN42BYNNUVH1	9	2.99	26.91
	OFFICE-2	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	6	3.96	23.76
	OFFICE-3	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	18	3.96	71.28
		YGFN30BXNWUVH1 + YUFN30BYNNUVH1	3	1.94	5.82
	OFFICE-4	YGFN48BXNWUVH1 + YUFN48BYMNUVH1	15	3.31	49.65
FIFTH FLOOR	OFFICE-1	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	4	3.96	15.84
		YGFN42BXNWUVH1 + YUFN42BYNNUVH1	3	2.99	8.97
	OFFICE-2	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	2	3.96	7.92
	OFFICE-3	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	6	3.96	23.76
		YGFN30BXNWUVH1 + YUFN30BYNNUVH1	1	1.94	1.94
	OFFICE-4	YGFN48BXNWUVH1 + YUFN48BYMNUVH1	5	3.31	16.55

Table 13 Existing ducted units (common areas)

FLOOR	AREA	DSAC Model	QTY	SELECTED CAPACITY (TR)	Total Capacity (TR)
GROUND FLOOR	MAIN ENTRANCE LOBBY	YEFN24BXNWUVH1 + YUFN24BYNNUVH1	2	1.63	3.26
		YGFN48BXNWUVH1 + YUFN48BYMNUVH1	1	3.31	3.31
FIRST FLOOR	HALLWAY WITH MALE & FEMALE W.C	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	3.96	3.96
		YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	3.31	6.62
SECOND FLOOR	HALLWAY WITH MALE & FEMALE W.C	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	3.96	3.96
		YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	3.31	6.62
THIRD FLOOR	HALLWAY WITH MALE & FEMALE W.C	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	3.96	3.96
		YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	3.31	6.62
FOURTH FLOOR	HALLWAY WITH MALE & FEMALE W.C	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	3.96	3.96
		YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	3.31	6.62
FIFTH FLOOR	HALLWAY WITH MALE & FEMALE W.C	YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	3.96	3.96
		YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	3.31	6.62

4.1.3 VRF Selection

For the purpose of this study, the data sheets provided from York products from Johnson Controls are used for the VRF units and the selection is shown in Tables 14 and 15 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 14 VRF selection (rentable areas)

FLOOR	AREA	VRF INDOOR UNITS	Qty	Capacity (TR)	Total Capacity (TR)	VRF OUTDOOR UNITS	Qty	Cooling Capacity (TR)	Total Capacity (TR)	Ratio (%)
GROUND FLOOR	SHOWROOM 01	YVGVXH140WAR--GX	6	3.33	19.98	YV2VYH	1	19.36	19.36	101.2
	SHOWROOM 02	YVGVXH160WAR--GX	7	3.75	26.25	YV2VYH 112KASFDA1	1	26.3	26.3	101.8
		YVGVXH071WAR--GX	1	1.73	1.73					
FIRST FLOOR	OFFICE-1	YVGVXH160WAR--GX	4	3.75	15	YV2VYH 095KASFDA1	1	23.88	23.88	98.8
		YVGVXH112WAR--GX	3	2.81	8.43					
	OFFICE-2	YVGVXH160WAR--GX	2	3.75	7.5	YV2VYH	1	8.19	8.19	90.8
	OFFICE-3	YVGVXH160WAR--GX	6	3.75	22.5	YV2VYH 101KASFDA1	1	24.51	24.51	99.8
		YVGVXH080WAR--GX	1	1.9	1.9					
	OFFICE-4	YVGVXH140WAR--GX	5	3.33	16.65	YV2VYH	1	17.06	17.06	99.5
TYPICAL FLOOR - 2nd to 4th FLOOR	OFFICE-1	YVGVXH160WAR--GX	12	3.75	45	YV2VYH 095KASFDA1	3	23.88	71.64	98.8
		YVGVXH112WAR--GX	9	2.81	25.29					
	OFFICE-2	YVGVXH160WAR--GX	6	3.75	22.5	YV2VYH	3	8.19	24.57	90.8
	OFFICE-3	YVGVXH160WAR--GX	18	3.75	67.5	YV2VYH 101KASFDA1	3	24.51	73.53	99.8
		YVGVXH080WAR--GX	3	1.9	5.7					
	OFFICE-4	YVGVXH140WAR--GX	15	3.33	49.95	YV2VYH	3	17.06	51.18	99.5
FIFTH FLOOR	OFFICE-1	YVGVXH160WAR--GX	4	3.75	15	YV2VYH 095KASFDA1	1	23.88	23.88	98.8
		YVGVXH112WAR--GX	3	2.81	8.43					
	OFFICE-2	YVGVXH160WAR--GX	2	3.75	7.5	YV2VYH	1	8.19	8.19	90.8
	OFFICE-3	YVGVXH160WAR--GX	6	3.75	22.5	YV2VYH 101KASFDA1	1	24.51	24.51	99.8
		YVGVXH080WAR--GX	1	1.9	1.9					
	OFFICE-4	YVGVXH140WAR--GX	5	3.33	16.65	YV2VYH	1	17.06	17.06	99.5

Table 15 VRF selection (common areas)

FLOOR	AREA	VRF INDOOR UNITS	Qty	Capacity (TR)	Total Capacity (TR)	VRF OUTDOOR UNITS	Qty	Cooling Capacity (TR)	Total Capacity (TR)	Ratio (%)
GROUND FLOOR	MAIN ENTRANCE LOBBY	YVGVXH160WAR--GX	2	3.75	7.5					
		YVGVXH140WAR--GX	1	3.33	3.33					
FIRST FLOOR	HALLWAY WITH MALE & FEMALE W.C	YVGVXH160WAR--GX	1	3.75	3.75	YV2VYH130KASFDA1	1	31.61	31.61	99
		YVGVXH140WAR--GX	2	3.33	6.66					
SECOND FLOOR	HALLWAY WITH MALE & FEMALE W.C	YVGVXH160WAR--GX	1	3.75	3.75					
		YVGVXH140WAR--GX	2	3.33	6.66					
THIRD FLOOR	HALLWAY WITH MALE & FEMALE W.C	YVGVXH160WAR--GX	1	3.75	3.75					
		YVGVXH140WAR--GX	2	3.33	6.66					
FOURTH FLOOR	HALLWAY WITH MALE & FEMALE W.C	YVGVXH160WAR--GX	1	3.75	3.75	YV2VYH130KASFDA1	1	31.61	31.61	97.7
		YVGVXH140WAR--GX	2	3.33	6.66					
FIFTH FLOOR	HALLWAY WITH MALE & FEMALE W.C	YVGVXH160WAR--GX	1	3.75	3.75					
		YVGVXH140WAR--GX	2	3.33	6.66					

4.2 LCC Analysis

4.2.1 Initial Investment

In order to have an accurate and fair comparison between the two air conditioning systems, a lifetime of 15 years is considered and all the costs were considered: initial, operating and maintenance costs. The initial investment cost covers the main equipment of both systems such as the CRF and VRF units. Also, it covers the ducting, piping, insulation, dampers, grills and diffusers and other accessories.

The summary of the initial investment cost is tabulated in Table 16. The cost of diffusers and ducting works are the same since the same indoor units quantities and capacities were selected in both systems. The VRF system is 23% more expensive than the traditional CRF system.

Table 16 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

4.2.2 Operating Cost

In this study, the outdoor units of both systems are compared and the indoor units are neglected since their electrical consumption is minimal compared to the outdoor units and the same indoor units' capacities in both systems are kept.

Hence, the variation in the fans' speed that is depended on the cooling load is the same for the two type of systems and it is not considered in this study. First, the total power input required for the outdoor units of the CRF system is calculated to be

635 kW using the manufacturer’s datasheets. These numbers correspond to 100% cooling load capacity since it is a constant refrigeration flow system as explained earlier.

Table 17 CRF total power input in KW

DSAC Model	QTY	Outdoor Power Input (KW)	Total Power Input (KW)
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	6	4.46	26.76
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	7	5.16	36.12
YEFN18BXNWUVH1 + YUFN18BYNNUVH1	1	1.705	1.705
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	4	5.16	20.64
YGFN42BXNWUVH1 + YUFN42BYNNUVH1	3	3.794	11.382
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	2	5.16	10.32
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	6	5.16	30.96
YGFN30BXNWUVH1 + YUFN30BYNNUVH1	1	2.53	2.53
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	5	4.46	22.3
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	12	5.16	61.92
YGFN42BXNWUVH1 + YUFN42BYNNUVH1	9	3.794	34.146
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	6	5.16	30.96
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	18	5.16	92.88
YGFN30BXNWUVH1 + YUFN30BYNNUVH1	3	2.53	7.59
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	15	4.46	66.9
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	4	5.16	20.64
YGFN42BXNWUVH1 + YUFN42BYNNUVH1	3	3.794	11.382
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	2	5.16	10.32
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	6	5.16	30.96
YGFN30BXNWUVH1 + YUFN30BYNNUVH1	1	2.53	2.53
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	5	4.46	22.3
YEFN24BXNWUVH1 + YUFN24BYNNUVH1	2	2.178	4.356
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	1	4.46	4.46
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	5.16	5.16
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	4.46	8.92
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	5.16	5.16
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	4.46	8.92
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	5.16	5.16
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	4.46	8.92
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	5.16	5.16
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	4.46	8.92
YGFN60BZMWUVH1 + YUFN60BYMNUVH1	1	5.16	5.16
YGFN48BXNWUVH1 + YUFN48BYMNUVH1	2	4.46	8.92
		Total	634.461

Then, the power input for the VRF outdoor units was calculated at 100%, 75%, 50% and 25% of cooling capacity shown in Table 18. Linear interpolation was also used to obtain the needed power input at these precise percentages. Based from the Air-Conditioning, Heating and Refrigeration Institute (AHRI), the VRF units will be running on 100% load for 2% of the time only, while for the 75%, 50% and 25% loads they will run 61.7%, 23.8% and 12.5% of the time [24].

The integrated energy efficiency ratio (IEER) was developed to address the actual efficiency of HVAC equipment that operates at different load levels. This ratio accounts for both full load and part load efficiencies. It does so by weighting energy efficiency ratio values at different load capacities and adding them together.

Most of the weight exists within the 50% and 75% load with a total of 85.5% of running hours. This is the main benefit of the VRF technology using the variable speed compressors.

Table 18 Total power input for VRF units (KW)

VRF OUTDOOR UNITS	Qty	100% Power Input per unit (KW)	100% Total Power Input (KW)	75% Power Input per unit (KW)	75% Total Power Input (KW)	50% Power Input per unit (KW)	50% Total Power Input (KW)	25% Power Input per unit (KW)	25% Total Power Input (KW)
YV2VYH080KASFDA1	1	23.43	23.43	16.36	16.36	9.59	9.59	2.21	2.21
YV2VYH112KASFDA1	1	32.74	32.74	22.87	22.87	13.35	13.35	2.99	2.99
YV2VYH095KASFDA1	1	28.71	28.71	19.80	19.80	11.56	11.56	2.41	2.41
YV2VYH033KASFDA1	1	9.92	9.92	6.80	6.80	3.97	3.97	0.82	0.82
YV2VYH101KASFDA1	1	30.54	30.54	21.10	21.10	12.33	12.33	2.61	2.61
YV2VYH068KASFDA1	1	20.46	20.46	14.12	14.12	8.22	8.22	1.71	1.71
YV2VYH095KASFDA1	3	28.71	86.13	19.80	59.40	11.56	34.68	2.41	7.23
YV2VYH033KASFDA1	3	9.92	29.76	6.80	20.40	3.97	11.91	0.82	2.46
YV2VYH101KASFDA1	3	30.54	91.62	21.10	63.30	12.33	36.99	2.61	7.83
YV2VYH068KASFDA1	3	20.46	61.38	14.12	42.36	8.22	24.66	1.71	5.13
YV2VYH095KASFDA1	1	28.71	28.71	19.80	19.80	11.56	11.56	2.41	2.41
YV2VYH033KASFDA1	1	9.92	9.92	6.80	6.80	3.97	3.97	0.82	0.82
YV2VYH101KASFDA1	1	30.54	30.54	21.10	21.10	12.33	12.33	2.61	2.61
YV2VYH068KASFDA1	1	20.46	20.46	14.12	14.12	8.22	8.22	1.71	1.71
YV2VYH130KASFDA1	1	38.75	38.75	26.92	26.92	15.75	15.75	3.49	3.49
YV2VYH130KASFDA1	1	38.75	38.75	26.92	26.92	15.75	15.75	3.49	3.49
Total			581.82		402.17		234.84		49.93

For this study two operational scenarios will be considered. The first scenario covers 12 hours of air conditioning while the second covers 24 hours 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 high temperature and humidity.

The average tariff obtained from Kahramaa (local power company) is 0.18 QAR per kW and it is used to calculate the total operating cost of the CRF and VRF systems in both scenarios. The air conditioning machines will function 12 months per year, 25 days per months and 12 hours per day for the first scenario and 24 hours per day for the second scenario. The running time of the ducted units is 70% considering that the compressor will rest once it reaches the set temperature point and restart again when the inside temperature rises. [25]. The operating cost is calculated by using the following formula:

$$\text{Operating cost} = \text{sum of (weight x running hours) x Tariff} \quad (9)$$

The details of the operating cost for both scenarios are tabulated in Tables 19 and 20.

The operating cost of the CRF is 38% higher than the VRF for both scenarios.

Table 19 Operating cost (scenario 1)

		Scenario 1 (12 hours)			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%	2,221	893,300			
50%	23.80%	857	201,211			
25%	12.50%	450	22,469			
Total		3,600	1,158,870	1,598,842		

Table 20 Operating cost (scenario 2)

Loading	Weightage	Scenario 2 (24 hours) Running hours per year	KWh VRF	KWh CRF	Operating cost (QAR) VRF	Operating cost (QAR) CRF
100%	2%	96	55,855	2,131,789	278,129	383,722
75%	61.70%	2,962	1,191,067			
50%	23.80%	1,142	268,281			
25%	12.50%	600	29,958			
Total		4,800	1,545,161	2,131,789		

4.2.3 Maintenance Cost

Next, the maintenance cost will be 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 [25].

4.2.4 Present Value

The initial, operating and maintenance costs for the two systems are developed in this study. A life cycle cost (LCC) analysis allows 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 9. The present worth cost technique is used to compare the total costs (initial, operating and maintenance) of the two alternative systems (CRF and VRF) considering the two operating scenarios (scenario 1 and 2) over the 15 years period. For scenarios 1 and 2, an extra investment of 546,000 QAR is paid for the VRF system, and the savings are 487,147 QAR for scenario 1 and 767,751 QAR for scenario 2.

Example of variation of overall present worth costs for both systems are shown in Fig. 25, Fig. 26, Fig. 27, Fig.28, Fig. 29 and Fig. 30 for representation purpose. Based on Table 9, for scenario 1 (12 hours operation) the present worth cost for VRF system is lower by 7-15% if compared to the CRF system and for scenario 2 (24 hours operation), the present worth cost for VRF system is lower by 10-18% 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 (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.

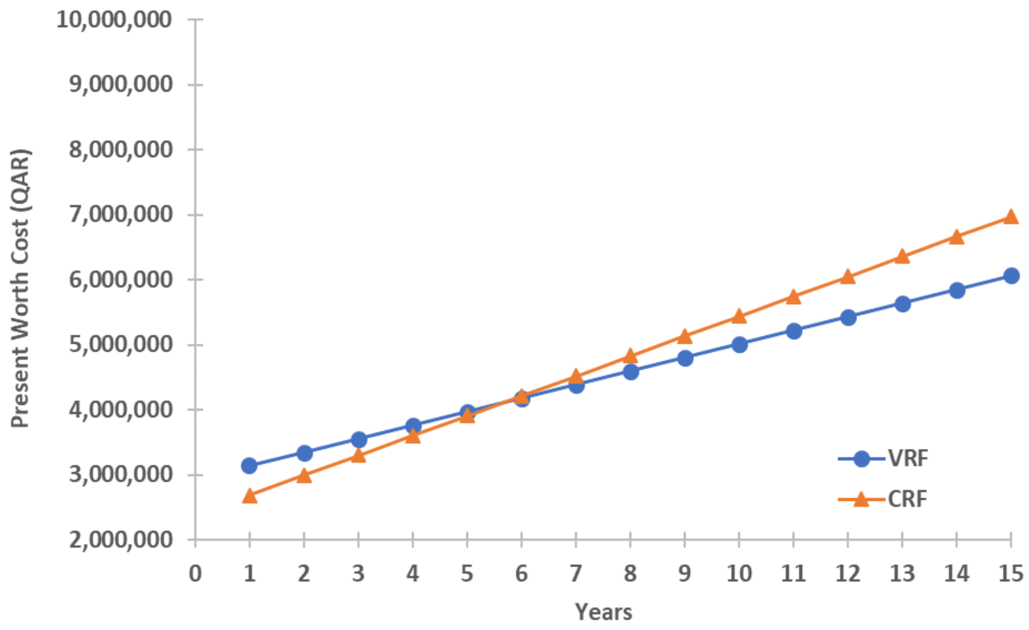

Figure 25 Present worth cost of scenario 1 (interest rate 3%, inflation rate 3%)

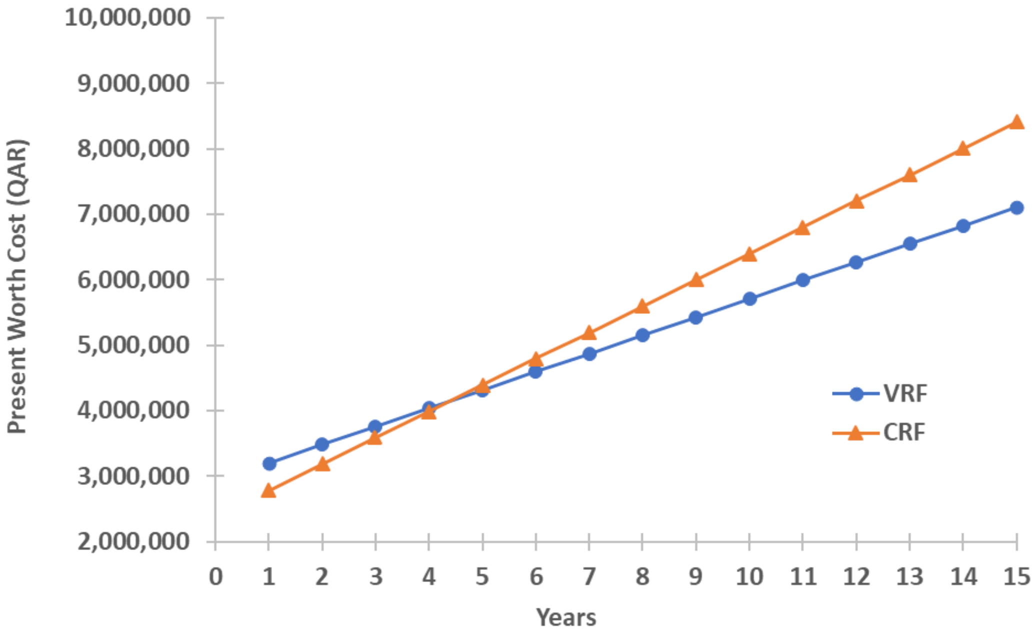

Figure 26 Present worth cost for scenario 2 (interest rate 3%. inflation rate 3%)

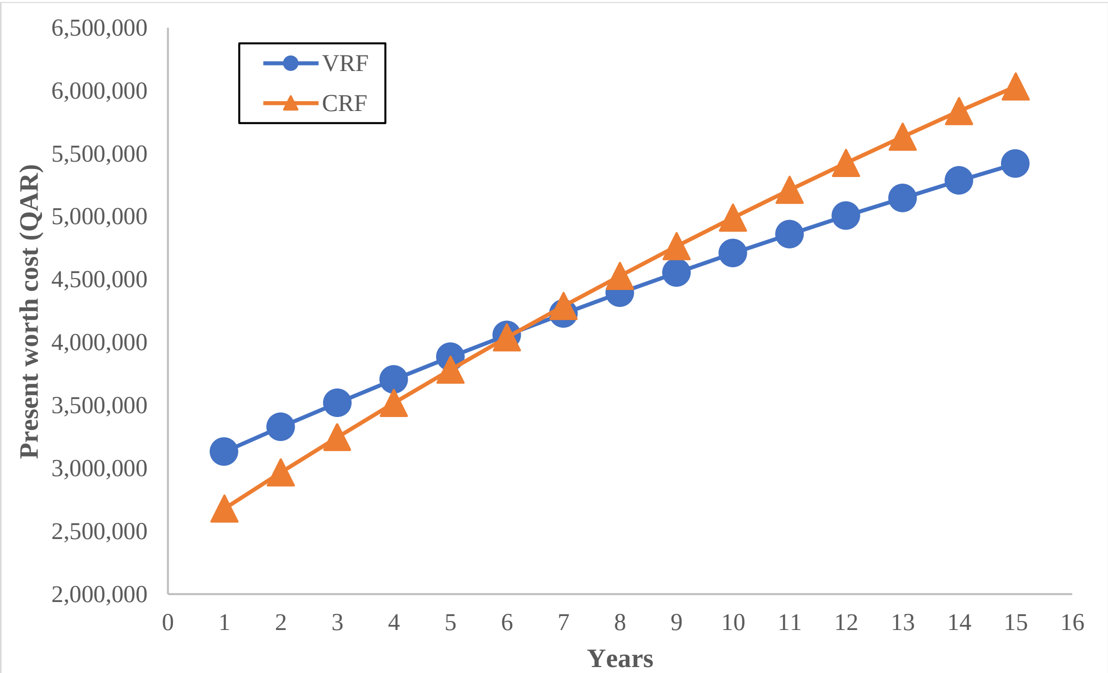

Figure 27 Present worth cost for scenario 1 (interest rate 3%, inflation rate 0%)

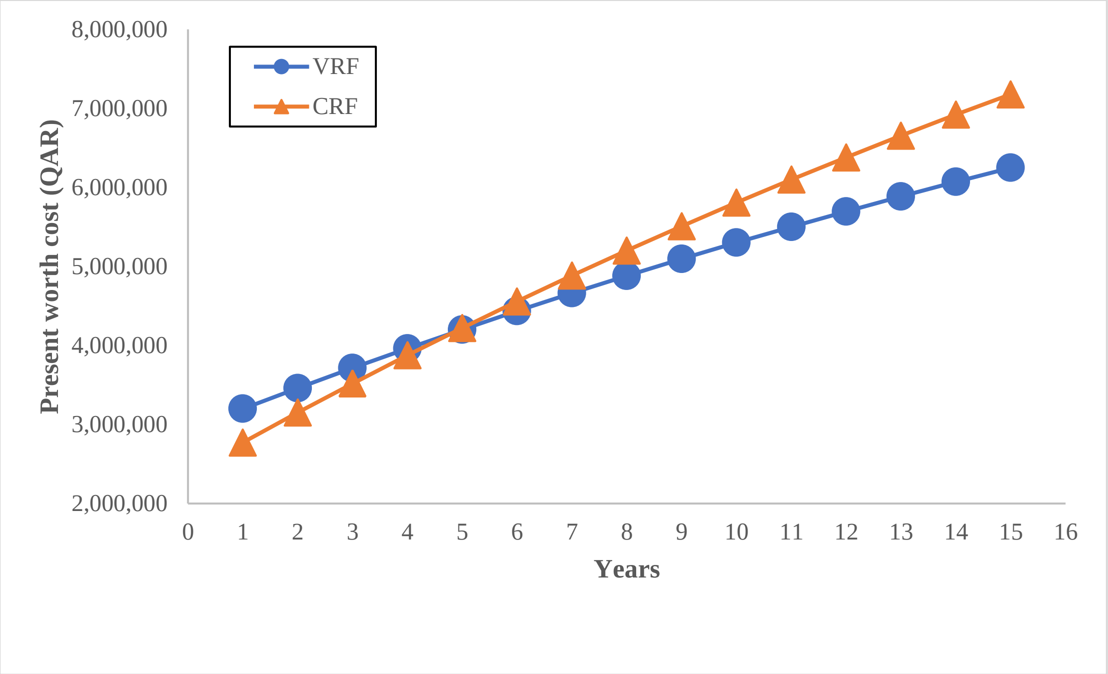

Figure 28 Present worth cost for scenario 2 (interest rate 3%, inflation rate 0%)

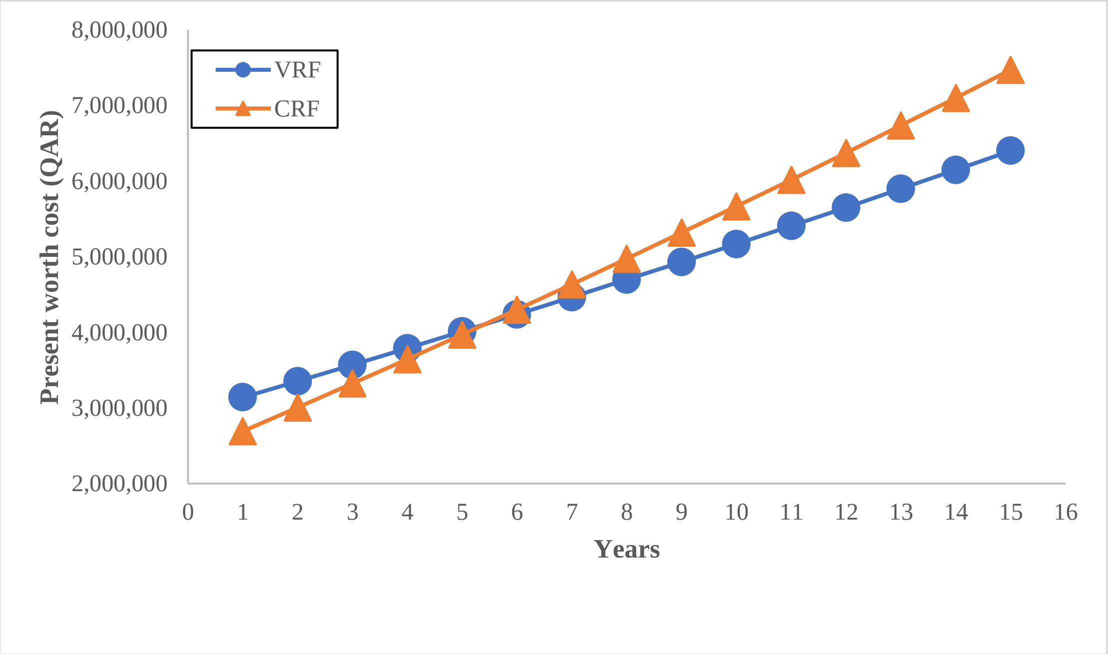

Figure 29 Present worth cost for scenario 1 (interest rate 4.65%, inflation rate 6%)

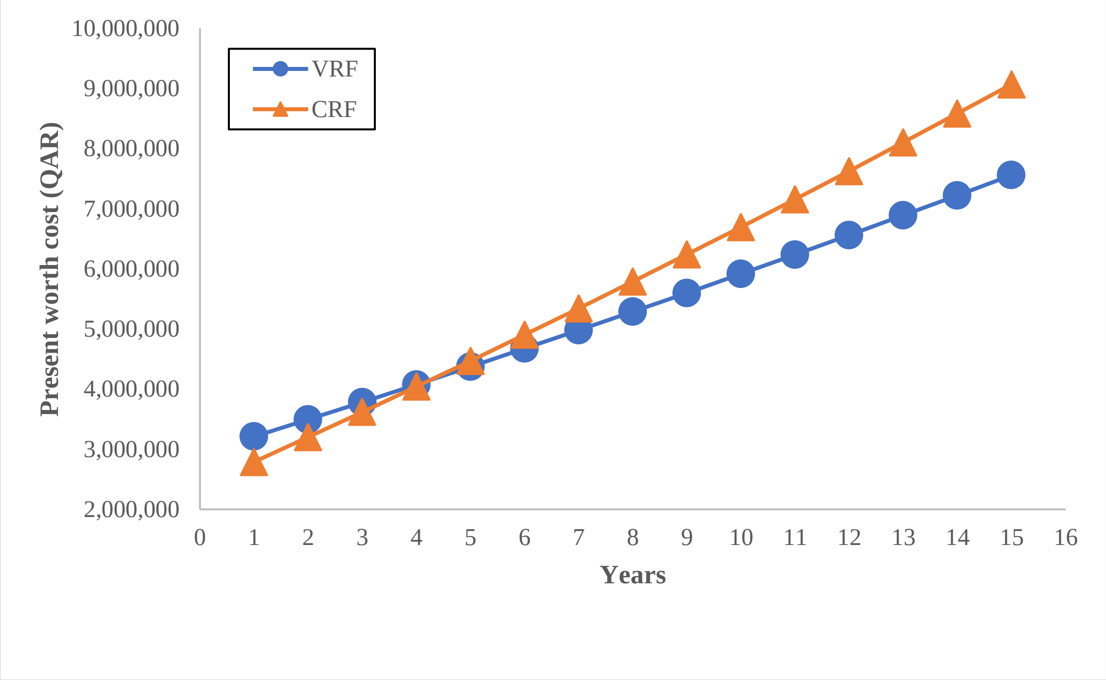

Figure 30 Present worth cost for scenario 2 (interest rate 4.65%, inflation rate 6%)

World leaders have been crafting national plans to significantly reduce global carbon emissions since the U.N.'s 2015 international treaty on climate change (The Paris Agreement) [40].

In the United States and by the end of 2050, 12 states and 160 cities have official goals to get 100% of their electricity from clean sources [38]. Building decarbonization plays an important role in the transformation of the HVAC systems.

There are two types of carbon in a building:

- embodied
- operational

Embodied carbon is the total greenhouse gas emissions from the materials and the construction process throughout the life cycle of the building. Operational carbon on the other hand, is continuously emitted and significantly outweighs the embodied carbon over a 50-year lifetime of a building. Variable Refrigerant Flow (VRF) systems have gained traction in recent years given their impact in decarbonization efforts globally [39].

The impact of the reduction in energy consumption due to VRF technology implementation can be appreciated through visualizing it through CO_2 reduction [37]. In the equivalency calculator, the energy reduction can be converted to carbon dioxide-equivalent greenhouse gas emissions reduction. Details of this benefit is shown in the below figure. In summary and by using VRF over CRF, an equivalent amount of 311,820 kg of CO_2 greenhouse gas is reduced.

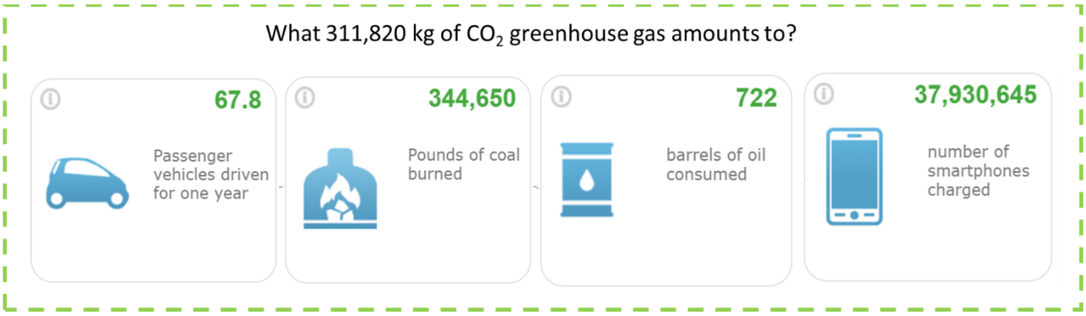

Figure 31 The amount of CO2 reduction due to utilization of VRF technoclogy in one building (case study)

In 2018, the weighted average combined fuel economy of cars and light trucks was 22.5 miles per gallon (FHWA 2020). The average vehicle miles traveled (VMT) in 2018 was 11,556 miles per year (FHWA 2020). The amount of carbon dioxide emitted per gallon of motor gasoline burned is 8.89 × 10-3 metric tons.

8.89 × 10-3 metric tons CO2/gallon gasoline × 11,556 VMT car/truck average ×

1/22.5 miles per gallon car/truck average × 1 CO_2, CH_4, and N_2O/0.993 CO_2 = 4.60 metric tons CO_2E/vehicle /year.

While 439,972 kilowatts-hours of electricity is equivalent to 312 metric tons of Carbon Dioxide so the equivalent number of vehicles is 312/4.6= 67.8

4.3 VRF Roadmap Implementation on a National Level

4.3.1 Roadmap Objective

The ultimate goal of this roadmap is to create a clear path to reducing air conditioning energy consumption and expenditure on a national level in the State of Qatar. It can be divided into four levels as shown in the figure below:

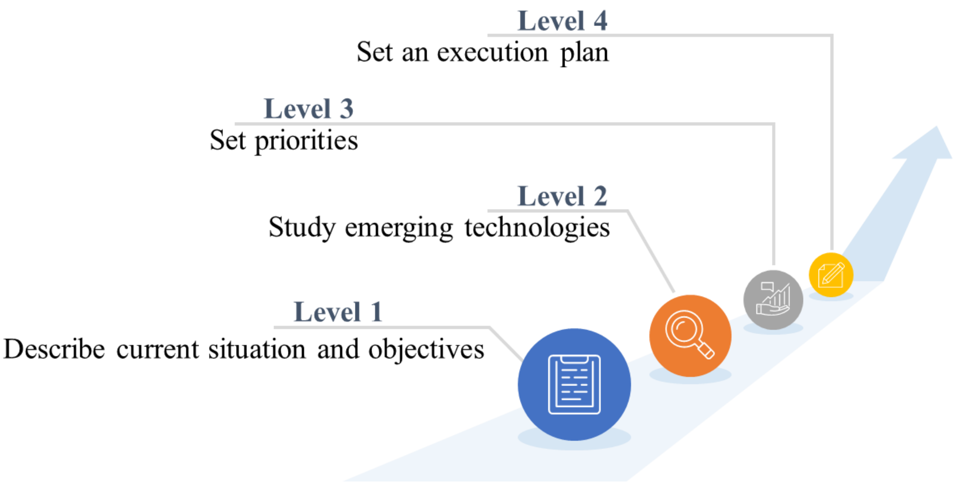

Figure 32 Roadmap to air conditioning energy consumption in Qatar

4.3.1.1 Level 1: Describe Current Situation and Objectives

In the State of Qatar, HVAC accounts for 60 to 70% of the electrical demand in commercial and residential buildings. Therefore, the energy savings that the VRF system is showing, are very important when applied on a national scale. When considering a combination ratio of 100%, those savings reached 27%. In reality, the combination ratio can be increased depending on the design criteria and on the manufacturer’s recommendations. It is certain that these savings will increase with higher combination ratios.

Kahramaa, the power provider in Qatar, is increasing the power grid capacities every year to meet the increasing demand in the country. Sub-stations from all sizes are being tendered and constructed in all regions. Some of the old stations are being renovated and expanded in an attempt to close the gap between supply and demand and to plan for the future expansions. Hence, the VRF implementation will have a significant cost reduction impact on Kahramaa in terms of reducing the HVAC electrical demand and allowing this energy to be used somewhere else. Detailed studies can be performed to determine the value of the savings in terms of Qatari Riyals. These studies have to be divided into two segments: new projects and retrofitting projects. In our paper, we explored the new project option while the other one requires additional details such as: building type, existence of suitable shafts, type of false ceiling, location of indoor and outdoor units, the cost related to these activities and many other parameters. This extra cost has to be incorporated in the life cycle analysis to determine the break-even point. Changing the air conditioning system in an existing building is a challenging task. Therefore, major technical steps have to be followed to ensure the success of this project:

- It can be very useful to keep the same indoor units’ capacities and quantities so that we minimize the works inside the building. We can use the same power outlets and the same drainage points.

- This way, we limit the false ceiling works inside the building and we reduce the extra cost.

- The VRF system offers the advantages of connecting multiple type of indoor units which could resolve a lot of technical problems on site. If there is no space for ducted units, we can always choose high wall units or floor mounted units.

- The location of the outdoor units is important so that the manufacturer recommendations are always respected.
- Depending on the site conditions, we can always propose to combine multiple areas or rooms in one or more outdoor VRF unit. This will contribute tremendously in reducing the additional cost.
- Finally, we can increase the combination ratio above 100% to achieve more energy savings within the manufacturer's recommendations and the project requirements.

Hence, as a start, existing research done in this area must be reviewed and studied carefully and clear objectives have to be well defined. For example, is the government looking to reduce the air conditioning consumption in residential and commercial buildings only or is it going to expand the research to cover the industrial buildings. Other objectives can also be defined such as pollution and CO_2 emission reduction, attractive consumer Kahramaa rates, etc…

4.3.1.2 Level 2: Study Emerging Technologies

It would be very useful to study past roadmaps if any and identify the technologies involved at that time. Then, recent research about the emerging technologies must be conducted in coordination with all concerned stakeholders. Suppliers have to provide technical details and manufacturer's recommendations. Kahramaa and other governmental departments have to study the feasibility of these new technologies compared to the existing situation on the ground. The study should include a life cycle assessment to determine the best alternative that is meeting the objectives. In addition to the operational energy, there should be an investigation regarding the embodied energy as well. The manufacturing process of each alternative should be studied to determine all of its aspects. A factory in China could have different standards than a factory in Japan. The Carbon Dioxide emissions could be different between the two of them in addition to many other factors that must be included in the life cycle assessment. It is also noted that each technology presents different levels of required training and expertise.

At the time of the study, there was no local factory in Qatar but in the future this possibility has to be studied as well to compare the transportation impact on the life cycle assessment. In brief, all stakeholders must present their input before moving to the third level. In this paper, we showcase the VRF technology in details and we aim for a wide implementation on a national level.

4.3.1.3 Level 3: Set Priorities

Many initiatives and ideas will be presented during the roadmap course of work. Therefore, it is essential to prioritize them by using qualitative and quantitative scoring systems. Different criteria will be scored such technical potential, financial capability and others. So, targets have to be developed in order to keep the focus in the right direction. In our study on VRF technology, the cost reduction related to the sub-stations will be decreased or the usage of the substations will be more efficient.

Second, the government will reduce its own bill in terms of carbon emissions and pollution that is linked to the health sector which is in return covered by the State of Qatar. For these reasons, incentives can be offered to the building owners to adopt the implementation of the VRF systems, encouraging them to invest in this technology. Even though the initial cost is higher, the owners will benefit from a better life cycle cost and from governmental incentives such as tax reductions or reduced Kahramaa unit rates. Such targets can be defined and the roadmap will be designed to achieve them.

4.3.1.4 Level 4: Set an Execution Plan

Once the first three levels are accomplished, an execution plan must be prepared comprising the following major components:

- Identify each stakeholder’s role and communicate properly and professionally.
- Prepare a realistic schedule and highlight the milestones.
- Define the tasks in a work breakdown structure (WBS) with well defined responsibilities and reporting systems.
- Set a budget for all the works involved and keep a contingency plan ready for execution.

CHAPTER 5 – CONCLUSION

5.1 Summary of Major Findings

When comparing the VRF and CRF systems in this study, initial, operating and maintenance costs are calculated for Al Muftah Plaza building in Qatar. The present worth cost method and the LCC analysis are used for two different scenarios. At the end of 15 years, the present worth cost of the VRF system is found to be always lower than the present worth cost of the CRF system, the conventional ducted units in our case. When the operating hours are longer, scenario 2, the VRF system shows a bigger economical advantage over the CRF system. 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.

5.2 Contribution of the Study

This study presents a scientific document proving that the use of the VRF technology in the air conditioning field can play a major role in terms of energy savings and cost reductions. Therefore, stakeholders such as government, building owners, designers, consultants, suppliers and contractors can push furthermore for this kind of green technology to attain higher levels of sustainability on a national scale. This study will become a baseline for future works as part of a bigger plan that will help the State of Qatar achieve the 2030 vision.

5.3 Limitation of the Study

This study was conducted for an office building only without considering an energy model or an energy simulation study to obtain detailed information about the energy consumption difference between the day and night, summer and winter. This study was conducted for the purpose of implementing the VRF technology for the new buildings while the retrofitting works have to be studied in details.

5.4 Future Work

The present work focuses on comparing the outdoor units of both VRF and CRF systems in an office building while keeping the same indoor units' capacities. In reality, the VRF system can be designed with a combination ratio higher than 100% so that it offers higher values of energy savings. Hence, a simulation study with an accurate energy model can be conducted to investigate further energy savings and cost reductions in both residential and commercial buildings. The energy model will create a virtual simulation of the building and will perform the calculations taking into account the weather conditions of an entire year. This way we can predict the future results more accurately. The energy model will be based on the design load and energy analysis. The design part was discussed in our paper while the energy analysis part will be able to predict monthly energy consumption, annual energy cost, CO_2 emission and determine the life cycle payback. Another study can focus on the energy savings related to Kahramaa by using the VRF technology and the incentive plans that the government can provide to its citizens and residents. This study can cover the entire State of Qatar taking into consideration that some new laws have to be introduced and the incentive plans will be interconnected between the ministry of finance, Kahramaa and the ministry of power.

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