Energy and power savings through thermal energy storage in an airport air conditioning system

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Abstract:

This study presents the modelling and simulation of an airport terminal using EnergyPlus software considering the conditions currently faced by the terminal, the cooling demand attended to by chillers and an alternative situation in which a thermal energy storage (TES) tank is employed. The airport terminal was modelled considering real materials, occupation schedules and equipment usage coupled to the climatic file for the specific city where the airport is located. The electrical energy consumption and power demand were adjusted to match the energy and demand bills issued by the local electricity utility company. The air-conditioning system was modelled using performance data obtained from the manufacturers of the equipment. The electricity cost reduction was estimated in US$ 285,000.00 per year, mainly due to an electrical demand reduction of almost 24% at peak hours. The use of different operating strategies such as night operation allowed for a higher coefficient of performance (COP) to be achieved. Considering only the summer months, a general energy reduction of 5% was estimated for the HVAC system plant equipment. Another important benefit of TES is the possibility of increasing the airport's cooling capacity by approximately 25% through the simultaneous use of the HVAC system and cooling storage tank capacities.

Keywords:

Cooling storage, EnergyPlus simulation, Coefficient of Performance, Off-peak demand.

1. Introduction

Energy consumption in buildings is a major concern in many countries, and it is estimated that this sector currently accounts for approximately one-third of worldwide final energy use. Energy regulations have set minimum energy efficiency requirements for the design and construction of new buildings and retrofitting of old ones, and a 20% energy reduction is achievable through conventional building technologies. The HVAC system is considered the most energy-demanding system in a building, and performance comparisons thereof should be based on energy simulations of particular buildings and HVAC systems [1-2]. The Brazilian government recently devised a new federal regulation for energy efficiency levels in buildings that is divided into three parts: lighting system, HVAC system and building envelope. A total of 5,000 alternatives were simulated to develop two regression equations for two groups of building volumes. The results of the simulation yielded an electricity consumption indicator that is classified into five efficiency levels ranging from A to E [3].

Many countries have different electricity rates between peak and off-peak periods of the day. In Brazil, the peak period is usually from 6 to 9 pm and the rate value is usually approximately 6 times greater for the peak period. The majority of the TES systems installed seek to benefit from the electricity demand and consumption reduction due to the shift in the refrigeration operation time out of the peak period; thus, the electricity demand during this period is limited to that associated with cold water pumping and the ambient air distribution consumption of fans. Some studies have also indicated benefits of thermal storage for heat pumps. Other benefits include the better COP obtained, which is due to a lower condensing temperature, because usually lower temperatures occur at night and the early hours of the day, and a smaller refrigeration system, which is sized to match the average cooling demand of the day. The disadvantages are the extra cost of the storage systems, which must be carefully dimensioned, and the lower evaporation temperature required, mainly when ice is used to store the cooling load [4-9].

Electrical utilities experience difficulties in maintaining sufficient capacity to meet the peak customer demand while at the same time supplying reasonably priced electricity. One way to defer or avoid the construction of new power plants is to level local electrical loads over time. To this end, a standard practice methodology (SPM) is commonly used for evaluating the cost-effectiveness of both new supply resources and demand-side management (DSM) measures. Several reported case studies by the ARI (American Refrigeration Institute) and IEA (International Energy Agency) demonstrate how TES systems provide energy savings and reduce the environmental impact, illustrating clever applications of TES equipment in new buildings to reduce initial costs [5].

TES coupled with a conventional air-conditioning system was considered a suitable method for electric load levelling in Saudi Arabia. The peak cooling load demand reduction was estimated to be 30-40% as well as 10-20% in peak electrical demand. Other benefits include savings in energy costs, transformers and switchgear costs, maintenance costs and fire protection water tank costs [6].

In a review about research on cold thermal storage, Saito [4] mentioned improvements in air-conditioning efficiencies for universities, schools and apartment buildings using both cold-water-type storage and ice-making storage. For a school utilising an ice-making storage system, the payback period was estimated to be less than 4.2 years without taking advantage of utility incentive payments. The use of phase change materials (PCM) for cooling and heating purposes has been extensively studied for many different applications, including medical and food protection from temperature increases in transport systems, passive bioclimatic storage, temperature maintenance in electronic devices, cooling of engines and turbines, spacecraft thermal systems, solar systems and buildings. Some reported disadvantages to using PCM for cooling purposes are the random character of crystallisation and the delay to start solidification (undercooling) what leads to the study of new materials to enhance PCM performance like graphite particles [10-11].

One important issue to address when trying to match a TES system and cooling equipment is the correct size that yields the best results. This match can be accomplished through commercial software offered by equipment manufacturers. Tools for HVAC design and analysis can be categorised with respect to the problems they are meant to address. Although these problems are not mutually exclusive and some tools can handle several problems, they do tend to be investigated in isolation from each other.

Tools for equipment sizing and selection offer HVAC equipment sizing (Carrier HAP, Trane TRACE 700, EnergyPlus etc.) and are based on standard procedures and algorithms established by, for example, the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE), but many are proprietary software products distributed or sold by equipment manufacturers. Tools for energy performance analysis are designed to predict the annual energy consumption of an HVAC system. Based on a system of equations that define the thermal performance of buildings and systems, and with given boundary conditions, operation strategy and controls, these tools perform (hourly or sub-hourly) simulations (Carrier HAP, Trane TRACE 700, DOE-2, eQUEST, EnergyPlus, ESP-r, IDA ICE, TRNSYS, HVACSIM+, VA114, SIMBAD, etc.). These tools are typically used to calculate and analyse full- and part-load performances, analyse system operation strategies, compare different design alternatives etc. [12].

The estimation of energy consumption on an hourly basis is very important in understanding a building’s energy profile and to determine whether a TES system is adequate [13]. Fumo et al. [14] proposed special coefficients generated through EnergyPlus simulation to use on electricity and fuel utility bills to estimate hourly energy building consumption according to type and climate zone. The method proposed can eliminate the need for creating highly sophisticated simulation models and improve the estimation of building hourly energy consumption based on information that is known to be true [14, 15].

A method for calculating industrial energy savings using utility billing, production and weather data is able to disaggregate saving into production-dependent, weather-dependent and independent components, providing additional insight into the nature and effectiveness of the individual saving measures. The use of whole-plant energy use data captures the net effect of synergisms between sub-systems, provided that the energy use of non-retrofitted equipment remains unchanged between the pre- and post-retrofit periods [16].

The use of TESs is able to increase air-conditioning cooling capacity, as studied in German's pharmaceutical industry, which showed a return of investment time of 6 years for additional cooling systems and 3 years for a TES system [17]. One extra benefit considered was the greater reliability of the TES system.

EnergyPlus is a powerful tool for studying building energy consumption on an hourly basis, provided that good cooling equipment and TES models are available. Ihm et al. [18] developed a thermal energy storage model for EnergyPlus by considering two chillers in addition to a TES system: a base-load chiller to directly meet the building cooling load and a dedicated TES chiller to charge the TES system. The simulation was performed for different control strategies, chiller and storage tank sizes and showed that conventional control strategies can reduce energy costs, but better control strategies might be considered to evaluate TES systems.

2. Methodology

Considering that the main focus of this work is air-conditioning systems, with or without a TES, the building thermal zones were chosen in a simplified manner to characterise the thermal load throughout the whole year. Material modifications, such as insulation, glass film or wall thickness, and operational strategies, such lighting or shading control, were not proposed and may be addressed in future work.

2.1. Building characteristics

The building was divided into eight thermal zones, and all data regarding the roof, wall, floor and window materials were introduced along with their corresponding properties according to ASHRAE [19] tables. The airport terminal, modelled using the OpenStudio interface for EnergyPlus, is shown in Fig. 1.

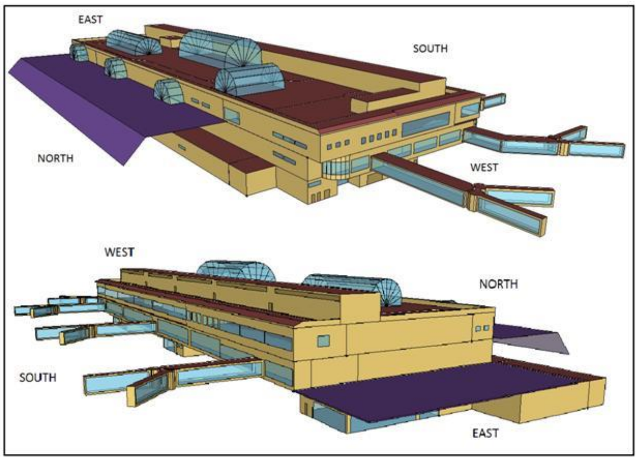


Fig. 1. Airport terminal modelled in OpenStudio

The internal gains were introduced in EnergyPlus using the maximum value for each zone, and through appropriate schedules, usage fractions were applied considering the characteristic values of each zone. Occupation schedules were determined using official data about passengers transported and airport workers, which are very realistic and account for differences over days and periods of the year. The lighting and equipment intensity [W m^{-2}], as well as radiant, visible and latent fractions, were determined based on typical values reported in the literature and some adjustments made using airport electrical bills. The lighting intensity varied from 5 to 12 W m^{-2}, and the equipment intensity varied from 20 to 80 W m^{-2}. Compared with the real values obtained from electricity bills, the results obtained from the baseline simulation were considered satisfactory, as shown in Fig. 2.

The usage fractions adjusted to match real consumption achieved reasonable results, as seen, but the adjustments were limited due to the opposite behaviour displayed by the demand values during summer months.

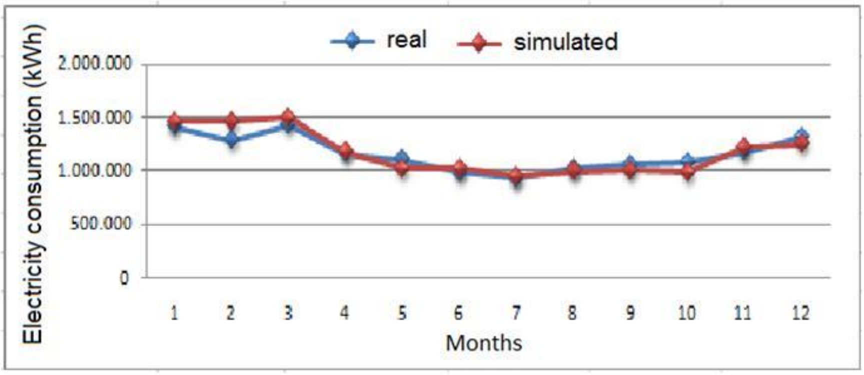


Fig. 2. Comparison between real and simulated electricity consumption based on utility bills

2.2. Air-conditioning system

The airport air-conditioning system is composed of three chillers with a rated capacity of 1283 kW each. Each unit has two screw compressors, a water-cooled condenser, fixed speed pumps for both condensing and cold water in the primary circuit and three cooling towers with variable speed fans for condensing water. The secondary circuit is composed of three variable speed pumps that supply cold water to eight air-handling units with variable speed fans and return- and outdoor-air mixing. The ambient temperature is controlled through a variable air volume that varies the amount of cold air introduced connected to a proportional valve to control cold water flow to each unit. A schematic of the system is presented in Fig. 3, showing both circuits and the TES system, which is not used at the moment.

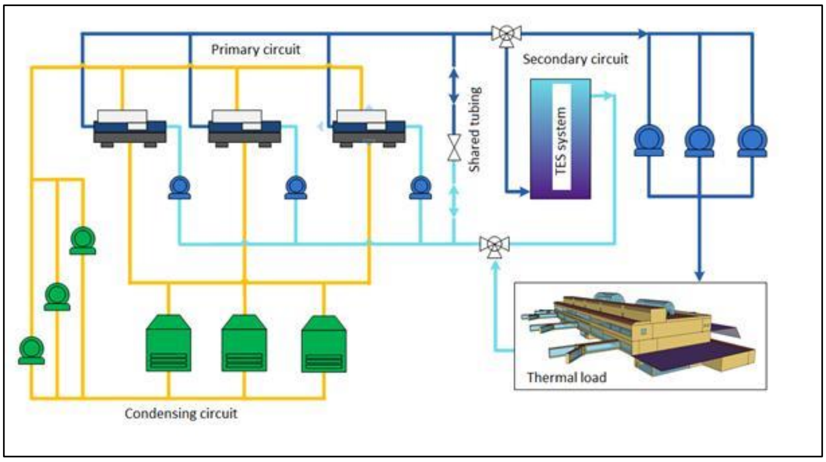


Fig. 3. Schematic of the airport air-conditioning system

The storage tank, not used for the cooling system, has a total capacity of 2,000 m^3 and was not introduced into the simulation of the base case.

2.2.1. Air-conditioning system modelling

Each component of the cooling system was modelled using a specific module from the EnergyPlus library. The thermal performance is determined using the data obtained from the equipment manufacturer or literature information and introduced by the user as a polynomial equation.

The EnergyPlus modules used included the following:

- Chiller:Electric:EIR: chiller units;
- CoolingTower:VariableSpeed: cooling tower;
- HeaderedPumps:ConstantSpeed: chiller primary circuit and condensing pumps;
- HeaderedPumps:VariableSpeed: secondary circuit (to the air handling units);
- Fan:VariableVolume: air handling units;
- ThermalStorage:ChilledWater:Stratified: water storage tank.

The partial performance of each component was introduced by considering the different ambient temperatures and thermal loads of the system through factors used by EnergyPlus to correct the nominal performance.

When modelling water storage tank operation, the EnergyPlus HVAC template for thermal storage considers that there is a charging side (loop between the chiller system and the tank supplying it with cold water) and a discharging side (loop between the water tank and the air-conditioning system). The real system is different because the chiller was designed to simultaneously pump water to the air handling units and charge the storage tank, which was sized to meet the peak hour cooling load alone and thus used for only three hours daily.

The solution to modelling the real situation accurately was the creation of an additional virtual cooling water coil placed in parallel to the charging side (water side) and in series with the original cooling water coil (air side). This new coil receives cold water from the chiller during non-peak hours, when the original coil is not operating, and is idle during peak hours, when the original coil receives cold water from the water storage tank. This solution was considered better than having a new set of refrigeration systems, which would include all of the associated equipment, such as pumps and cooling towers [18]. Of course, the new cooling coil has no air pressure drop that would erroneously increase the fan power.

2.3. Simulation conditions

The base case was simulated using the refrigeration system strategy, which is based on reducing the chiller capacity (four screw compressors, each with a slide valve system) according to the water return temperature. The cooling coil capacity is controlled by the ambient temperature, which acts on the fan speed to deliver the amount of cold air required. The main results extracted from the simulation included water flow rates, entering and leaving water temperatures and electric power and consumption from each refrigeration system component. Moreover, the outdoor wet bulb and indoor dry bulb temperatures were required, in addition to the chiller COP, actual cooling capacity and non-cooling equipment consumption.

After setting the parameters of the base case simulation, the TES system was introduced and new simulations were performed. The higher efficiencies achieved with the TES system are attributed to the greater COP of the cooling equipment operating at its nominal capacity rather than at partial capacity and with lower condensing temperatures due to night operation. These situations were simulated separately first and then grouped to observe the global results.

3. Results and discussion

The first simulation results were compiled considering the electrical demand and consumption data obtained for the different air-conditioning equipment shown in Tab. 1.

Tab. 1 shows that the air-conditioning-related equipment constitute the majority of the airport demand and consumption values during the summer, although the winter period values are not negligible. The values are the maximum registered for demand and the period average for consumption.

The introduction of the TES system allowed for the evaluation of the operation of the equipment mainly at their nominal capacity because load levelling was assumed by the TES system. Although the COP of the chiller units, for cold water at 6.0 ^{o}C, decreases from 4.64 to 4.34 when comparing full load to partial load operation, the simulation results did not present a large difference, as shown in Tab. 2.

Table 1. Preliminary data of airport air-conditioning system (monthly)

Source of Consumption	**Summer**		**Winter**	
	Demand (kW)	**Consumption (kWh)**	**Demand (kW)**	**Consumption (kWh)**
Chiller Units	852	435,128	149	68,344
Cooling towers fans	44	15,248	2	465
Condensing pumps	52	33,156	17	12,508
Primary circuit pumps	34	11,497	11	8,278
Secondary circuit pumps	67	31,526	10	5,444
Air-conditioning fans	372	171,979	183	131,933
Other sources	1,392	746,613	1,392	746,613
TOTAL	**2,813**	**1,445,147**	**1,764**	**973,585**

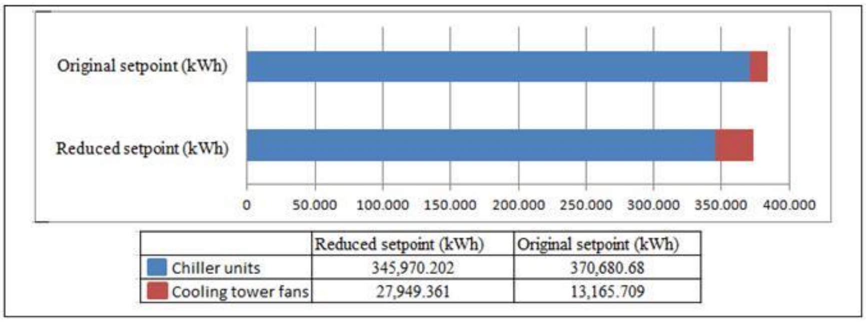
The slightly better results obtained for partial load charging may be attributed to the characteristics of the chiller unit design, which features one condenser for each of the two compressors; thus, the greater condensing area compensates for the smaller compressor efficiency in partial load operation under the same conditions.

Table 2. Chiller electricity consumption under two operation strategies

Strategies	**Chiller 1**	**Chiller 2**	**Chiller 3**	**TOTAL**
Full load TES charging [kWh]	157,067	145,023	68,590	**370,680**
Partial load TES charging [kWh]	157,008	144,969	68,564	**370,541**

Another benefit of the TES system is the night operation of the chillers, which provides lower condensing temperatures linked to the outdoor wet bulb temperatures [20]. A chiller nominal COP of 4.76 is achieved with a cold water temperature of 6.7 ^{o}C and condensing water entering at 29.5 ^{o}C (water temperature leaving the cooling tower), but if the water temperature is decreased to 20 °C (minimum value allowed by the chiller manufacturer), the COP increases to 6.05. The cooling tower leaving temperature is regulated by its fan speed to achieve the set point of 29.5 ^{o}C, even with the possibility of free convection operation. Two simulations were performed: the first considering the standard procedure already described and the second managing to achieve the lower limit leaving water temperature of 20 °C. The energy results were divided into those associated with the chiller and those associated with the cooling tower consumption and are presented in Fig. 4.

The strategy of reducing the condensing water set point produced lower overall consumption, although the fans' consumption increased by more than 100%. The chiller consumption decreased due to the reduced condensing temperature, but not as much as expected. It is important to note that the wet bulb data for a typical summer day showed temperatures above 20 ^{o}C for many hours; therefore, the cooling tower water temperature reached the set point in less than 4 hours during the early hours of the day and was greater than 24 °C throughout the whole afternoon.



	Reduced setpoint (kWh)	Original setpoint (kWh)
🟦 Chiller units	345,970.202	370,680.68
🟥 Cooling tower fans	27,949.361	13,165.709

Fig. 4. Energy comparison of two cooling tower operation strategies

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Another important datum obtained from the simulations is the cooling capacity gathered from the airport air handling units. Considering the hottest day in the meteorological year used, the actual refrigeration system, without TES, reaches its maximum capacity by the end of the day, as shown in Fig. 5.

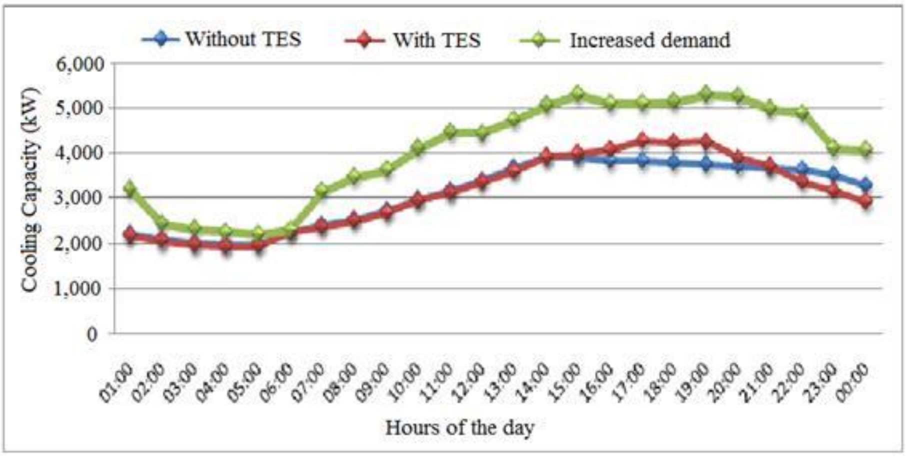

Fig. 5. Cooling capacity with and without TES

Incorporating the TES system leads to an increase in the cooling capacity [17, 21], indicating that the actual system is not able to fully meet the air-conditioning need of the terminal, and an increase in the demand will require a new air-conditioning system. The green line in Fig. 5 was simulated by increasing the occupancy and equipment use of the terminal up to the limit when the ambient temperature was kept within the set point established for actual condition, while the cooling demand was simultaneously met by the chiller units and the TES system. It can be seen that an increase of approximately 25% in the cooling capacity is possible without the need to install new air-conditioning equipment.

Taking into account all of the equipment of the air-conditioning system for the whole summer month of January, an analysis of the global plant COP (not only from the chiller) reveals that a reasonable decrease in energy consumption of 53,046 kWh (8%) is possible while increasing the COP by 9% (Tab. 3). Tab. 3 shows that the cooling capacity is almost the same, as expected, and the greatest reduction is achieved for the chillers.

Table 3. Global COP considering all equipment for January (summer)

Month of JANUARY	Electricity Consumption [kWh]				Integrated Cooling Capacity [kWh]	**Global COP**
	Chillers	VAV	Pumps	Towers		

Without TES	381,139	172,524	89,967	31,958	1,872,770	**2.77**
With TES	339,641	172,201	82,799	27,901	1,870,940	**3.01**

Another important piece of information extracted from Tab. 3 is that the auxiliary equipment of the primary circuit and the terminal cooling equipment of the secondary circuit account for approximately 77% and 83% of the chiller energy consumption, respectively, without and with TES, thereby greatly reducing the global COP compared to the chiller COP alone.

The abovementioned results were obtained by considering the following configuration: priority to TES charging at night; charging at full capacity of the chillers; condensing water temperature set point fixed to 20 °C; and TES system operation only at peak hours, unless the chillers were not able to meet the terminal thermal load. Both the actual and the TES system were simulated throughout the entire year, and the results for energy and demand were evaluated for each refrigeration system component, determining the energy cost for both systems. The electricity tariff scheme of the airport considers different values for peak and non-peak hours for both energy and demand and also the season (dry and wet). Table 4 presents the values obtained for the month of January alone, including the costs, and Tab. 5 presents the cooling equipment demand and energy values for all months of the year. One important observation to make is that the cost calculation was performed by adapting the electric energy utility contract to obtain a greater advantage, or lower cost, for each situation because the greatest benefit of TES is the ability to reduce peak demand values [4-8].

Table 4. Energy and demand comparison for the cooling system without and with TES

JANUARY								
	WITHOUT TES				WITH TES			
	PEAK		OFF-PEAK		PEAK		OFF-PEAK	
ENERGY SOURCE	Max power [kW]	Monthly Energy [kWh]	Max power [kW]	Monthly Energy [kWh]	Max power [kW]	Monthly Energy [kWh]	Max power [kW]	Monthly Energy [kWh]
Chillers	852	42,856	852	338,283	-	-	841	339,641
Cooling towers fans	44	3,040	44	28,918	-	-	44	27,901
Condenser pumps	52	3,585	52	34,084	-	-	52	32,895
Primary circ. pumps	34	2,278	34	18,940	-	-	34	18,824
Second. circ. pumps	66	3,672	66	27,408	66	4,408	66	26,672
VAV fans	376	17,986	379	154,538	393	20,058	398	152,143
Non cooling system	1,278	83,005	1,278	581,033	1,278	83,005	1,278	581,033
Billing values	2,702	156,422	2,705	1,183,204	1,737	107,471	2,713	1,155,165
Cost [US$]	101,6 K	22,7 K	21,2 K	108,1 K	48,1 K	15,6 K	16,1 K	107,7 K
	TOTAL [US$]		253,535.15		TOTAL [US$]		187,511.86	

For the month of January, the greatest total cost reduction of US$ 66,023.29 is achieved, approximately 26% of the total cost. The main cost reduction for the system with TES is that for the electrical peak demand value, which represents more than 40% of the total cost of the actual system, and 26% of the total cost of the system with TES. These advantages do not hold for the rest of the year, as shown in Tab. 5. During the cold season (from May to September), the difference in peak values is very small, although the off-peak demand for the system with TES is greater due to the more concentrated use of the equipment. The smallest cost difference is that for the month of May, with a value of US$ 10,736.00, similar to the difference observed for all of the colder months.

Similarly to January, when considering demand and energy costs for the whole year, the total cost reduction is US$ 285,000.00. From May to October, the energy consumption and the cost of the system with TES is always slightly greater, but because the contracted demand is smaller, the overall cost is lower. During the warm season (November to April), the benefits of shifting the working hours of the cooling equipment to the night and operating at the full load of the chiller [14, 15] reduce the energy consumption by 149,075 kWh, 4.7% less than that of the actual system, although the energy consumption during the cold season is 62,821 kWh lower for the actual system. The overall energy reduction is 1.86%, but the demands to be contracted with the utility company increase 8.8% during off-peak periods and decrease by 23.9% for the peak periods if the TES system is used.

4. Conclusions

In the present work, the complete simulation of an airport was performed using the EnergyPlus software to compare the actual cooling system implemented and a thermal energy storage (TES) system. The analysis was divided into cooling equipment consumption for individual changes, such as night operation, operation at the full load of the chiller or a decrease in condensing water temperature leading to a change in the cooling tower settings, and full system changes considering demand and energy values for the whole year.

Table 5. Demand and energy values of the cooling equipment for the whole year

	WITHOUT TES			WITH TES		
	Demand [kW]		Energy [kWh]	Demand [kW]		Energy [kWh]
MONTH	PEAK	OFF-PEAK	Full hours	PEAK	OFF-PEAK	Full hours
January	1,424	1,427	675,588	459	1,435	622,542
February	1,393	1,414	595,951	456	1,411	606,223
March	1,140	1,214	548,248	365	1,256	513,586
April	700	724	331,572	260	1,144	327,908
May	420	436	237,924	259	1,004	250,420
June	337	353	211,514	256	737	220,005
July	340	340	209,850	255	682	218,872
August	615	426	229,948	265	926	238,709
September	428	439	243,868	262	939	256,730
October	660	701	313,821	262	1,115	325,010
November	1,022	1,140	468,589	347	1,209	464,438
December	1,355	1,335	570,548	419	1,245	506,724
TOTAL [kWh]			4,637,421	TOTAL [kWh]		4,551,167

The main conclusion is that the greatest benefit of thermal storage is the possibility of peak demand reduction and consequently a lower electricity billing cost due to the shift in cooling equipment operation to the off-peak period. Despite the higher chiller coefficient of performance when the system is operated with a lower condensing water temperature, the whole-year analysis of the full system revealed that the benefits are not as great because the auxiliary equipment represent an important share of the total system power and the energy needs of the system with TES during the cold season is higher than those of the actual system.

The overall energy reduction using the TES system was 1.86%, considering a reduction of 4.7% during the warm season (November to April) and an increase of 4.3% during the cold season (May to October), but the demand need is 8.8% higher in the off-peak period and 23.9% lower in the peak period.

Another important advantage of the TES system is the possibility of increasing the cooling capacity by 25% with the simultaneous use of the stored cold water and the chiller equipment.

These results demonstrate the importance of a thorough analysis of a refrigeration system, including that of all of the auxiliary equipment and the system’s performance under other conditions during the whole year rather than only under the standard conditions.

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