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TECHNICAL-ECONOMIC COMPARISON OF UNITARY AIR CONDITIONING AND VRF SYSTEMS FOR HIGH STANDARD RESIDENCES IN MANAUS CITY

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Abstract. *Air conditioning aims to provide thermal comfort to the occupants of a given space, but it is also responsible for providing air quality and well-being. This paper aims to compare the different air conditioning strategies for high-end residences in Manaus city, using split and VRF (Variable Refrigerant Flow) systems. The annual cooling load profile was obtained for each building and the systems were sized to determine energy consumption, costs and payback, considering two scenarios, one for continuous use and the other for recreational use. The results showed that, in terms of energy, the VRF system is advantageous for both residences, as annual consumption is 41% lower in House A and 38% lower in House B, compared with split system. In addition, the payback of the VRF system proved to be attractive for the two residences with continuous use mode, as the financial return occurs in less than 3 years. On the other hand, in the case of recreational housing for sporadic use (House B), the unitary system with inverter splits becomes more advantageous since its initial investment is 64% lower than the VRF. Furthermore, in this B-house scenario, the VRF system had a very long payback (9.5 years), close to the end of its useful life, making its application unfeasible.*

Keywords: *COP, Split, VRF, Comparison.*

1. INTRODUCTION

The air conditioning project is one of the most critical factors in complementary architectural projects, as it can interfere with the structure, aesthetics and energy efficiency of the building. Sizing the air conditioning system can be challenging, as designing a system that meets all energy, legal requirements and also be suiTable for the architectural characteristics of a high-end residence, it may not be such a trivial task.

The choice of air conditioning system type will depend on the thermal load and building characteristics. In this sense, high-end single-family buildings, which have a more sophisticated architecture, usually go through the impasse of choosing between a low initial cost system (split), but with higher energy costs, and a more efficient system (VRF), but with higher initial investment (GOMES and CHAVES, 2012).

Although the VRF system has gained place in national market in recent years, mainly due its energy efficiency, the split system is still widely spread and used in the majority of brazilian homes (ROSA and LOPES, 2022).

Therefore, this research seeks to analyze which air conditioning system has the best cost-benefit for high-end homes, comparing the costs due to the acquisition, installation and electrical consumption of two high-end homes located in Manaus (AM), served by a split system and VRF system, considering continuous and seasonal occupancy.

2. LITERATURE REVIEW

The air conditioning consists of controlling the temperature and humidity indoor air, in order to guarantee thermal comfort or the ideal conditions of an industrial process (ASHRAE, 2013). Among the types of conventional systems, like split type, VRF, Self-contained and direct expansion (chillers) stand out, with the first two being the most used in small and medium-sized buildings.

According to Gomez and Chaves (2012), split systems basically consist of two separate units (internal and external) connected to each other by refrigerant gas pipes. The indoor unit has a fan, air filter, evaporator and expansion device. It is responsible for cooling and circulating air in the environment. The compressor, the condenser coil and its fan are located outside, and act on rejecting heat to the outside. The VRF system, according to Duarte (2014), is composed by a single condenser, which is the external unit, connected to several evaporators, which are the internal units. Each evaporator can be operated and controlled independently of the others ones. The compressor's power changes with the variation of its rotation and the flow of refrigerant fluid varies through electronic expansion valves located in each internal unit, which connects to the external unit through the same refrigeration circuit. The VRF system can be a good option compared to other technologies, because when the compressor operates at partial loads, it presents two advantages; energy efficiency and individualized service by environment (GOMES and CHAVES, 2012).

The advantages of using VRF systems over other ones are already known. For example, Santos (2017) compared VRF and split systems in an educational building in Belém-PA. It was estimated that the reduction in electricity consumption would be reduced by up to 32%, even with an initial investment 43% greater in relation to splits.

In a study led by Duarte *et al.* (2020), the use of VRF was compared with VAV (Variable Air Volume) in a commercial building in Florianópolis-SC. It was observed that the VRF showed lower consumption than the VAV with a standard chiller and a variable compressor chiller, respectively, up to 19.2% and 12.5%.

Bezerra *et al.* (2020) evaluated and compared the costs associated with retrofitting the existing split system being replaced by VRF in an educational building located in Natal-RN. It was observed that the VRF system would present a reduction of approximately 54% in energy consumption and would take less than 5 years to obtain economic return.

A similar result was obtained by Figueiredo (2023). In their work, the VRF system showed savings in electrical energy of 40% compared to split and return on investment was estimated at 4 years for a single-family residence located in Porto Alegre-RS.

On the other hand, the VRF system will not always be economically viable, according GRASS (2013), a residential building simulation model, also in Porto Alegre-RS, indicated that VRF system presented a 25.6% reduction in electrical consumption in relation to split, however it is not economically viable, because payback would be greater than 30 years, well beyond the equipment life cycle.

Based on cited works, it is possible to infer that the economic viability of the VRF system, in residential applications, is associated with the occupancy profile of conditioned space and the initial investment, because it can vary depending on the manufacturer and location of the installation. Therefore, a deeper investigation is necessary and the cost-benefit analysis must take into account the continuous and seasonal occupancy profile, a common situation in high-end residences used only on weekends, for example.

3. METHODOLOGY

3.1 Choice and presentation of Residences

A high-standard residence is one that provides greater comfort and luxury, which are rarely seen in more conventional residences. Its high standard is defined by several characteristics that make this type of housing more exclusive and authentic. They are spacious and have several bedrooms. They have a high monetary value, compared to popular residences. Two high-end residences were chosen to carry out the analyses, and can be seen in greater detail in the Figures 1 and 2.

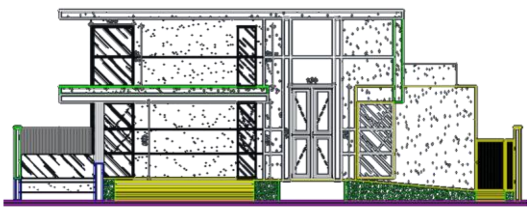

Figure 1 - Facade of house A

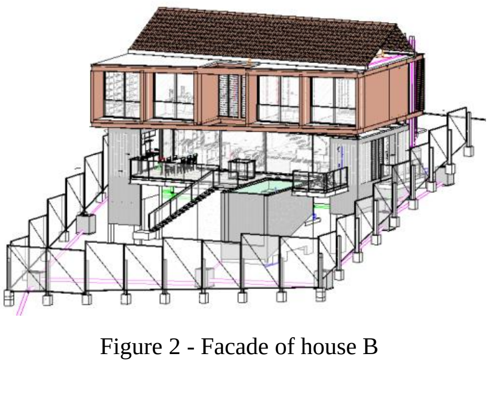

Figure 2 - Facade of house B

Table 1 presents a comparison between houses A and B, showing the technical characteristics of each residence. It is worth noting that house A is approximately 3 times larger than house B, in terms of area, and it is located in a residential condominium in the central region of the city, while house B is in the rural area. For this reason, house B will also be analyzed for recreational use, that is, only on weekends.

Table 1– Comparative Table of houses.

Description	House A	House B
Location	Central zone	Rural zone
Total area	417 m²	139 m²
Dorms	4	2
Master Suite	1	1
Bathrooms	6	3
Kitchen	2	1
Living room	Yes	Yes
Closets	Yes	no

The air conditioning systems proposed in this project are Split systems and VRF systems, for each residence both systems will be sized.

3.2 Cooling load profile

Cooling load is the amount of sensible and latent heat, generally expressed in Btu/h, kcal/h or W, that must be removed or placed in the enclosure in order to provide the desired conditions (CREDER, 2004).

For this study, the cooling load calculation was done using CLTD/SCL method based on NBR-16655/2019 for residential use. To obtain a cooling load profile, the typical monthly days of Manaus city were adopted from Azevedo's Work (2013), where external conditions were specified with hourly values in terms of dry bulb temperature and specific humidity. From this, the calculation of the cooling load was carried out using electronic spreadsheets for typical days of each month.

3.3 Avaluenting VRF systems COP

According to Chuang (2018), the Coefficient of Performance (COP) of an air conditioning system corresponds to its operational efficiency. Therefore, the higher the COP, the lower the energy consumption by the air conditioning system, and it highlights that the COP performance coefficient is the most used indicator to evaluate the performance of an air conditioning system.

Figure 3 shows the COP variation as a function of the partial load of the 12, 14 and 20 HP external units.

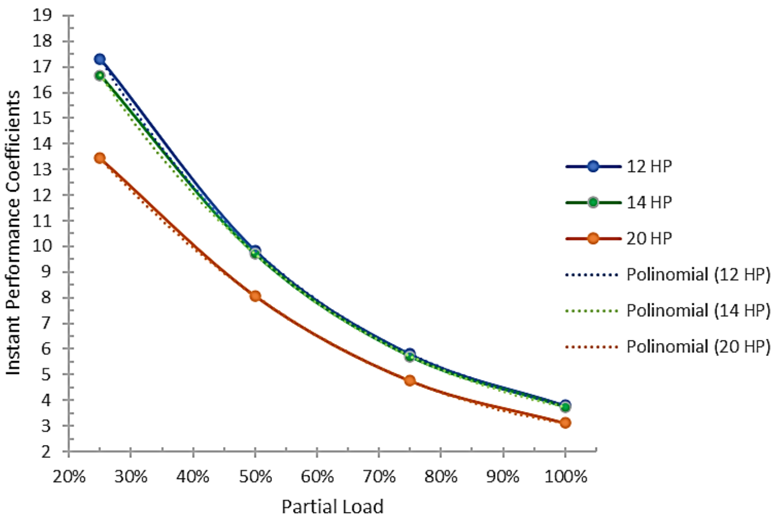

Figure 3 – COP of the 12, 14 and 20 HP VRF external units.

Through the trend curves plotted in Figure 3, obtained from data provided by a manufacturer of VRF systems, it was possible to define equations 1, 2 and 3 for the performance coefficient as a function of partial load (Cp) on the external units of 12, 14 and 20 HP, respectively.

$$COP_1 = -14.933Cp^3 + 49.92Cp^2 - 60.827Cp + 29.64 \quad (1)$$

$$COP_2 = -10.24Cp^3 + 39.2Cp^2 - 52.8Cp + 27.58 \quad (2)$$

$$COP_3 = -4.2667Cp^3 + 22.88Cp^2 - 36.773Cp + 21.27 \quad (3)$$

Since in VRF systems the external units operate interconnected forming a single set, the combined consumption was estimated from equation 4 taking into account the capacity ratio (R) between each condensing unit and the total load of the set.

$$\dot{W}_{comb} = R_1\left(\frac{\dot{Q}_1}{COP_1}\right) + R_2\left(\frac{\dot{Q}_2}{COP_2}\right) + R_3\left(\frac{\dot{Q}_3}{COP_3}\right) \quad (4)$$

3.4 Cost estimation and payback

The costs associated with the acquisition and installation of the systems were obtained from budgets made by local companies and the residential electricity tariff is R$ 0.98/kWh obtained from the local distributor (DEC/2022).

Using the machine's COP data obtained from manufacturer's catalogs and the hourly cooling load profile, it is possible to estimate electrical consumption costs of each system.

The payback can be evaluated based on the monetary discounts of the benefit provided by the electrical consumption cost reduction over time until they become positives.

4. RESULTS AND DISCUSSIONS

4.1 Cooling load profile and equipment selection for house A

The hourly profile of the monthly cooling loads is shown in Figure 4. It is possible to notice that the lowest total cooling load occurs in July, while the peak total load occurs in February and corresponds to 104.5 kW (29.7 tons). Peak load shows the overall thermal behavior of the building and it's useful for centralized systems sizing such as VRF.

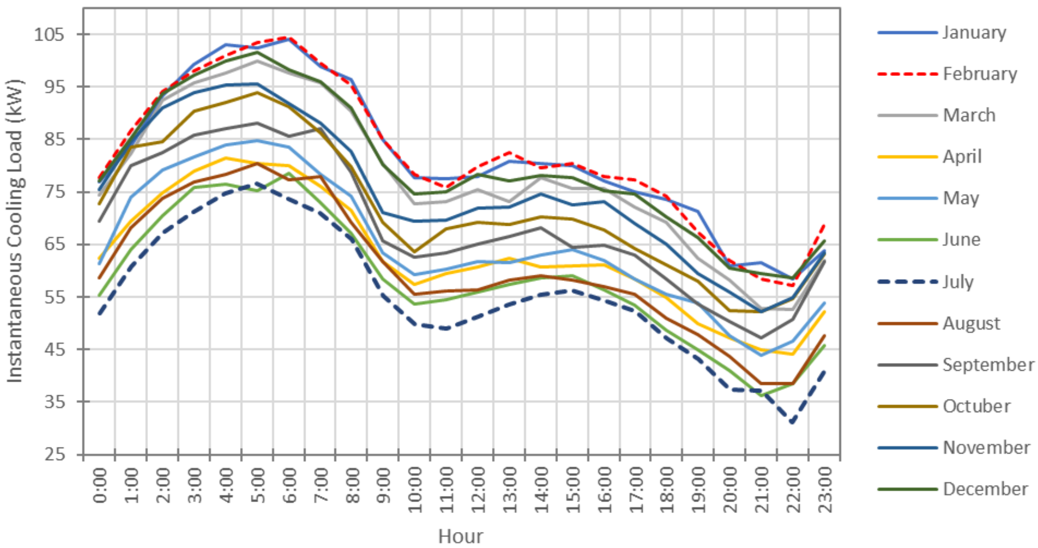

Figure 4 – Cooling load profiles for house A.

However, the selection of evaporator units depends on the individual peak cooling load of each room. Table 2 shows a summary of the equipment selection for house A, where it was taken as a criterion that the nominal capacities of the internal units are immediately higher than the peak cooling load, both for the split system and for the VRF.

Table 2– Equipment selection summary for house A.

Selection of indoor units in house A						
ENVIRONMENT	Cooling load (kW)		$\sum \dot{Q}_{T_{amb}}$ [Btu/h]	**Quantity**	**Split Capacity [Btu/hr]**	**Capacity VRF [Btu/hr]**
	Sensitive [Btu/hr]	**Latent** [Btu/hr]				
Service area	8,001	413	8,414	1	9,000	9,600
Gourmet	51,852	3,000	54,852	1	57,000	54,600
Deposit	5,369	413	5,782	1	9,000	7,500
Oratory	13,203	150	13,353	1	12,000	15,400
Service Room	4,711	413	5,124	1	9,000	7,500
Study room	14,495	1,033	15,528	1	18,000	15,400
Suite 02	16,057	413	16,469	1	18,000	15,400
Suite 03	16,476	413	16,889	1	18,000	15,400
Suite 04	13,831	413	14,243	1	18,000	15,400
Master Suite	23,710	413	24,123	1	24,000	24,200
Master Suite	11,001	413	11,414	1	12,000	12,300
Living/Leisure	82,313	5,400	87,713	2	48,000	47,800
Hall Living	83,983	3,607	87,590	2	48,000	47,800
SUBTOTAL	345,003	16,490	**SELECTED TOTAL CAPACITY**		396,000 [Btu/h]	383,900 [Btu/h]
TOTAL COOLING LOAD	361,493 [Btu/h]					
	30.2 TR				33 TR	32 TR

It is observed that the difference in the sum of the total capacities between the split system and VRF are very close, but they are not equal. There is a difference of 1.0 ton between the systems. It's occurs because the standard nominal capacities of the split systems are differents of VRF systems for the same nominal capacity.

Therefore, VRF system selection and sizing software was used, provided by the manufacturer. Figure 5 shows the layout of the VRF system in house A, where it can be seen that a set of 34 HP is needed with the 20 HP units plus two 12 HP units combined.

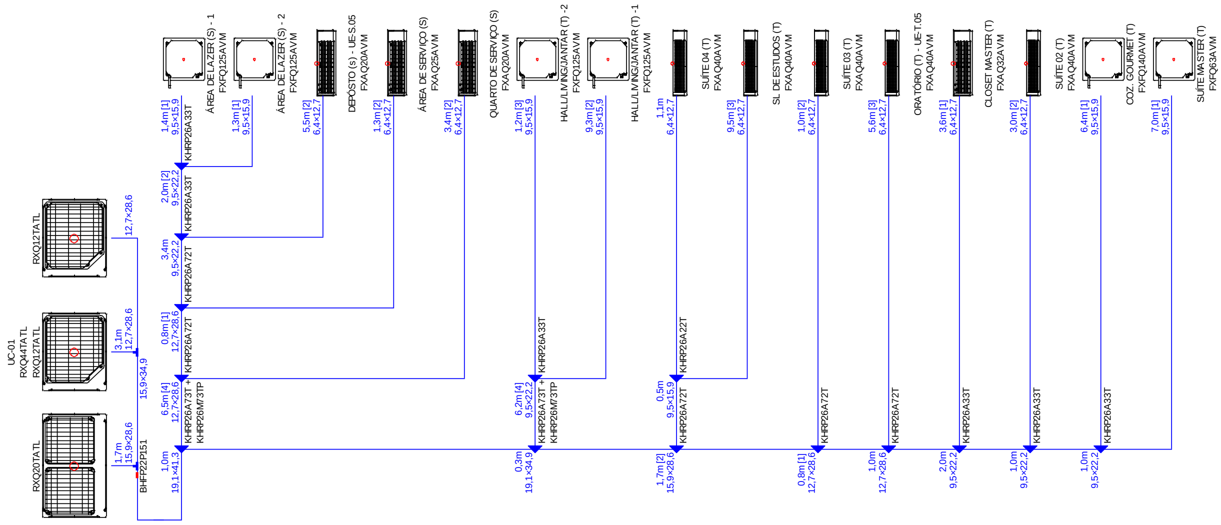

Figure 5 – VRF system diagram for house A.

4.2 Cooling load profile and equipment selection for house B

In a similar way, monthly hourly profiles were obtained for house B, as seen in Figure 6. It shows a peak total cooling load of 33.6 kW (9.5 tons) in December.

The summary of the selection of equipment for the environments of house B is shown in Table 3, with the same selection criteria as for house A. The total nominal capacities of the split and VRF systems were also very close, differing by only 0.06 ton. It's also possible to see that one room stands out for having a very high thermal load, which is the living room/kitchen, this happens because in this room there is a very large area of glass, in addition to a place with a high concentration of people, so the thermal load tends to be greater.

Although there are specific external VRF units for residential applications (up to 6.0 or 8.0 tons), the same family of condensing unit models as in house A was adopted. However, with a smaller capacity, due to the lower cooling load of 10.5 tons. Therefore, the nominal capacity of the external unit of the VRF system in house B was only 14 HP (Figure 7).

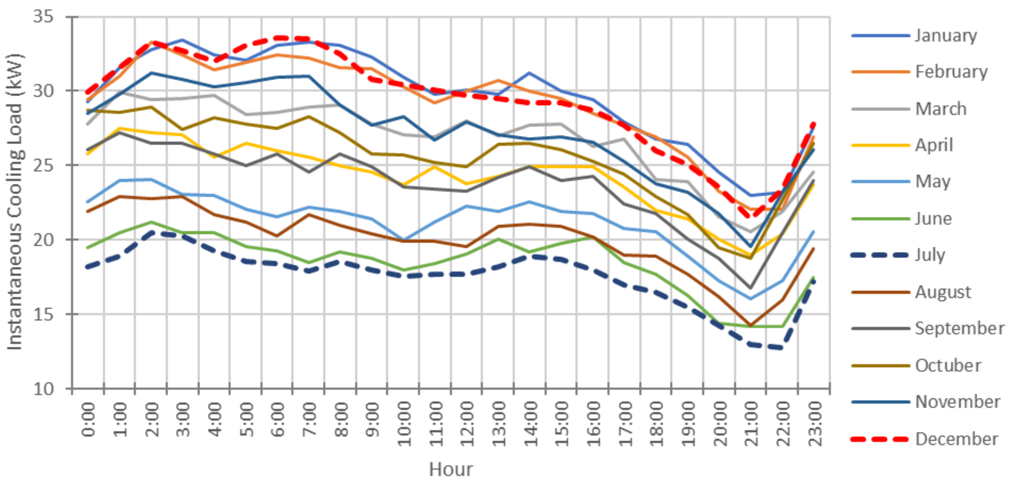

Figure 6 – Cooling load profiles for house B.

Table 3– Equipment selection summary for house B.

Selection of indoor units in house B						
ENVIRONMENT	Cooling load (kW)		$\sum \dot{Q}_{T_{amb}}$ [Btu/h]	Quantity	Split Capacity [Btu/hr]	Capacity VRF [Btu/hr]
	Sensitive [Btu/hr]	Latent [Btu/hr]				
living/kitchen	52,322	4,800	57,122	1	56,000	54,600
Music room	19,278	1,803	21,081	1	24,000	24,200
Master Suite	9,804	412.5	10,217	1	12,000	12,300
Suite 01	11,122	412.5	11,535	1	12,000	12,300
Suite 02	10,343	412.5	10,756	1	12,000	12,300
SUBTOTAL	102,869	7,841	SELECTED TOTAL CAPACITY		116,000 [Btu/h]	115,700 [Btu/h]
TOTAL COOLING LOAD	110,710 [Btu/h]				9.58 TR	9.64 TR
	9.22 TR					

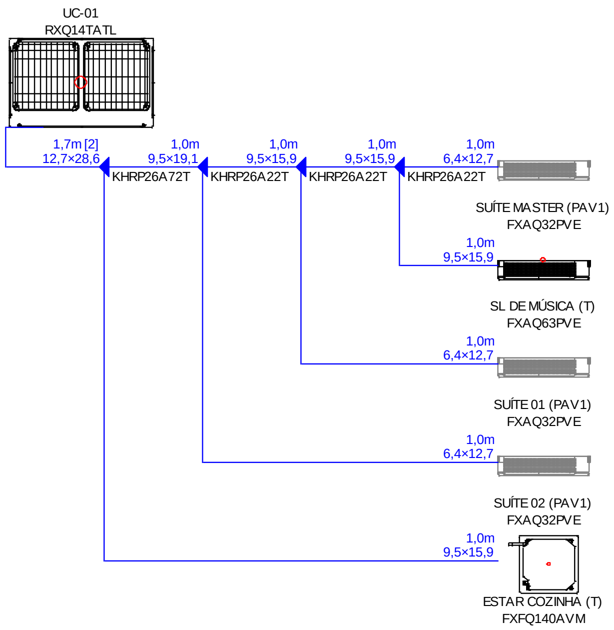

Figure 7 – VRF system diagram for house B.

4.3 Comparison of consumption of house A.

From the instantaneous consumption equations found, it was possible to establish the monthly consumption of each system throughout the year. Through Figure 8 it is possible to observe that January presented the highest monthly consumption, coinciding with the highest thermal demanded month, while July was the month with the lowest electrical consumption. The highest monthly consumption was 18,296.54 kWh for the split system, while in the same month the VRF system consumed 12,989.19 kWh, that is, 29% less. This advantage in VRF consumption versus split could be even greater, as observed in July, corresponding to 57%. This is mainly due to the fact that adopted VRF is more efficient when operating at lower partial loads. Annually, the split and VRF systems consumed 184,040 kWh and 108,645 kWh, respectively, which indicates a saving of 41% per year in VRF compared to the split system. In short, the VRF system is more advantageous all year round in terms of energy consumption.

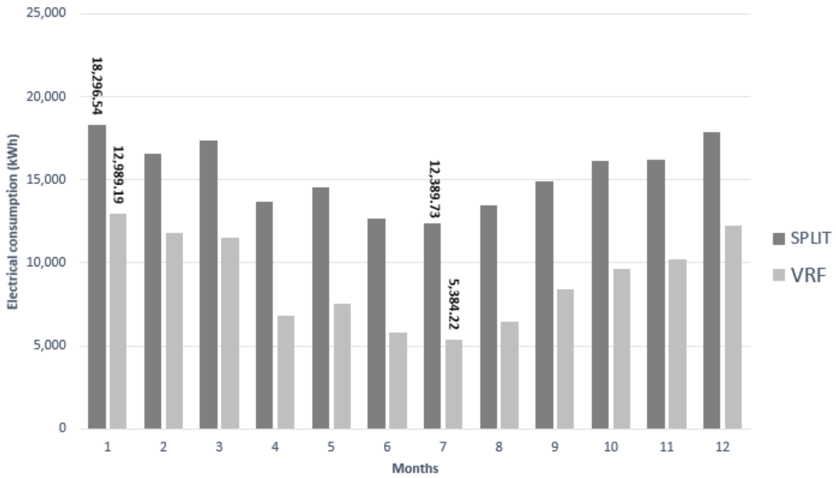

Figure 8 - Monthly consumption in kWh for house A.

Table 4 shows the relative difference between the consumption of air conditioning systems and the estimated expenditure on electrical energy throughout the year in continuous operation (24 hours a day).

Table 4 – Estimate of electrical consumption expenses for house A.

Diferença de consumo com energia - Casa A					
Mês	**Split [kWh]**	**VRF [kWh]**	**Diferença de consumo [kWh]**	**Diferença em percentual**	**Valor em R$**
1	18,296.53	12989.19	5307.35	-29%	R$ 5,201.20
2	16,572.28	11812.81	4759.48	-29%	R$ 4,664.29
3	17,365.60	11538.87	5826.73	-34%	R$ 5,710.20
4	13,659.03	6781.15	6877.88	-50%	R$ 6,740.33
5	14,527.98	7549.90	6978.08	-48%	R$ 6,838.52
6	12,633.43	5783.99	6849.44	-54%	R$ 6,712.45
7	12,389.72	5384.22	7005.51	-57%	R$ 6,865.40
8	13,499.00	6443.08	7055.93	-52%	R$ 6,914.81
9	14,911.44	8369.76	6541.69	-44%	R$ 6,410.86
10	16,122.80	9610.05	6512.75	-40%	R$ 6,382.49
11	16,207.22	10173.97	6033.25	-37%	R$ 5,912.59
12	17,854.87	12207.91	5646.97	-32%	R$ 5,534.03
Custo de Energia Anual [R$]	**R$ 180,359.10**	**R$ 106,472.01**	**Economia Anual de energia utilizando sistema VRF**	**-41%**	**R$ 73,887.16**

In this scenario, the split system has an annual energy cost of R$ 180,359.17 while the VRF presented R$ 106,472.01. There was a cost reduction of R$ 73,887.16, which in relative terms corresponds to 41% per year. This result converges with the estimates of most VRF system manufacturers, which indicate reductions between 40% and 60%. Furthermore, it is close to values found by several authors, such as Figueiredo (2023).

4.4 Comparison of consumption of house B.

Two scenarios were studied for house B. The first one considering the continuous use of the systems, 24 hours a day and 7 days a week. The second one took into account the hypothesis of recreational use of the property, common in Manaus, where the residence is only used on weekends, that is, twice a week. Figure 9 shows the monthly energy consumption of the systems in each scenario. In both scenarios, the VRF system presents an advantage in terms of energy consumption in all months, reducing consumption by almost 30% compared to split in the peak month (December) in continuous operation. However, when use is recreational, the difference observed is smaller, as in the peak month (January) the reduction observed is approximately 22%.

The estimated annual consumption of the split and VRF systems were, respectively, 64,427.23 kWh and 39,779.58 kWh in continuous mode. In recreational use, the recorded consumption was 16,964.58 kWh and 10,488.73 kWh for the split and VRF systems, respectively. In both cases, the observed reduction in energy consumption of 38% in relation to the split system, close to obtained for house A, differing by only 3%.

Table 5 shows the different consumption and costs of electrical energy for split and VRF systems in different situations.

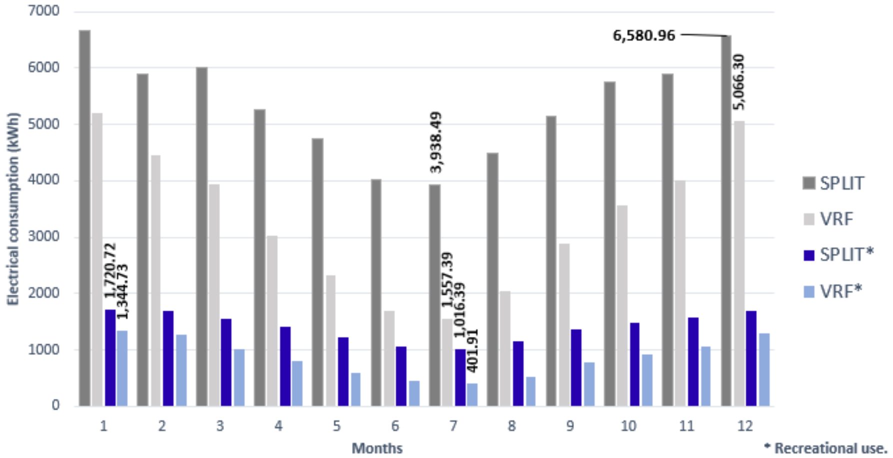

Figure 9 - Monthly consumption in kWh for house B.

Table 5 – Estimate of electrical consumption expenses for house B for different uses.

Difference in energy consumption - House B (*Recreational use, in grey)									
Month	Split [kWh]	Split* [kWh]	VRF [kWh]	VRF* [kWh]	Consumption difference [kWh]		Relative diference	Amount in BRL	
Janeiro	6,667.80	1,720.72	5,210.81	1,344.73	1,456.99	376.00	-22%	R$ 1,427.85	R$ 368.48
Fevereiro	5,902.77	1,686.51	4,454.61	1,272.75	1,448.16	413.76	-25%	R$ 1,419.19	R$ 405.48
Março	6,007.65	1,550.36	3,946.21	1,018.38	2,061.44	531.99	-34%	R$ 2,020.22	R$ 521.35
Abril	5,263.55	1,403.61	3,024.20	806.45	2,239.35	597.16	-43%	R$ 2,194.56	R$ 585.22
Maio	4,755.51	1,227.23	2,321.87	599.19	2,433.65	628.04	-51%	R$ 2,384.97	R$ 615.48
Junho	4,022.89	1,072.77	1,687.07	449.89	2,335.82	622.88	-58%	R$ 2,289.10	R$ 610.43
Julho	3,938.49	1,016.39	1,557.39	401.91	2,381.11	614.48	-60%	R$ 2,333.48	R$ 602.19
Agosto	4,489.40	1,158.55	2,056.69	530.76	2,432.71	627.79	-54%	R$ 2,384.05	R$ 615.24
Setembro	5,153.31	1,374.22	2,896.23	772.33	2,257.09	601.89	-44%	R$ 2,211.94	R$ 589.85
Outubro	5,742.47	1,481.93	3,557.06	917.95	2,185.41	563.98	-38%	R$ 2,141.70	R$ 552.70
Novembro	5,902.41	1,573.98	4,001.14	1,066.97	1,901.27	507.00	-32%	R$ 1,863.24	R$ 496.86
Dezembro	6,580.96	1,698.31	5,066.30	1,307.43	1,514.67	390.88	-23%	R$ 1,484.38	R$ 383.06
Annual energy cost	**R$ 63,138.68**	**R$ 16,625.29**	**R$ 38,983.99**	**R$ 10,278.95**	**Annual energy saving using VRF system**		**-38%**	**R$ 24,154.69**	**R$ 6,346.33**

Regarding the cost of electricity, the 38% reduction in consumption translates into savings of R$ 24,154.59 per year in continuous use and only R$ 6,346.33 per year when used for recreation. This result demonstrates that the VRF system will always tend to be more advantageous in terms of energy, regardless of the building's usage profile.

4.5 Purchase and installation costs

Table 6 – Implementation costs of each system for each house.

Implementation costs for each system			
House A		**House B**	
Split System	R$ 119,424.05	**Split System**	R$ 33,424.05
VRF system	R$ 241,205.74	**VRF system**	R$ 93,504.96
Difference in implementation cost of:		Difference in implementation cost of:	
R$ 121,781.69		R$ 60,080.81	

Table 6 summarizes the acquisition and installation costs of all equipment and accessories for each system in houses A and B. In this work, the term "implementation cost" refers to the total acquisition cost plus installation (labor). Through quotes obtained from local suppliers, it is possible to observe that the VRF system will always be more expensive than the unitary split system, costing little more than double (R$ 241,205.74) in house A and almost triple (R$ 93,504.96) in house B.

This denotes a relationship between the building area and implementation cost which the VRF/Split cost ratio will tend to be much higher as the size of the building decreases.

4.6 Simple Payback

For House A, if the system chosen is VRF, the investment difference needed by this system is R$ 121,781.69 more expensive than the implementation of the split system, however this system will consume around R$ 73,887.16 less annually than the system split, therefore, in around 20 months the system would pay that difference, as seen in the cash flow in Figure 10. Due to the investment time being less than two years, it can be inferred that the VRF system is economically viable for house A in continuous use, considering that the useful life of VRF systems is commonly estimated at 15 years (ASHRAE, 2015).

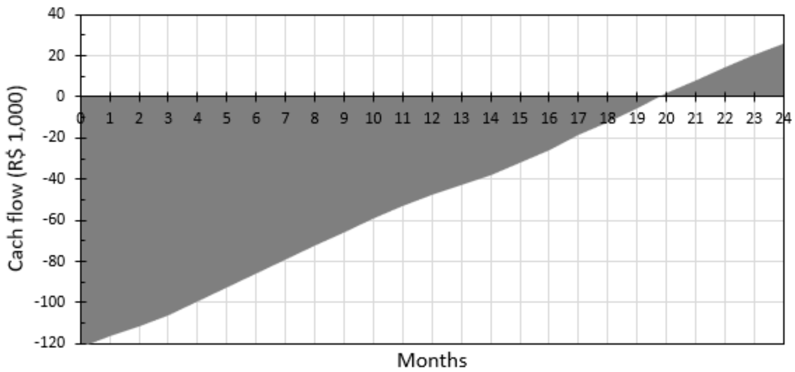

Figure 10 – Simple Payback for house A.

For house B, the difference in investment to install the VRF system is R$ 60,080.92 and the savings obtained in electrical consumption are R$ 24,154.69 per year, which takes a payback time of approximately 2.5 years, showing that the VRF system is also economically viable for the house in continuous operation, as seen in Figure 11. On the other hand, when the use is recreational, the benefit generated by the VRF system is R$ 6,346.33, which implies a payback time of 9.5 years.

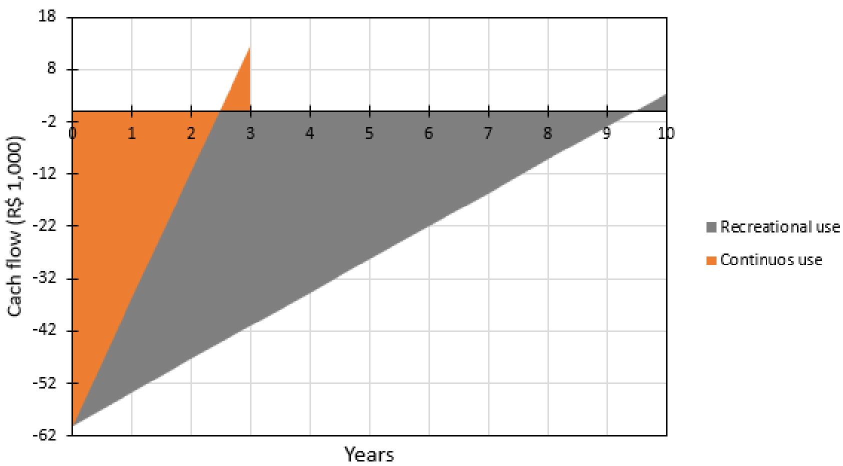

Figure 11 – Simple Payback for houses B.

Although the payback of the second scenario is lower than the expected life cycle for the VRF, due to the high initial investment cost compared to the split (almost triple), this system may be an unattractive strategy for high-standard buildings used only for recreation.

5. CONCLUSIONS

The VRF system will be more efficient in either situation. Energy consumption will always be favorable for this system, reaching annual savings of up to 40% compared to split systems, which corroborates the rates provided by manufacturers. However, for high-end homes used only for recreation, the split system ends up being more viable as the VRF system will take a long period to pay for itself, approaching its useful life.

It is clear that the larger the area of the building, the more advantageous it is to implement the VRF system. The VRF system is technically viable for the project in house A, since it has a high number of internal units, therefore, the VRF system will drastically reduce electricity costs compared to the split system, this reduction is in order of R$ 70,000.00 annually, and the system will pay for itself in 20 months.

The continuous use of house B will provide a payback of up to 2.5 years, however, when the use is recreational, the most attractive system will be split, since the total cost for implementation is R$ 33,424.05, while the VRF is R$ 93,504.97, that is, 64% cheaper. In addition, under these conditions of use, the VRF system's payback time would be 9.5 years.

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7. RESPONSIBILITY NOTICE

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