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Life Cycle Cost Analysis of Hybrid Solar Thermal VRF System for Space Conditioning: A Case Study of Hall in Dhunche

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Abstract

Solar thermal system (STS) and Variable Refrigerant Flow (VRF) both are promising technologies for providing thermal comfort in buildings. However, each individual system has its own advantages and drawbacks. STS utilizes free energy, but it has high initial cost since it requires large number of collectors to meet total thermal demand. VRF system is usually preferred for its low installation cost and lower footrprint but its operation appears to be costly in the long run than STS. By combining STS and VRF to form hybrid system, advantages of both the system can be utilized while diminishing some major drawbacks. This research intends to assess the cost effectivenss of hybrid system in a commercial sector of Nepal by analyzing the life cycle cost (LCC) of the system for 25 years. A space has been designed in Dhunche, following architecture design standards, requiring heating load of 7.77 KW and cooling load of 3.3 KW. The heating load will be shared by STS and VRF system while only VRF will meet cooling load. LCC analysis is done for possible combination of STS and VRF for meeting total thermal load, and at 48.5% sharing by STS and 51.5% sharing by VRF of total heating load, the LCC is found minimum. Comparing values with the standalone system, it is found that LCC of standalone solar thermal system is less than both standalone VRF system and hybrid system for 25 years of service life; however, standalone solar thermal system consumes large space and cannot be utilized for cooling purpose.

Keywords

Hybrid System, Life Cycle Cost, Space Conditioning, Solar Thermal System, VRF System

1. Introduction

Every year, massive quantity of energy is consumed for meeting total thermal load of the buildings. The buildings account for about 40% of the global energy consumption and contribute over 30% of the CO_2 emissions [1]. In case of Nepal, about 4% of total energy consumed is for the purpose of space heating [2]. Many technologies are emerging for providing thermal comfort at reduced energy use and carbon emission. Variable Refrigerant Flow (VRF), Solar Thermal System (STS) and heat pumps are major promising technologies for meeting total thermal load around the world.

Providing indoor thermal comfort and reducing energy use in buildings are becoming increasingly difficult and has called for new ways of thinking and re-evaluation of the existing methods of tackling this problem [3]. Hybrid systems exploiting a mix of conventional fuels and Renewable Energy System (RES) for heating and cooling has shown remarkable results with improved system performance and can bring important savings to the yearly building energy consumptions [4].

Solar heat pumps (SHPs) are hybrid systems where heat pumps are combined with solar thermal, solar photovoltaic, or both. Solar thermal collectors can be combined either in parallel or in series with heat pumps. In parallel systems both solar collector and heat pump provide heat for the loads either directly or via the store, while in series, heat from the solar collector is used indirectly as the heat source for the heat pump evaporator [5]. The parallel configuration is simpler in design, installation and control and, furthermore, is more energetically efficient when solar radiation is high enough [6].

Integrating solar heating technology with heat pumps can maximize the utilization of solar energy by overcoming the irregular intensity of solar irradiance, and enhancing the Coefficient of Performace (COP) of the heat pump [7]. Lerch studied different combinations of solar thermal and heat pump systems through dynamic system simulations in TRNSYS. With a combined parallel solar thermal HP system, the system performance compared to a conventional HP system was found to increase significantly [8]. Carbonell studied three combined systems: solar and air source heat pump, solar and ground source heat pump, and solar source heat pump in combination with an ice storage and found that the absolute electricity savings of air source was higher [6].

Most of the research in hybrid system show that the dominant source of solar assisted heat pumps is liquid with a thermal storage. Only few studies have investigated the possibilities of combining a solar system with an air source heat pump (ASHP). VRF is more advanced than ASHP; it can be used both for summer and winter, has large capacity and more efficient than ASHP. Integration of STS with VRF to form hybrid system can utilize advantages of both the individual system while diminishing their major drawbacks.

Nepal has huge potential of solar energy with 300 sunny days a year and average sunshine hour of 6.8 per day [9]. But use of solar thermal technology for space heating is still not practiced much in the country as large number of solar collectors are required for meeting total thermal load, hence high investment cost and large space requirement [10]. VRF system is usually preferred as it has low initial cost than STS and requires less space. However, its operation appears to be costly than STS in the long run [11]. The hybrid system can reduce the total cost for meeting total thermal load in building. In this research, the solar thermal will be combined in parallel with VRF for space conditioning in commercial sector at Dhunche and life cycle cost analysis will be computed for selection of hybrid system and comparison with its equivalent standalone system.

2. Methodology

2.1 Selection of suitable site and space

A reference commercial building in Dhunche has been considered. Analyzing the average monthly maximum and minimum temperature values at Dhunche of five years (from 2013 to 2017 AD) taken from Department of Hydrology and Meteorology, it has been found that heating is required for around 7 months of the year (from October to certain days of April) and around 3 months of cooling (May, June, and July) is required, considering comfortable design temperature of 22 $°C$ [12]. The minimum temperature is around 3 $°C$ in January and maximum temperature is around 25 $°C$ in June. A meeting hall comprising of around 20-25 persons was designed, following architecture design standards, with total floor area of 500 ft^2 and room height of 9 ft^2 as shown in figure 1. The meeting hall is located on the top floor of the three storey building with total floor area of 1560 ft^2.

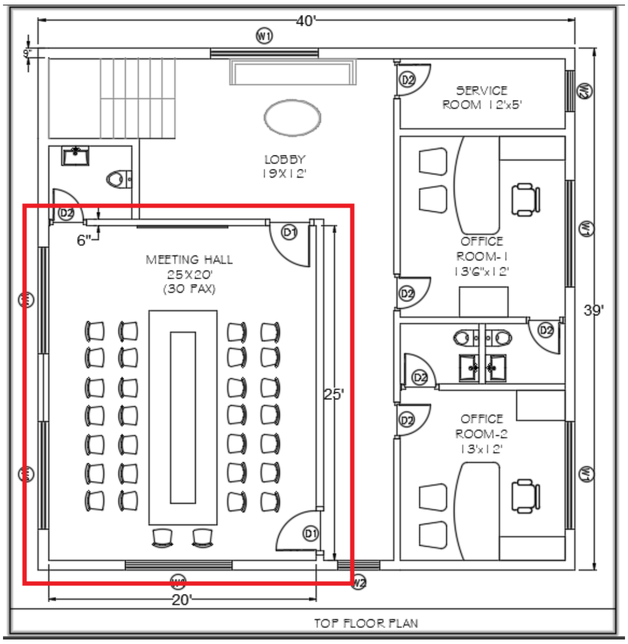

Figure 1: Top floor plan with meeting hall

2.2 Estimation of overall heat transfer coefficient

The overall heat transfer coefficient values were calculated for different components of the room to account for different modes of heat transfer. The heat transfer coefficients from different modes were combined to form an overall heat transfer coefficient. The overall heat transfer coefficient for a multi-layered wall with fluid flow on each side of the wall can be calculated as:

$$1 / U*A = 1 / h_i*A_i + S_n / k_n*A_n + 1 / h_o*A_o$$

where,
U = overall heat transfer coefficient (W/(m^2 K)),
k_n = thermal conductivity of material in layer n (W/(mK)),
$h_{i,o}$ = inside or outside wall individual fluid convection heat transfer coefficient (W/(m^2 K)),

S_n = thickness of layer n (m)

Table 1 shows the U value computed for various components of the hall using above formulae.

Table 1: U value for various components of hall

Components of Room	U Value (W/m^2K)
Outside Wall	2.15
Floor	2.03
Roof	5.33
Partition	2.39
Door	0.64
Window	5.94

2.3 Estimation of heating and cooling load

Heat loss occurs in a room by means of transmission and infiltration whereas heat gain occurs in a room through transmission, infiltration, fenestration, internal heat gain through lights, occupants, etc. The amount of heat transfer has been calculated as per guidelines given in ASHRAE handbook. By energy amount of heat balance, the heat loss or gain must be compensated by thermal system for maintaining constant comfortable room temperature. This amount of energy to be added or taken by thermal system is called thermal load, which is heating load in case of heat loss and cooling load in case of heat gain.

The total heating load for the meeting hall has been calculated and obtained as 7.77 KW and total cooling load to be 3.3 KW. The hybrid thermal system must be able to supply thermal energy at this rate to maintain the meeting hall at comfortable temperature of $22°C$ [12].

2.4 Possible combinations of hybrid system for meeting thermal load

VRF system alone will meet the cooling load of 3.3 KW while both STS and VRF will be sharing certain percentage to meet heating load of 7.77 KW. So, the size range for VRF was from 3.3 KW to 7.77 KW. Two standard sizes for VRF were available in market within this range; of 4 KW and 5.8 KW heating load. If 5.8 KW of heating load was met by VRF, 2 KW would be met by STS, resulting in 25.3%-74.7% STS/VRF sharing and if 4 KW of heating load was met by VRF, 3.8 KW would be met by STS, resulting in 48.5%-51.5% STS/VRF sharing, as shown in table 2. So, two possible hybrid combination of STS and VRF system were found out.

Table 2: Possible combination of solar thermal and VRF system

Combination	System	% Sharing	Heating load (KW)
1	STS	25.3%	2
	VRF	74.7%	5.8
2	STS	48.5%	3.8
	VRF	51.5%	4.0

2.5 Selection of hybrid system based on LCC analysis

For VRF, standard size of indoor and outdoor components were used. While, for STS, sizing of all componens required was done for meeting 2 KW and 3.8 KW of heating load. Number of solar collectors, size of storage tank required in litres, number of panel radiator required to be installed in room, size of pump in W, and length of pipes required were computed using necessary design formulaes. After sizing of components, cost of each required equipment was obtained from local suppliers in market by preparing Bill of Quantities (BoQ). After that, the capital cost and annual operation and maintenance (O&M) cost were calculated. The capital cost included cost of equipment, labour cost for installation and transportation cost. The service life was assumed to be for 25 years for both VRF and STS. The LCC for two possible combinations of hybrid system was computed and hybrid thermal system with less LCC was selected for comparison with their equivalent standalone systems.

Life Cycle Cost is given by: LCC = Present Value of Capital Cost + Present Value of Maintenance Cost + Present Value of Energy Cost

3. Results and Discussions

3.1 Capital Cost for Solar Thermal System

After calculating size of required components, the capital cost was obtained from local suppliers who import and distribute such components from international market. The obtained capital cost for STS for 48.5% sharing and 25.3% sharing of heating load has been shown in table 3.

Table 3: Capital cost for STS

Components	Capital Cost for 48.5% sharing	Capital Cost for 25.3% sharing
Solar Flat Plate Collectors	220,944	110,472
Collector Stand	35,292	17,646
Auxiliary Heating Device (2KW)	2,000	2,000
Hot Water Storage Tank	330,000	192,500
Circulating Pump 1 (from storage tank to collector)	5,000	5,000
Circulating Pump 2 (from radiator to storage tank)	5,000	5,000
Radiator	46,000	23,000
CPVC Pipe (1 inch diameter)	12,600	6,300
CPVC Pipe (1/2 inch diameter)	8,510	4,440
Pipe Fittings	6,000	4,000
Pipe Insulation (Elastomer)	11,400	5,850
Solenoid Valve	5,000	5,000
Pressure Bypass Valve	3,000	3,000
Temperature Sensor	3,800	3,800
CPVC Ball Valve	1,770	1,770
Installation Cost	7,000	5,000
Total Capital Cost	703,316	394,778

3.2 Capital Cost for VRF system

Air cooled single split unit system is selected, which can be utilized both for cooling as well as heating. The total capital cost for indoor and outdoor component for such system for 74.7% sharing and 51.5% sharing of total heating load is shown in table 4.

Table 4: Capital cost for VRF system

Components	Capital Cost for 74.4% sharing	Capital Cost for 51.3% sharing
Air Cooled, Single Split Unit	160,000	125,000
Refrigerant Grade K Class Pipe	4,290	4,290
Closed Cell Thermal Insulation	690	690
CPVC Drain Pipe	4,500	4,500
Closed Cell Tubular Insulation for Condensate Drain Pipe	1,650	1,650
Electrical Cables & Control Cables	750	750
Miscellaneous (Labour, Travel, Installation) Cost	10,000	10,000
Total Cost	181,880	146,880
VAT	13%	13%
Grand Total Cost	205,524.40	165,974.40

3.3 Annual Operation and Maintenance Cost for Solar Thermal System

The service life is assumed as 25 years after installation without any further investments and major overhaul. The electricity charge is assumed to be NRs. 11.2 per KWh for commercial sector [13]. The auxiliary heating device is assumed to run half an hour every day. The system is assumed to run for total of 210 days during winter in a year. The annual O&M cost mainly comprise of the electricity cost for operation of two pumps, auxiliary heating device and cleaning charge for collector plus general maintenance. The annual O&M cost for 48.5% sharing and 25.3% sharing of total heating load has been shown in table 5.

Table 5: Annual O&M cost for STS

Particulars	Annual Cost for 48.5% sharing	Annual Cost for 25.3% sharing
Pump Running Cost	2,118	1,412
Auxiliary Heating Device	2,352	2,352
Collector Cleaning Charge + General Maintenance	3,500	2,500
Total Cost	7,970	6,264

3.4 Annual Operation and Maintenance Cost for VRF

For VRF also, the service life is assumed as 25 years after installation without any further investments and major overhaul. The operation cost for VRF includes electricity cost for operating indoor and outdoor units. The annual O&M cost for 75.7% sharing and 51.5% sharing of total heating load has been shown in table 6.

Table 6: Annual O&M cost for VRF

Particulars	O&M Cost for 75.7% sharing	O&M Cost for 51.5% sharing
Annual electricity cost	26,651.63	13,454.22
Annual Maintenance cost	10,000	5,000
Total Yearly O&M Cost	36,651.63	18,454.22

3.5 Total Life Cycle cost for hybrid system

The average yearly inflation rate has been assumed to be around 4.5% [14] and discount rate to be around 10%. Table 7 shows the total life cycle cost calculated for two possible combinations of hybrid system.

Table 7: LCC Cost for Hybrid System

Particulars	Solar Thermal	VRF Split Unit
At 48.5% - 51.5% sharing		
LCC Cost	1,026,211.2	913,625.6
Total	1,939,836.8	
At 25.3% - 74.7% sharing		
LCC Cost	648,556.6	1,690,422.3
Total	2,338,978.9	

From the table 7, it can be seen that the life cycle cost is less at 48.5% - 51.5% sharing than at 25.3% - 74.7% sharing by STS-VRF systems by around 17.06%. So, hybrid combination having 48.5% - 51.5% sharing by STS-VRF system is selected.

In the selected hybrid system, 3.77 KW of total heating load will be covered by STS and 4 KW of load will be covered by air cooled VRF system. Six collectors, each of area 2 m^2, are required. The collectors are paired in two, and the pairs are then connected in parallel to get the output temperature of water 50 $°C$. Insulated tank of capacity 6000L is used.

One inch CPVC pipe insulated from outside is employed in collector side and 0.5 inch CPVC pipe is used in radiator side. Two pumps of capacity 45 W each are employed in collector side and radiator side respectively to circulate water.

3.6 Comparison with standalone system

The sizing of components required for standalone use of STS were calculated using design formulaes. For VRF, standard nearby size available in market was selected. After finalization of sizing of required components, the capital cost for standalone STS and VRF system were obtained from local suppliers by preparing BoQ. The calculations are shown in tables 8, 9, 10 and 11.

Table 8: Capital cost for standalone STS

Components	Capital Cost
Solar Flat Plate Collectors	441,888
Collector Stand	70,584
Auxiliary Heating Device (2KW)	2,000
Hot Water Storage Tank	660,000
Circulating Pump 1 (from storage tank to collector)	5,000
Circulating Pump 2 (from radiator to storage tank)	5,000
Radiator	92,000
CPVC Pipe (1 inch diameter)	25,620
CPVC Pipe (1/2 inch diameter)	11,655
Pipe Fittings	10,000
Pipe Insulation (Elastomer)	18,600
Solenoid Valve	5,000
Pressure Bypass Valve	3,000
Temperature Sensor	3,800
CPVC Ball Valve	1,770
Installation Cost	10,000
Total Capital Cost	1,365,917

Table 9: Capital cost for Standalone VRF system

Components	Capital Cost
Air Cooled, Single Split Unit	1,85,000
Refrigerant Grade K Class Pipe	14,040
Closed Cell Thermal Insulation	1,920
CPVC Drain Pipe	4,500
Closed Cell Tubular Insulation for Condensate Drain Pipe	1,650
Electrical Cables & Control Cables	2,000
Miscellaneous (Labour, Travel, Installation) Cost	10,000
Total Cost	219,110
VAT	13%
Grand Total Cost	247,594.30

Table 10: Annual O&M cost for Standalone STS

Particulars	Annual O&M cost
Pump Running Cost	2,824
Auxiliary Heating Device	2,352
Collector Cleaning Charge + General Maintenance	5,000
Total Cost	10,176

Table 11: Annual O&M cost for Standalone VRF System

Particulars	Annual O&M Cost
Annual Electricity cost	43,989.68
Annual Maintenance cost	15,000
Total Yearly O&M Cost	58,989.68

In the similar manner, LCC for standalone STS and VRF system was calculated. Table 12 shows the total life cycle cost calculated for standalone STS and VRF system. For comparison, only heating mode of VRF is assumed to run for total of 210 operating days during winter.

Table 12: LCC Cost for Standalone System

Particulars	Solar Thermal	VRF Split Unit
At 100% sharing Total LCC Cost	1,778,185.7	2,637,492.0

Comparing LCC values of selected hybrid system with its standalone solar thermal system and VRF system, it can be seen that the life cycle cost of selected hybrid system is less than standalone VRF system by around 26.45%. The LCC of standalone STS is minimum than LCC of selected hybrid system by around 8.33% and standalone VRF system by around 48.32%for meeting total heating load of 7.77 KW, however, in the calculation, space costs by STS has not been considered and STS cannot be utilized for cooling purpose unlike VRF.

4. Conclusions

Dhunche was selected as preferred location as it has heating requirement (for seven months of the year) dominant than cooling requirement (only for three months of the year). A reference meeting hall comprising of 20-25 persons was designed following architecture design standards, for which, the heating load was obtained to be 7.77 KW and the cooling load to be 3.3 KW. Since VRF alone had to meet cooling load of 3.3 KW during summer, so the minimum size for combination started with 3.3 KW. Two standard sizes of VRF were available in market from 3.3 KW to 7.77 KW. So, two different combinations of solar thermal plus VRF system was found to be possible for calculated thermal load. First combination was 48.5% STS and 51.5% VRF and second combination was 25.3% STS and 74.7% VRF. After detailed design and system sizing, the BoQ was prepared for both hybrid combinations. Installation cost and O and M cost for service period of 25 years were computed for both combination of hybrid systems for conducting LCC analysis. Between two combinations, the LCC for 48.5% STS and 51.5% VRF was obtained to be minimum. Comparing the LCC of selected hybrid system with its standalone STS and standalone VRF system, the LCC of selected hybrid system was found to be less than standalone VRF. It was found that LCC of standalone solar thermal system was less than LCC of both standalone VRF system and hybrid system for 25 years of service life, however, standalone solar thermal system consumes large space and cannot be utilized for cooling purpose. So, the designed hybrid system is financially more cost effective than standalone VRF system, and can be utilized for providing thermal comfort in both summer and winter.

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