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Energy and Cost Comparison of Building Cooling Systems

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Cooling a building can be approached with several different methods but determining which method to pursue can be a matter of operator preference. This study examines four equipment systems of building cooling (Variable Refrigerant Flow, Rooftop Units, Hydronic Chiller, and Split Systems) and their capacities, abilities, and inabilities. These systems are then compared against one another for efficiency and operating cost in a one-year timeframe. Yearly operating cost, energy usage, and system operating time were analyzed from each unit's performance and then compared against one another. The efficiencies, energy usage, and cost are compared to find the most efficient and cost-effective system for various owner needs and applications. Depending on the performance of the individual systems, it may be more suited to a specific application. Variable Refrigerant Flow was the most efficient due to its method of heat rejection and higher efficiency components. The chiller was also an efficient option, with the heat rejection through water being an efficient method. Rooftop units and split systems were less efficient but lowered initial capital cost. Overall, capital cost and operating expense priority determine the best method for an individual application.

Key Words: HVAC, Energy, Cooling, Efficiency, Cost, Building Cooling Systems

Introduction and Background

The conditioning of indoor spaces has been one of the more significant advances of comfort in the last 100 years. However, the method in which spaces and buildings are cooled, heated, and ventilated is a varied and widely studied field that is advancing daily. There are many independent and combinations of possibilities in accomplishing the same goal, from variable refrigerant flow systems to closed-loop chilled water systems. While other factors differentiate all the cooling methods, the most significant factor in the balance of energy efficiency is the yearly operating cost and the initial capital investment (Medjugorac et al., 2020). The owner often decides which direction to take, assisted by a life-cycle cost analysis. This energy analysis exposes future costs operating costs and maintenance, and upkeep.

The importance of energy analysis is driven by the increase of energy consumption by modern building systems (Kumar et al., 2017). As the density of building construction increases, especially in urban centers, conventional energy sources are becoming depleted. (Kumar et al., 2017). This has led

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building owners to be more aware of their energy usage and selected equipment. In conjunction with the awareness of an owner's energy usage, conditioning equipment manufacturers have installed options with their equipment, which have reduced energy consumption through different methods. Heat Recovery devices, such as thermal wheels or air-to-air fixed-plate heat exchangers, have been shown to reduce energy consumption by reusing waste heat from a system (Papakostas et al., 2018). Energy savings are not just used for an owner's energy savings but are mandated by various code authorities. ASHRAE 90.1 has been used to take advantage of outdoor air conditions for cooling a space using an airside economizer in specific cooling equipment capacities (Quirk, 2011).

In addition to specialty equipment accessories, there are also aspects of building design that are inherently passive and help with energy conservation. Energy management in building design is not solely the engineer's obligation but can also be looked at from an architect's perspective. An architect's inputs to a reduced energy load include green building aspects, including double-skin façades, green roofs, and window blinds (Randelovic et al., 2020). Sensible building controls are another method to balance a building's energy usage. Using specific temperature setpoints for a building's intended usage while also balancing the comfort of the building's occupants has also been shown to be a practical approach for energy conservation (Kwak et al., 2019). Overall, there are many ways to manage a building's energy usage for its conditioning, but this study will focus on the several types of equipment used to achieve that end.

An older approach to cooling space is a Roof Top Unit (RTU). RTU's, also known as packaged units, or DX (Direct Exchange) units. Compared to other methods, they have a low initial capital cost and straightforward installation (Silhol, 2021). Silhol also shows that since all the cooling and heating coils and fan sections are contained within the unit, RTU's are a good option for projects with limited interior mechanical space. While RTU's are commonplace, they may sometimes sacrifice efficiency for ease of use and low cost. This is often due to the continued manufacture of RTU's with single-speed components, regardless of new requirements for multi-speed supply fan operation (Cai et al., 2018). However, this has been addressed by retrofitting variable speed components to existing units (Wang et al., 2019). With variable speed components, Wang was able to show a 31% improvement in cooling efficiency. Li et al. (2015) mentioned in their research that manufacturers have begun to see the long-term benefit of using these variable speed drives, making them standard in their packaged units. These package units are combined with new power modeling approaches for these variable speed drives in RTU's (Li et al., 2015), bringing a traditional RTU approach closer to the higher efficiencies of other cooling technologies.

One of the other cooling methods is using water as a heat transfer medium, which is most often utilized with a water-cooled chiller using a cooling tower. Heat is taken from the conditioned space and transferred to the water. Water is run through a cooling tower, rejecting the heat into the atmosphere, and the water returns into the system. While this method is simple to understand and operate, it has noticeably lower efficiencies than other cooling methods (Li et al., 2021). While efficiencies are still low compared to other methods like variable refrigerant flow, chilled water systems have improved. Chilled water systems with an energy efficiency ratio (EER) less than 3.8 have begun to be phased out (Hua et al., 2010). Chilled water systems are still in use because of their larger cooling capacity compared to other methods. Chillers are readily available (not custom built) for up to 500 tons of cooling (6,000 MBH) by most major manufacturers. The use of chillers is most often seen in large-scale commercial buildings such as office buildings, and the choice to use them is often a balance of energy efficiency and overall capacity (Suamir et al., 2018).

While commercial approaches to cooling are widely varied, most residential applications use a similar method of a split system. A dedicated outdoor heat pump or condenser is connected by refrigerant line sets to an indoor air handler (or furnace). This system is commonplace in most homes but can be commercialized for smaller building applications. The benefit of a split system can be seen in its versatility of applications, use of various refrigerants, and versatility in installation location (Elgendy et al., 2017). The most significant benefit is their low cost, as demonstrated by their use in most homes. However, once the system size increases, it may not be feasible to use split systems. A Variable Refrigerant flow system can be up to 12% more energy efficient with the same capacity (Li et al., 2017). Li explains this by showing that most split systems use single-speed fans and variable capacity units, like VRF (Variable Refrigerant Flow), to reduce stop-start energy waste. Regardless of these findings, split systems continue to be commonplace and will remain, so unit other small capacity options are available at comparable prices.

As mentioned previously, one of the most competitive systems available today in building HVAC systems is Variable Refrigerant Flow or VRF. Invented by Daiken as VRV© (Variable Refrigerant Volume) in the 1980s, VRF is just now becoming commonplace in most new building designs. It works on taking heat rejected from the parts of a building that need cooling and using it to heat other areas of the building that need heating. This system has improved with the improvement of refrigerants for the cooling and heat cycles and the introduction of variable speed components (Saab et al., 2018). It differs from other systems in its heat reuse and can save up to 47% compared to traditional methods like an RTU (Lee et al., 2018). Energy and subsequently money savings like this have taken the attention of many building owners. They can explain why half of the new medium-sized commercial buildings and a third of new large commercial buildings use VRF today (Aliehyaei, 2020). They are considered first in energy-efficient design due to their very operation being efficient with heat rejection. Using VRF and other building design options has allowed the construction of buildings with a net-zero or net-negative energy impact (Kim et al., 2019). The efficient nature of the system, its interchangeability of components, and more accurate modeling techniques (Kim et al., 2020) have allowed design engineers to layout a building's lifecycle energy consumption more accurately. This has increased importance as the focus shifts more towards overall lifecycle impact than initial capital cost.

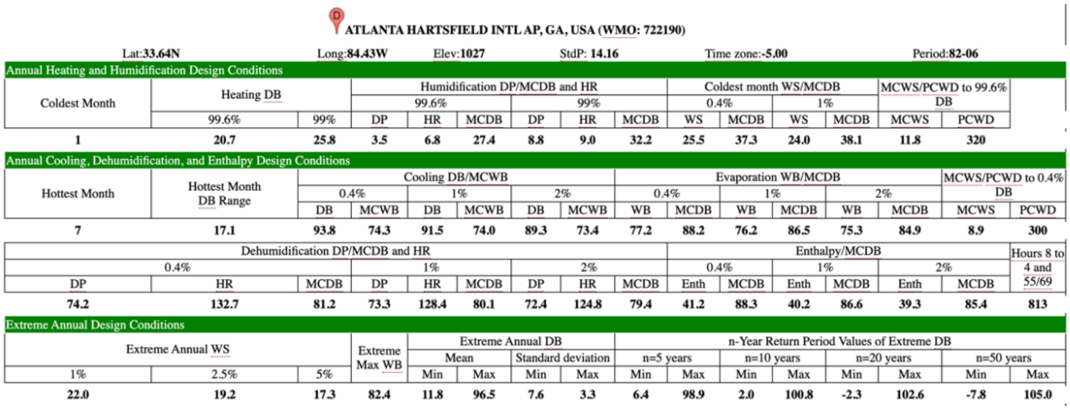
As there are many different options in conditioning space, it is essential to consider each system’s benefits. Selection depends entirely on the end user's needs, and it is necessary to see how each system will perform given the same circumstance. Capital cost may be valued over energy efficiency, or the opposite may take priority. In either case, a comparison of all options is helpful for engineering analysis. This study will take the known abilities of the given systems and compare them against one another to find what system is ideal for a given circumstance.

Methodology

Rooftop units, hydronic systems, split systems, and variable refrigerant flow have unique capabilities and disadvantages. To compare these four cooling systems to one another accurately, a comparison including all four methods needed to be run at once. Systems in each of the four categories were selected from Carrier’s lineup of products to control the information supplied for the performance of each system. As Carrier makes each system, the product information provided was similar across all systems and made the comparison more practical. These four systems and their performance in the baseline environment were the focus of this study.

For the baseline environment, a basic test building was modeled to map the energy use of each system given the same parameters. Using Carrier’s Hourly Analysis Program (HAP), each system was run simultaneously in the identical test building, with the same building envelope parameters. Fenestration, wall and floor composition, and roof composition were all modeled to see how energy was used and directed within this building. This level of modeling allowed for the simulation of not only instantaneous use of electricity in each system but power usage throughout the year as demand for cooling increased and declined. The efficiencies of each system were mapped and simultaneously compared to one another, showing how each system performs in varying climatic conditions throughout the year. A complete comparison of the energy usage and efficiency of the four systems was collected and then subsequently compared against one another.

Before the four cooling systems could be analyzed, the test conditions needed to be established to ensure a consistent comparison baseline. The first step in creating a baseline test environment was to select weather data that would allow for an accurate analysis of system performance over the course of a year. ASHRAE weather conditions from the Atlanta Hartsfield International Airport measuring station were used for this project. A sample of the data recorded from the Atlanta measuring station is shown in Figure 1. All temperatures shown are in degrees Fahrenheit. A number of weather stations are in the area, but the Atlanta airport readings, shown as selection D, are some of the oldest, most accurate, and well-kept conditions in the area and provided excellent data points to input into the Carrier HAP software for comparison. Among the data collected in the report were the average dry bulb and wet bulb temperatures of each month and the extremes in the hottest month of the year. Also included were the average dewpoints for dehumidification calculations and the extreme design conditions for 5, 10, 20, and 50-year averages. All of this data was incorporated into the weather information of the HAP program to show the energy usage of each system throughout the year.



D ATLANTA HARTSFIELD INTL AP, GA, USA (WMO: 722190)

Lat:**33.64N** Long:**84.43W** Elev:**1027** StdP: **14.16** Time zone:**-5.00** Period:**82-06**

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB	
			99.6%			99%			0.4%		1%			
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
1	**20.7**	**25.8**	**3.5**	**6.8**	**27.4**	**8.8**	**9.0**	**32.2**	**25.5**	**37.3**	**24.0**	**38.1**	**11.8**	**320**

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
7	**17.1**	**93.8**	**74.3**	**91.5**	**74.0**	**89.3**	**73.4**	**77.2**	**88.2**	**76.2**	**86.5**	**75.3**	**84.9**	**8.9**	**300**

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 55/69
0.4%			1%			2%			0.4%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
74.2	**132.7**	**81.2**	**73.3**	**128.4**	**80.1**	**72.4**	**124.8**	**79.4**	**41.2**	**88.3**	**40.2**	**86.6**	**39.3**	**85.4**	**813**

Extreme Annual Design Conditions

Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
22.0	**19.2**	**17.3**	**82.4**	**11.8**	**96.5**	**7.6**	**3.3**	**6.4**	**98.9**	**2.0**	**100.8**	**-2.3**	**102.6**	**-7.8**	**105.0**

Figure 1: ASHRAE Weather Conditions

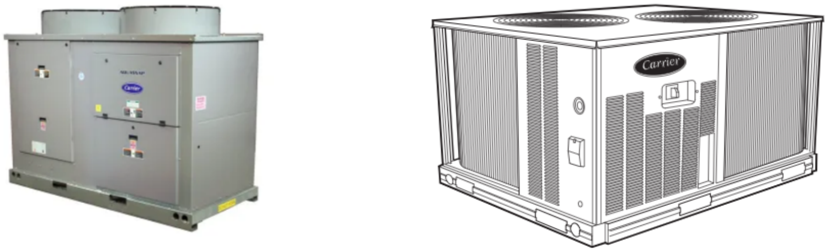
In addition to the weather data used, a test building needed to be designed so that these systems could show realistic performance in a building, not just their hypothetical performance or performance metrics from the manufacturer. A model building, shown in Figure 2, was created using Autodesk's Revit software to the model square footage of different spaces. In addition, this allowed window convection rates and wall, roof, and floor transmission rates. These values added parameters that allowed for a higher level of accuracy in modeling the performance of each of these cooling systems. When run over a year, the peak loads for each building component were calculated and added to the entire system performance. Window and skylight solar loads were 8,390 BTU/h at peak, window transmission from convection was 3,206 BTU/h, wall transmission was 3,946 BTU/h, floor transmission was 586 BTU/h, door transmission was 467 BTU/h, and roof transmission was 10,831 BTU/h. In addition, overhead lighting added 4,178 BTU/h of load, and miscellaneous electrical loads added 3,908 BTU/h. This adds to a total of 35,512 BTU/h, or roughly 3.55 MBH. While this would typically require a system with around 3 tons of cooling capacity, each system was sized to an entire 10-ton unit.

Figure 2 : Building used to Cooling System

For the systems to be analyzed, their parameters and performance capabilities had to be input into HAP. This included their net and gross cooling capacities, electrical data, heat gain from fans and other accessories, as well as their efficiencies. In addition to these different parameters, standard parameters such as the cooling setpoint were also set. For this study, the cooling setpoint was established at 75°F. This allowed the program to simulate when cooling systems would run based on outdoor conditions as well as how the indoor conditions held and rejected heat. Another aspect of putting this data into HAP was the simultaneous simulation of all the systems. If a parameter needed to be changed, it could update all systems at once, once they had been modeled. Additionally, system psychometrics for each system were generated, mainly to check when the highest load occurred and to match it to the hottest month for ASHRAE weather conditions.

a. 10 Ton WeatherMaker RTU

b. Carrier VRF Heat Pump



c. AquaSnap Air-Cooled Liquid Chiller

d. Gemini Split System – 10 Ton Split System

Figure 3: Four different Cooling Systems

Once the test building was established and input into HAP, each system and its performance needed to be input, tested, and analyzed, all systems tested were made by Carrier, which allowed for the same parameters to be explored across all four different systems, namely: a) 10 Ton WeatherMaker RTU, b) Carrier VRF Heat Pump, c) AquaSnap Air-Cooled Liquid Chiller, and d) Gemini Split System – 10 Ton Split System. The four units are shown below in Figure 3.

Data Analysis and Results

When modeled with the test building, the WeatherMaker RTU used over half of the building's energy in cooling. The distribution of energy is shown in Figure 4, with 20.2% of the energy going to other electric equipment and 23% going to the building lighting. The total cost of energy for the RTU over one year was $1,119, calculated by an 8,760-hour simulation. The energy distribution of the building when using the variable refrigerant flow system is shown in Figure 4. Only 43.5% of the building's energy went towards cooling, with 26.4% in electrical equipment and the final 30% towards building lighting. As explained previously, this efficiency is from the heat pump's ability to redistribute waste heat. The annual cost of the heat pump in cooling mode only was $749 but had a higher cooling cost in the winter months at $22 and $16 in January and December, respectively. Again, this is due to the cooling mode constantly running even in seasons that require the most heat. Overall, this system's efficient process and components had a low cost for cooling relative to the rest of the building cost.

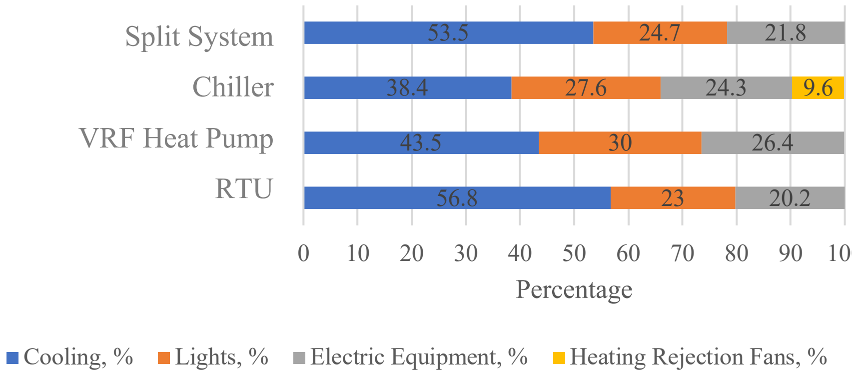


Figure 4: Four different Cooling System Energy Usage

While this unit did have more components needing to be powered, the overall percentage of building electricity to operate this chiller is 48%. This is split between 38.4% of the energy going towards the chiller operation and 9.6% going towards the heat rejection fans on this chiller. While this is a higher energy usage than purely refrigerant-based solutions, it should be noted that hydronic chillers such as this one are more efficient at distributing and dissipating heat from a system. The additional load of this building includes 24.3% of the building's energy going towards electrical equipment and 27.6% going to building lighting, shown in the distribution in Figure 4. The cooling cost in this system is $901 for the year, mainly during the cooling months. The highest cost of running this chiller is in the hottest month of the year, July, at the cost of $171. Virtually no cost was incurred in the winter months as the chiller would not be running. The split system cooling method for this building net 53.5% of building energy being used on cooling. While all components for cooling are in one package, it still had the disadvantage of a refrigerant line set connecting to indoor distribution units. 21.8% of electricity was used for electrical equipment, and 24.7% was used for building lighting, shown in Figure 4. The cooling cost for this system over the year was $1,279, having the highest costs in July and August at $229 and $213, respectively. While this is higher than other systems, no cooling cost was incurred in the winter, as heating could only run if cooling was not.

After all of the systems were analyzed, their relative performance was then measured. Using the Cobb county energy rate of $0.10 per kWh, the energy cost for each system was calculated over the course of a year, broken into 12 months. This fluctuation in cost is shown in Figure 5. The highest cooling cost is in the summer when outdoor air temperatures are highest, with the rooftop unit having the highest cost at $229. It should be noted that the rooftop unit also has the lowest cost in the wintertime. The variable refrigerant flow had the lowest energy cost in the summer, at $112, due to its reuse of waste heat but had the lowest change in cost between winter heating and summer cooling seasons. It is clear to see the differences in the cost of the monthly operation of each system in this breakdown, given a constant energy rate.

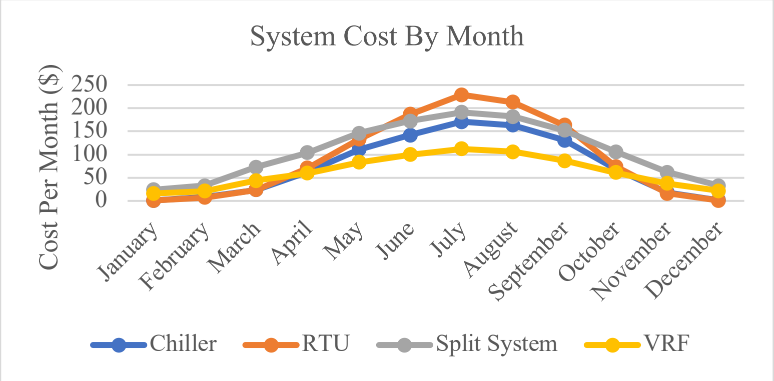


Figure 5: Energy Cost of the Four Systems by Month

Another cost breakdown can be shown with the amount of money given to each category. As the same building test parameters were held constant in this study, a baseline cost of $974 across all systems accounts for building lighting and other electrical loads. This distribution, shown in Figure 6, shows that the split system has the highest yearly cost at $2,253 for building operation over 12 months. The rooftop unit had the following highest cost, at $2,093. While using both electricity for water circulation and heat rejection, the chiller system had the second-lowest yearly cost at $1,875. The lowest summer cost shows that variable refrigerant flow also had the lowest annual operation cost at $1,723. VRF has the lowest operation cost over a year in this scenario from an operation standpoint. Since this was only looking at cooling over a year, this ordering could shift with the introduction of measuring heating costs.

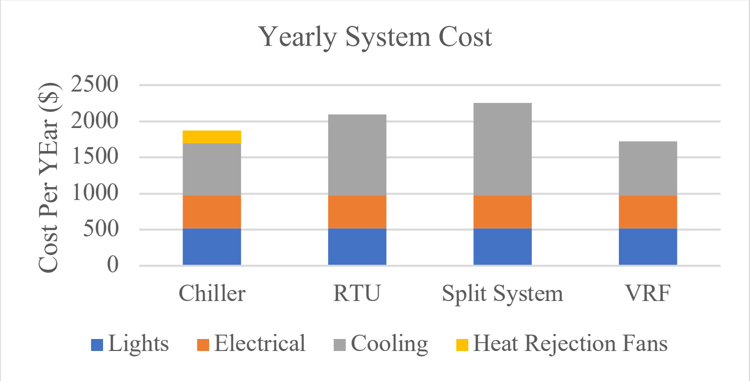


Figure 6: Distribution of Energy Usage of the Four Systems

The final aspect of the system's performance that was analyzed was the usage per month of each unit. This study found that the unit's more efficient, the less it ran over any given month. The unit's energy usage was measured against the capacity required from the space and climatic conditions over the course of one year. The VRF unit ran the least, only running 44% of the time in the highest load month of July. The rooftop unit ran 83% of the time in this same month. Higher efficiency units were able to cool the same space, with less energy in less time. This allowed the unit to cycle down or even shut off in lower loads (night or winter). The distribution of the runtimes as a percentage of the time in the month is shown below in Figure 7.

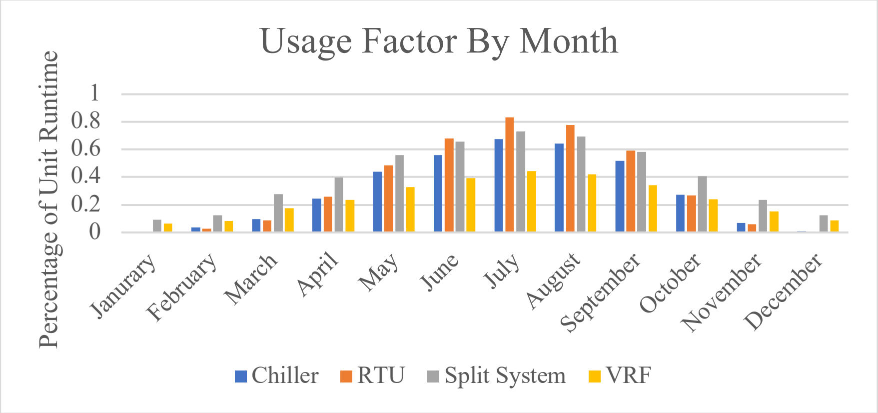


Figure 7: Monthly Usage of the Four Systems

Conclusion

Individual performances of each system were analyzed and compared. It was clear that the variable refrigerant flow system had the highest efficiency and subsequently lowest operating cost. While it is inherently efficient due to the fundamentally different handling of heat rejection, it is also efficient from the components used, such as digital scroll compressors or brushless direct-drive fans. Overall, this technology's higher initial capital investment pays off in the cost savings seen over the unit's lifespan. The next most efficient and cost-sensitive system was the chiller. While less efficient than the VRF system, chillers are also very efficient in handling heat. As the chiller system size increases, the cost-benefit of having a hydronic system also increases. Since this system was limited to only 10 tons, its efficiency was hampered. On the lower end of the performance was the rooftop unit. While this system did not perform as efficiently as others, it is offset by its lower cost and simpler design. These rooftop units are often easier to install and operate, which may be attractive for some consumers. The least efficient system in this study was the split system. This had a number of disadvantages, including less efficient components, a refrigerant line set, and low tonnage capability. However, it should be noted that this system is one of the most commonly sold, especially in the residential market. This is because they are often the most simple to operate as well as some of the lowest initial capital costs. To determine the best system, each building needs to be analyzed, and the owner's needs need to be met. If the owner is initially looking for lower capital cost, they may settle for a less efficient system. If they pursue energy efficiency or an energy rating, they may need to set aside additional funding for a more efficient unit. Each system's application is unique and depends entirely on the circumstances. However, this study's variety of mechanical cooling equipment shows a system for every application.

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