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Effects of external weather on the water consumption of Thermal-Energy-Storage Air-Conditioning system

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ABSTRACT

Thermal-Energy-Storage Air-Conditioning (TES-AC), a sustainable form of Air-Conditioning (AC) operates by storing thermal energy as chilled water when energy demand is low during nighttime. Later it uses the stored thermal energy during the daytime to cool the indoor air of the building the next day. However, the stored thermal energy in the form of water in the tanks of the chiller plant might be affected by external weather factors. It is essential to understand whether there is a relation between external weather conditions and water consumption in the TES-AC system. Without verifying the relation, applying computational intelligence for Thermal-Energy-Storage (TES) in Heating, Ventilation, and Air Conditioning (HVAC) would not be appropriate. However, not much research has focused on applying such techniques in HVAC for facility management and maintenance. Moreover, identifying these features by discovering the relation between weather and water consumption is a crucial part to apply computational intelligence such as machine learning techniques for predictive maintenance of this facility as it heavily relies on water volume for TES-AC charging. During warmer weather, the stored thermal energy might have an effectual loss due to evaporation which would mean more water consumption by TES-AC for cooling. Hence, this research investigates whether external weather data has any effect on the water consumption of TES-AC and discusses how external weather may affect the water consumption of TES-AC and if it is important to factor it in whilst utilizing computational intelligence for charging load prediction of TES-AC.

1. Introduction

As climate change becomes evident across the globe, communities are trying to act for more sustainable living [1]. With climate change, heat waves are being felt more along with a significant increase in heat and humidity which leads to tropical countries having even warmer weather conditions than what is generally experienced. With warmer weather conditions, the Air Conditioner (AC), a facility that is used to condition the indoor air by providing cool and desirable temperatures indoors, must work harder to provide such satisfactory outcomes [2]. A conventional AC conditions the air by removing the unwanted heat and humidity outdoors which contributes negatively to the atmosphere. More so, such conventional AC increases the overall building energy consumption mainly in tropical or subtropical countries to provide desirable temperatures and transfer heat and humidity outdoors besides releasing harmful greenhouse gasses [3,4]. Hence, Thermal-Energy-Storage Air-Conditioning (TES-AC) systems are being focused by some major environmentally friendly corporations as this is a more sustainable form of AC that provides similar desirable cool air conditions but with a lower energy consumption [5].

1.1. Overview of thermal-energy-storage air-conditioning

Thermal energy in the form of chilled water for warmer countries or hot water for colder countries is produced during periods of off-peak electrical demand and then collected in a thermal energy storage tank. Afterward, the stored thermal energy is withdrawn and distributed to the building during on-peak periods. Warm and chilled water enters and exits the tank through diffusers located at the top and bottom to eliminate turbulence and allow the water in the tank to stratify, with the colder water at the bottom and the warmer water at the top to form a sharply defined thermocline i.e., a transition layer of water, between the warm and cold-water regions. All through the discharge mode, the chillers and related condensing equipment are de-energized, and chilled water from the TES tank is circulated to the building facility for cooling the air [6]. After the discharge operation is completed, the tank will

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contain mostly warm water and is prepared for the “charging” mode phase where warm water is withdrawn through the top diffuser, dispatched to the chiller plant, and then cold is returned to the tank through the bottom diffuser after being cooled by a chiller system [7]. When that process is finished, one thermal energy storage cycle is completed, and the tank again is ready to be discharged. It is clear from the operating system of TES-AC that water is an essential component and being used for charging the system.

Besides, the way TES-AC systems achieve lower energy consumption is simply by transferring the charging load from the on-peak hours to off-peak hours, and load shifting control is one of the most effective peak demand management methods [8]. It is to be noted that in warmer countries, the tanks of the chiller plant system of a building facility are generally located in the basement underground as a sensible heat storage strategy to minimize energy loss in the form of evaporation [9]. As much as a TES-AC system lowers building management costs, it is tedious for facility managers to ensure smooth ongoing of daily operations with this system including keeping the management costs low since, if the charging load is not handled appropriately, it can more than double the energy consumption. Such maintenance of a TES-AC system is complicated and to ease the process of managing and maintaining this facility, one can rely on computational intelligence to benefit facility managers from the perspective of predictive maintenance [10]. However, before implementing advanced computational intelligence, such as deep learning techniques for the predictive maintenance of a TES-AC system, it is important to establish the impact of weather on TES-AC water consumption, in order to consider it as a feature. Although various other influential parameters have been investigated such as inlet temperature of heat transfer fluid during charging and discharging periods, air flow rate, and surrounding temperature, not much research has focused on analyzing weather data and determining which weather factors might affect the TES-AC system’s water consumption [11].

1.2. Significance of research

This research aims to determine whether external weather metrics such as temperature, humidity and atmospheric pressure have any effect on the water consumption of TES-AC systems as this is an essential factor to consider in applying computational intelligence such as machine learning to the problem. The significance of determining this relationship of weather data with TES-AC systems is foundational because it intends to facilitate this sustainable form of AC without the need of sensor data thereby making more facility managers inclined to use the TES-AC system as they will find it less complicated. Moreover, it is assumed that external factors such as weather data and occupancy in the building have more effects on a TES-AC system than sensor data coming from chiller equipment. The sensor data came from chiller equipment is important in predicting a component’s condition, but such sensor data is not an essential factor in determining the charging load or the water consumption of a TES-AC system.

2. Literature review

Thermal-Energy-Storage (TES) plays an important role in eradicating the discrepancy between energy supply and energy demand and it is discussed how latent heat thermal energy storage (LHTES) is more useful than sensible energy storage due to the high storage capacity per unit volume/mass at nearly constant temperatures [12,13]. Due to the efficiency in energy consumption, various forms of TES applications are being investigated and phase-change materials (PCM) based TES applications are thoroughly reviewed through which it is demonstrated that air-conditioning is one of the main applications of TES [14]. Application of TES for AC systems and its benefits have been investigated where long lifetime energy storage without typical issues such as hysteresis cycles are highlighted [15]. Mehari et al. [16] mentioned that absorption TES is appealing for utilizing solar energy, waste heat, off-peak electricity demand due to its high energy storage density and long-term storage capability. Dincer [17] discussed various methods and applications of TES systems in buildings and how the applications with energy saving techniques can have environmental benefits.

A thorough review is presented regarding the evolution of TES and how utilizing this technology for cooling-based applications such as conditioning indoor air to provide cool air can benefit the environment [18]. In previous research it was established that there is a link between different components and system performance and additionally that thermal front degradation negatively affects plant efficiency which indicates more research needs to be conducted that will facilitate the application of TES [19]. Sorption TES, a promising technology for effectively utilizing renewable energy, industrial waste heat, and off-peak electricity, is the latest thermal energy storage technology in recent decades. It is currently in the laboratory investigation stage and its advantages include high energy storage density and achievable long-term energy preservation with minimal heat loss [20]. It is evident that researchers are focusing on minimizing heat loss when it comes to utilizing the TES system. Stropnik et al. [21] conducted an experimental analysis for nearly zero energy buildings utilizing latent PCM-based TES tanks. Through a critical review, implementation of TES in district heating and cooling is explored as the heat reservoir of a TES system has characteristics of optimally tackling heat and electricity demand evolution, changes in energy prices, extreme weather conditions and intermittent nature of renewable sources [22]. Tang and Wang [23] proposed a model predictive control for TES where the maximum indoor temperature is reduced without extra energy being consumed whilst achieving the expected building power reduction. Kohlhepp et al. [24] demonstrated how advantageous it was to implement TES due to its potential utilization of renewable energy by conducting an international field study of 16 mass integration of residential TES-AC. A hypothesis related to thermal energy storage with unconventional methods is discussed for small residential use and it outlines the low environmental impact of such methods [25]. Huang and Khajepour [26] proposed a novel approach with TES which showed an improvement in expansion and compression efficiencies. As the interest in using TES at a large scale for cooling is growing, the time is due to research further into optimizing TES-AC systems to ease the transition process from conventional AC to TES-AC [10].

When there are warm weather conditions, people tend to use Air Conditioners (ACs) as a basic amenity to reduce the discomforts of nature, which consumes a lot of electrical energy [27,28,29]. Nguyen et al. [28] proposed a short-term prediction of energy consumption due to air conditioners in residential buildings as they are a main source of building energy consumption based on weather forecast information to improve energy efficiency with a thermal simulation. In the study conducted to measure household electricity demand under hot weather in a residential area in Kuala Lumpur, Malaysia, which included total and AC electricity consumption [30]. The results from the study [30] of the residential area indicated that the average AC electricity consumption extended from 19.4% to 52.3% during the measurement period and the values suggest the AC electricity contributed to a major portion of total household electricity consumption.

According to the previous studies, AC usage drastically increases electricity consumption during hot weather conditions which shows that people require AC usage more in hot weather [31,30,32]. Besides temperature, humidity is an important weather metric as dehumidification in buildings remains as a primary contributor to cooling load in hot-humid climate regions, thereby consuming much energy, and contributing to environmental impact through greenhouse gas emissions [33,34]. Shehadi [35] discussed humidity control in a building to meet the comfort level of building occupants. Since high levels of thermal comfort come at the expense of high energy demands, researchers are focusing on adaptive approaches to achieve thermal comfort. This research [36] analyses the climatic zones to propose a prediction model that reduces energy demands and has better thermal comfort which shows that there is a relationship between weather variables and energy demand and consumption. Sun et al. [8] mention how further efforts are required to develop more applicable load-shifting strategies that will optimize the energy efficiency of buildings that use TES-AC.

Recent studies regarding water demand prediction have shown that water demand is driven by weather variables, but it does not determine the extent of the effect on water consumption [37]. Zubaidi et al. [38] tried to better understand the effects of weather variables on water demand demonstrating that there is a relationship between water demand and weather [38]. With a proposed novel methodology, Zubaidi et al. [39] predicted the monthly municipal water demand based on weather variables. Water demand has a relation with weather variables, and since TES-AC depends on water as a charging load, there is also a relationship between load demand and weather variables. The research in [40] proposed a model for the evaluation of peak load reduction and change in overall energy consumption for a residential AC condenser with and without thermal storage. Any type of on-site water storage or even stored water can be utilized as a heat sink for the condenser during peak hours, which allows even more efficient and lower power compressor operation, and can be re-chilled at night during off-peak hours. The model used by Upshaw et al. [40] used simulated cooling load data for a typical home in Austin, Texas based on the summer of 2011 and typical meteorological year (TMY) datasets where the system demonstrated that the performance varied depending on weather data, the individual compressor as well as the thermal storage volume in the tanks. Additionally, it also mentions that total compressor energy consumption increases 5–15% due to the inefficiencies of re-cooling the thermal mass during the summer [40].

Shan et al. [41] suggested a new model predictive control strategy for controlling the charging/discharging of TES and the on/off behavior of chillers to achieve high efficiency. The suggested model partially dissociates the demand side and the supply side, so that the large chillers are either operated in high efficiency or turned off and solves the problem of frequent chiller fluctuations due to too low load in winter conditions [41]. Shan et al. [41] validated a proposed strategy on a dynamic platform based on the existing chiller plant in a high-rise commercial building during both summer and winter conditions based on real operational data which showed an improvement in the efficiency of chillers by 3.10% and 22.94% in summer and winter conditions, respectively. From these efficiency results, it is quite evident that TES-AC systems are susceptible to weather conditions. As a TES-AC system depends on water volume as charging load, it is important to understand how weather conditions have an impact on this system. As shown in the literature review above, aspects of temperature and humidity play important roles in the system, and these roles have yet to be fully investigated.

3. Material and methods

3.1. Research design and context

This research has been conducted with an industry collaboration that utilizes TES-AC for its commercial building operations and working with their data which spans several years. Subsequently, the weather data based on the location of the chiller plant is retrieved to conduct an analysis in determining the impact of external weather data to the water consumption of the TES-AC system. Fig. 1 shows the research framework in this study.

3.1.1. TES-AC HVAC system

The TES-AC in this HVAC system consists of three main components, i.e.: the water-cooled chillers that use a liquid refrigerant to cool water, the water thermal storage tanks that store the cooled water from the chiller, and finally the cooling tower on the rooftop that cools down the refrigerant in the chiller. The process is straightforward. Initially water is pumped throughout the chillers that cool down the water using the refrigerant and send it for storage in the water tanks. Condenser water carries over the heat from the refrigerant and heads to the cooling tower where excess heat is emitted outside. The cooled condenser water is sent back to the chiller to get more heat from the refrigerant.

During building operations, the stored chilled water is sent to the AHUs throughout the building using risers to cool down the air. The returned warm water gets sent back into the tanks. The system has enough tanks to hold cold water and warm water separately. If the stored chilled water is not sufficient for a day, then the chiller starts chilling water once again and sending it directly to the building. The warm water in the tanks can be sent again to the chiller for cooling the next day. Fig. 2 depicts the aforementioned TES-AC design.

3.2. Methodology and instrumentation

When solving a Machine Learning problem, it is important to have the right data to get the right results. A TES-AC system is very useful to reduce the negative effects on the environment compared to the traditional ACs. One of the main elements that could allow the TES-AC to function in a more efficient and energy-saving way is the volume of water that needs to be chilled (or charged) during the night. This research aims to investigate external data that might be impacting the volume of water charged, besides using only the conventional data that can be obtained from TES-AC sensors.

As already mentioned, weather is one of the main external factors that may affect the TES-AC systems. Generally, it is assumed that harsh weather conditions may impact the amount of water charged in TES-AC, especially in hot countries, where the AC needs to function more to lower the temperatures down to a comfortable level. Regardless, this relation between weather conditions and water consumption of TES-AC requires further investigation through computational analysis.

This research is conducted on a TES-AC in Subang Jaya, Malaysia, a tropical country with warm weather conditions. The chiller plant is responsible for a commercial building that houses 222 office units and 250 retail shops. Initially the weather data was scraped using the Beautiful Soup Python library from timeanddate.com. A simple scraping script was run to automatically navigate through the weather table on the website and save the data into CSV files.

There were multiple data types in the scraped data, however, the focus was on three main types i.e. temperature, humidity, and atmospheric pressure. This is because they are most impactful on the weather and consist of numeric values which are easier to calculate and analyze, compared to weather descriptions for example.

The objective here was to determine whether the extreme values in these different weather data types have a noticeable impact on the volume of water used in the TES-AC. A noticeable impact does not necessarily mean an obvious difference. In order to set an easy reproducible way of conducting this analysis, water usage or chilled volume data was converted into different classes of water level based on an even set range. This is because it is easier to carry out an analysis by checking if the water consumption falls into specific water level categories more often in the more extreme weather values.

3.2.1. Data classification

The water consumption data was therefore classified into 10 different levels, consisting of three low consumption levels, three medium consumption levels, three high consumption levels, and one level for extremely high consumption. By classifying the water consumption data, it is easier to draw conclusions and make comparisons. All the water values are in tons and were grouped into categories based on a range of water consumption values. Water consumption was calculated by increasing the water values that decrease from the storage water tanks during operation hours. This ensures that we are calculating the water consumed to cool the building. During the period where the water tanks are being charged the water levels decrease to send warm water back to the chiller but this is not calculated. Water level sensors are already

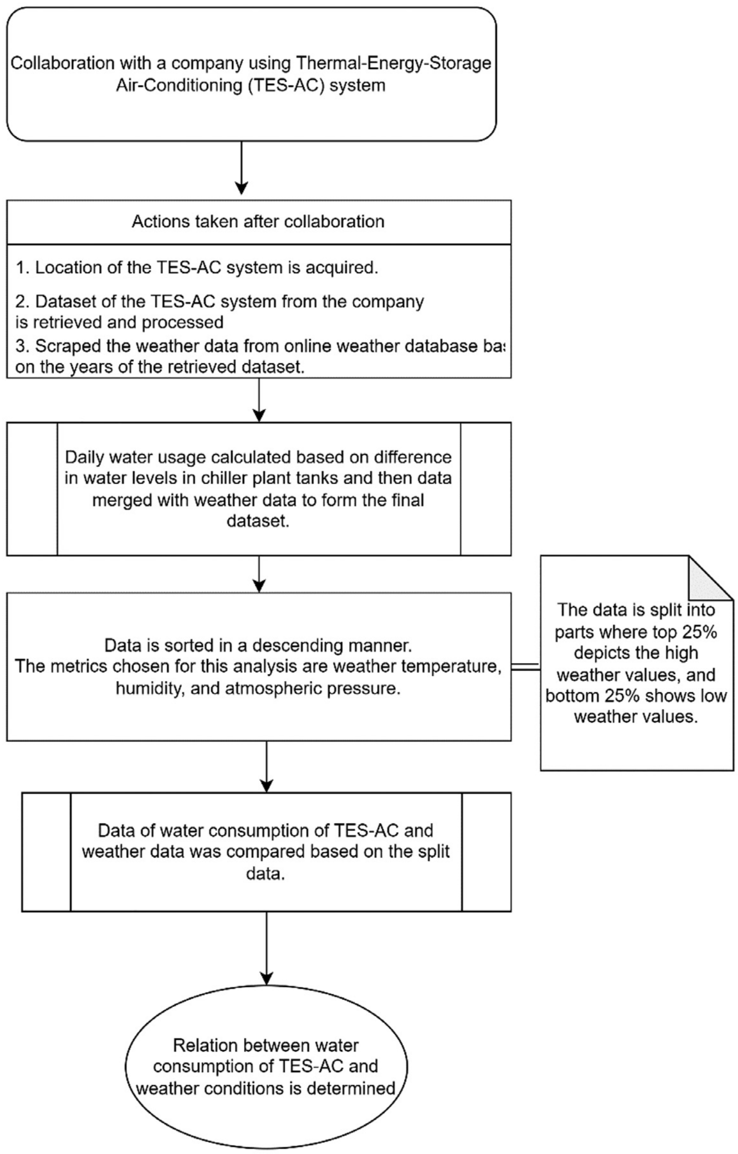

Fig. 1. Research framework showcasing a summary of the steps taken.

placed inside the water thermal tanks in question by the manufacturer of the TES-AC system.

The weather data was based on a 15-minute interval and therefore the data had to be calculated based on daily averages to match the water consumption format, which is one value per day. It should be noted that this problem was purposefully designed to consider values on a daily basis and not based on 15-minute intervals, despite the water consumption value being available on a 15-minute interval basis as well. The reasoning is that the differences in the values for every 15 min would be too small and negligible to draw any useful conclusions out of it. As stated earlier, the differences in water consumption using a small-time lag were not expected to be significant in realistic circumstances, and therefore conducting this analysis on a 15-minute interval data was expected to not be productive.

Finally, the two datasets were merged based on the date. If any row in the combined dataset contained any missing values, it was removed. The final dataset contained data for 2418 days and the next step was to start sorting the data by each of the weather data types and do comparisons.

The main idea here was to check how many times high water consumption occurs when the weather values are high compared to when those values are low. However, it is important to determine how many days should be considered as the dates with high or extreme weather values. Initially the top 10% and the bottom 10% were considered for the comparisons, however, the number of high-water consumption days was insufficient for a meaningful comparison. Eventually, it was set at 25%. That takes into consideration the top quarter and the bottom quarter while assuming half of the data, which lies in the middle, as non-extreme values.

3.2.2. *Data evaluation*

Each of the three weather data types (temperature, humidity, atmospheric pressure) was evaluated separately by sorting the data based on that weather data type in a descending order, to keep the highest value at the top. After the sorting was done, the top 25% of the data was split into a separate set, and the same procedure was done with the bottom 25%. Moreover, each of the separate sets was then looped through and the classifier in each day was compared with the eligible values and the count of high-water consumption days and low consumption days was recorded for each. Finally, the sum of those counts was calculated and set aside for comparison. The same procedure was applied to each of the three weather data types for temperature, humidity, and atmospheric pressure.

It is to be noted that the research was conducted while being fully aware that weather is not the only external factor that might be impacting the water consumption in the TES-AC. Other factors, such as which

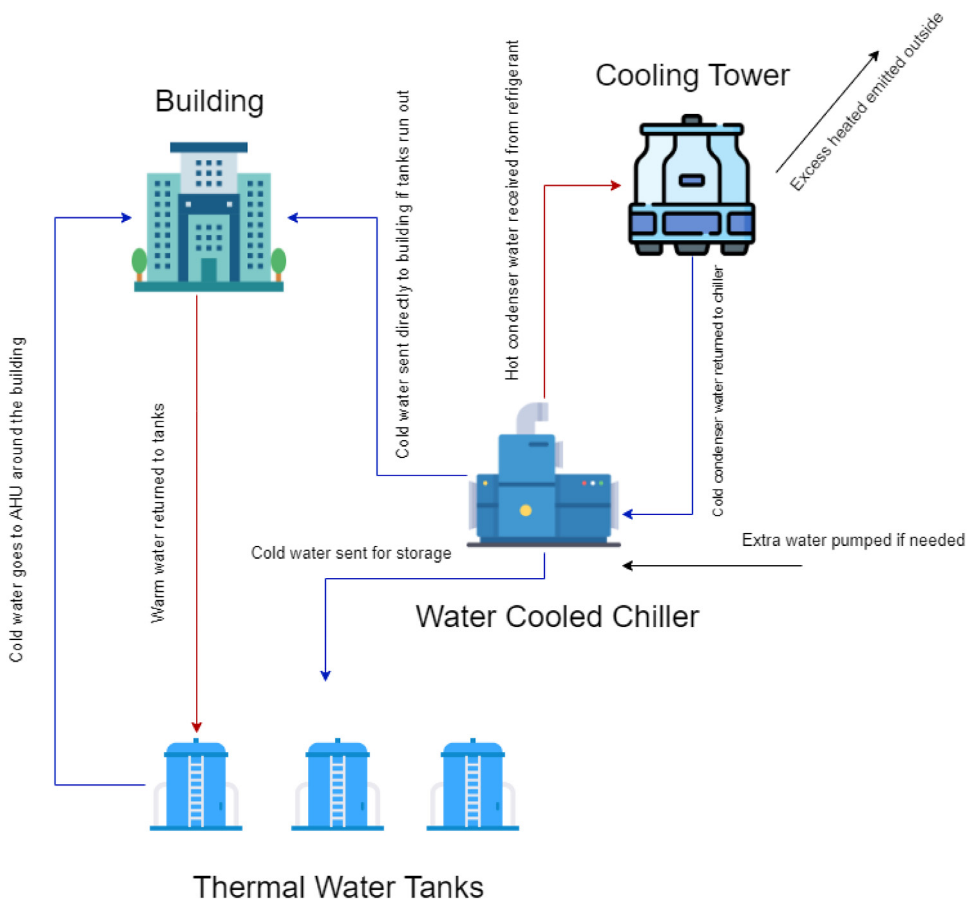

Fig. 2. Design of the TES-AC HVAC system used for this research.

day of the week is being considered or whether a day falls on a public holiday or not might also have an impact. While calculating the count of days where the weather data was high in each of the sets created, it was also counted how many of those days were weekends and how many were public holidays. The reasoning is to see if those days with high-water consumption depended on the day of the week or whether the day was a public holiday. Furthermore, this method makes the conclusions drawn from this study stronger and indicates that the differences observed are largely due to the external weather data and not which day of the week it is.

The study was conducted on a Jupyter notebook on the popular Machine Learning platform Kaggle. The main data manipulation Python libraries were Pandas and Numpy, which were used to manipulate and split the data to get the desired outcome and help in the analysis. Beautiful Soup was used for the weather data scraping, and the Holiday library was used to retrieve data on public holidays in the state of Selangor where Subang Jaya is located. The reason for specifying only public holidays in the state of Selangor is because not all states in Malaysia share the same public holidays.

4. Empirical finding

It has been proven that spring-summer warm temperatures and snow-free ground surfaces may induce significant increases in water consumption, both indoors and outdoors [42]. Additionally, this research depends on the theory that the hotter it gets outside, the harder an Air Conditioner (AC) system has to work to keep the indoor air cool [2]. Another hypothesis mentions that humidity and temperature affect the performance of air-conditioning systems as humidity cancels out the cooling effect making the indoor feel warmer than it actually is [43].

According to the theories mentioned, the external weather factors would affect the water consumption of the TES-AC system though a TES-AC differs from a conventional AC as TES-AC depends on water volume as a factor for charging load. Moreover, with relatively elevated humidity, the body's ability to lose heat through perspiration and evaporation would be reduced which can be factored in whilst considering the water consumption of TES-AC systems as it might have an effect [44]. This research does not try to refute claims that other external factors do not affect the water consumption in TES-AC according to the theories mentioned. However, it is trying to show that weather data provides one main set of external factors that do have an impact on the water consumption of a TES-AC system. This word considers the metrics of temperature, humidity, and atmospheric pressure for analyzing the effect on water consumption of the TES chiller plant.

5. Results

Each one of the different weather data types was tested separately but using the same procedure. As discussed earlier, the data gets sorted by the chosen weather metric in descending order and then the top 25% of the data and the bottom 25% of the data are split and kept separately. With regards to this research, the data in between these two ranges was ignored as we are more interested in the extreme weather values.

Starting with the most common weather metric, temperature, it was observed that in the top 25% of the data which is equivalent to the days with the highest temperatures, the water consumption was high a total of 42 days or 6.95% of the time. Table 1 shows the overall analysis. The percentage was calculated based on how many days manifested high water consumption over the total number of days in the top 25%, which in this case is 604 days. It was also calculated how many days out of the high-water consumption days were either weekends or public holidays. A total of 11 days out of 42 were weekends (26.19%) and just one day was a public holiday (2.38%). On the opposite side where the temperatures were at their lowest, we have again 604 days to compare with. A

Table 1
Analysis of temperature effect on water consumption of TES-AC.

	Temperature						
	High water consumption days	High water consumption days (%)	Weekends	Weekends (%)	Public Holidays	Public Holidays (%)	Ratio of high water consumption days to total number of high water consumption days
Top 25%	42	6.95	11	26.19	1	2.38	25.45
Bottom 25%	36	5.96	6	16.67	2	5.56	21.82

Table 2
Analysis of humidity effect on water consumption of TES-AC.

	Humidity						
	High water consumption days	High water consumption days (%)	Weekends	Weekends (%)	Public Holidays	Public Holidays (%)	Ratio of high water consumption days to total number of high water consumption days
Top 25%	35	5.79	6	17.14	2	5.71	21.21
Bottom 25%	47	7.78	13	27.66	3	6.38	28.48

Table 3
Analysis of atmospheric pressure effect on water consumption of TES-AC.

	Atmospheric Pressure						
	High water consumption days	High water consumption days (%)	Weekends	Weekends (%)	Public Holidays	Public Holidays (%)	Ratio of high water consumption days to total number of high water consumption days
Top 25%	47	7.78	12	25.53	1	2.13	28.48
Bottom 25%	44	7.28	11	25	1	2.27	26.67

total of 36 days had high water consumption (5.96%) of which 6 days were weekends (16.67%) and 2 days were public holidays (5.56%). It is to be noted that the highest temperature was around 31 °Celsius, and the lowest temperature was 21 °Celsius.

Humidity was considered for comparison next, and the data was sorted in an equivalent way as shown in Table 2. This metric is calculated as a percentage of how much humidity is in the air with 100% being the maximum value in the data and 0% being the minimum value. At the top 25% of the data where the humidity values were the highest a total of 35 days had high water consumption (5.79%) of which 6 were weekends (17.14%) and 2 were public holidays (5.71%). On the other hand, at the bottom 25% of the data where the humidity values were the lowest a total of 47 days had high water consumption (7.78%) of which 13 days were weekends (27.66%) and 3 days were public holidays (6.38%). The total number of days at the top 25% and the bottom 25% were the same as temperature, with 604 days each.

Finally, the atmospheric pressure was the last variable to be investigated, and the data was sorted accordingly as shown in Table 3. The maximum atmospheric pressure was 1014 mbar, and the minimum was 1008.8 mbar. At the top 25% of the data a total of 47 days had high water consumption (7.78%) of which 12 days were weekends (25.53%) and 1 day was a public holiday (2.13%). At the bottom 25% of the data a total of 44 days had high water consumption (7.28%) out of which 11 were weekends (25%) and 1 day was a public holiday (2.27%).

It is to be noted that out of the 2418 days in the dataset, only a total of 165 days had high consumption (6.82%) out of which 38 days were weekends (23.03%) and 6 days were public holidays (3.64%). Considering that high water consumption days do not occur frequently, it makes sense to calculate the percentage of high-water consumption days in relation to the total number of days (including non-extreme days) in which the water consumption was high, to get a clearer idea about the impact. This gives a better understanding of how much each metric affects the days with high water consumption. For the temperature metric, the top 25% of the data had 25.45% of the total number of days (including non-extreme days) with high water consumption, while the bottom 25% had 21.82% of the total number of days.

Similarly for humidity the top 25% had 21.21% of the total days and the bottom 25% had 28.48% of the total days. Finally, the atmospheric pressure had 28.48% of the total days in the top 25% and 26.67% in the bottom 25%. Fig. 3 shows in graphical form the water consumption comparison in relation to the weather metrics of temperature, humidity, and atmospheric pressure.

6. Discussion

The results displayed some predicted outcomes and some unexpected outcomes. There are limitations to this study that will be discussed at the end of this section. However, the analysis of each weather metric and how it impacts the water consumption is as follows.

6.1. Temperature

As one of the first weather metrics that typically comes to mind, temperature was expected to have an impact on water consumption. As shown above, at the top 25% of the data where the temperatures were the highest and most extreme, there was a total of 42 days observed with high water consumption which amounted to 6.95% of the days in the top 25%. However, given that high water consumption days do not occur very frequently, it is wiser to compare with the full totality of high consumption days. From this perspective, the 42 days represent 25.45% of all days with high water consumption. On the other hand, at the bottom 25% of the data, there were 36 days with high-water consumption, which is equivalent to 21.82% of the total data. That means that the higher temperatures resulted in a 3.63% increase in water consumption days. The percentage might seem small but when considering the fact that high water consumption days are not frequent, the difference is not insignificant.

Out of the high-water consumption days in the higher temperatures, 11 days or 26.19% of those days were weekends, which shows that the

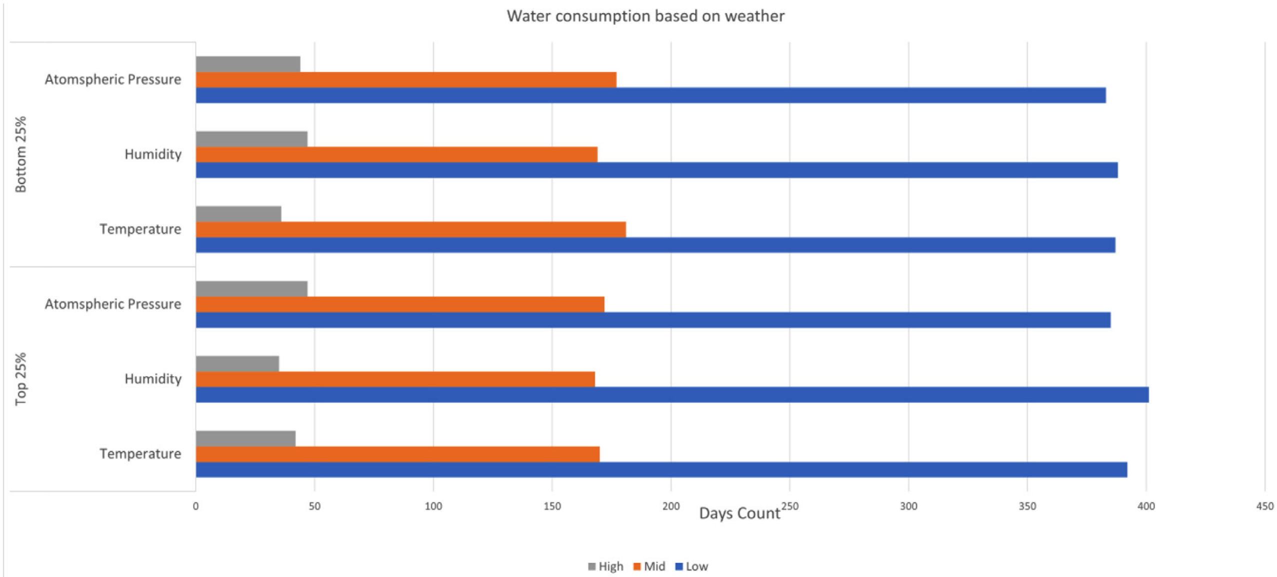

Fig. 3. Graphical display of the relation of water consumption by TES-AC chiller with weather metrics.

difference is more reliant on the temperature and not on whether the day was a weekend or not. A similar observation could be made about the high-water consumption days in the lower temperatures, where 6 days or 16.67% were weekends. The public holidays are insignificant and do not seem to be having an effect.

6.2. Humidity

Out of the three metrics analyzed, humidity had the biggest impact on water consumption. However, unlike initially predicted, the water consumption seemed to increase as the humidity decreased. The exact reason humidity could have this sort of effect requires more research to understand the underlying reasons. As noticed in the table, out of the top 25% values with the highest humidity 35 days or 21.21% of the entire high water consumption days were present. Surprisingly, in the bottom 25% of the data 47 days or 28.48% were high water consumption days. That means that in the days with the lower humidity values there was 7.27% more water consumption. This suggests that humidity has roughly twice as much of an effect on TES-AC water consumption compared to the weather temperature.

Keeping in line with how weekends and public holidays factor into the results, it was seen that out of the 35 days of high-water consumption in the top 25% of the data, 6 were weekends (25.53%) and for the bottom 25% there were 13 days falling on weekends (27.66%). Similar to the temperature results, public holidays were much scarcer and did not appear to have had a noticeable effect.

6.3. Atmospheric pressure

The weakest result in the three metrics analyzed pertains to atmospheric pressure. The difference between high water consumption days between the top 25% and the bottom 25% was only 3 days amounting to an increase of 1.82% in the set of days with the higher atmospheric pressure. However, this does not necessarily imply that this is a metric that should be ignored when trying to factor in features for a Machine Learning solution.

In order to figure out if atmospheric pressure is relevant, it is important to look at the maximum and minimum values in the dataset. The maximum atmospheric pressure observed was 1014 mbar while the minimum was 1008.8 mbar. The difference between both extremes is relatively small and therefore additional data needs to be collected, covering a wider range, before any conclusions can be reached about the usefulness of this feature.

6.4. Effect of weekends on water consumption

By looking at the tables and results, one might put forth the idea that the real reason there is any difference in water consumption is the presence of more weekends in the data that has more water consumption. For example, it can be observed across all three metrics that when there are more days with high water consumption, there is always a larger number of weekends. While this research is not denying that weekends could be a factor contributing to the amount of water consumed, it also points to a simpler explanation.

A week consists of 7 days and the probability of any day being a weekend is 0.29. Therefore, when the weather affects the water consumption and leads to more days with high water consumption, it is only natural that there will be more high-consumption days as weekends, since for every new day with high water consumption because of the weather, there is a 0.29 chance of that day being a weekend. This is consistent with the fact that weather changes, conditioned on what day of the week it is, tend to be relatively small. The weather is unpredictable and can change whether it is in the middle of the week or on the weekend. Therefore, as more days are having high water consumption, more of those days will be weekends. The number of public holidays on the other hand tends to be small, and yet it will be expected to be larger if the high-water consumption days are more frequent, but this increase is likely to be practically negligible.

7. Conclusions

Based on the results and the discussion, these results have shown evidence that external weather data has an impact on the water consumption of TES-AC. However, some of the weather metrics have more impact than others. According to the results, humidity had the biggest impact on the water consumption followed by temperature and finally atmospheric pressure. Including weather data as features in a machine learning solution to try and predict the chiller's next day's water charging load seems like a practical idea that might lead to satisfactory results.

The research does not by any means reject any other external factors as having an impact on water consumption, however, weather does have a significant effect. Including weekends and public holiday data could still be beneficial, mainly because weekends seem to increase with water consumption and that could be helpful for deep learning models. Deep learning models have the ability to find patterns in complex data with complex relationships. By including weather data alongside weekends and public holidays, a solid foundation for a deep learning model to predict the water charge for the next day might be achieved.

It also must be noted that this research was conducted on a chiller in Malaysia, where the difference in temperatures between the maximum and minimum over 2418 days was only 10 °Celsius. Based on the findings, this research suggests that data in cities or countries that have more significant differences in weather data could yield more obvious results and show the impact of weather data more clearly. For example, many cities in Europe would have average temperatures of 25 °Celsius in the summer, and temperatures as low as −2 °Celsius (or lower) in the winter. With more obvious temperature changes, water consumption values might vary across a broader range and might be easier to analyze if research is conducted in such areas.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] H.Z. Sharif, M. S, S. Murugan, S. Rajkumar, Research and analysis of air-conditioning system with cooling air and supplying warm-water, Technol. Rep. Kansai Univ. 62 (261) (2020) 267.

[2] K. Lundgren-Kownacki, E.D. Hornyanszky, T.A. Chu, J.A. Olsson, P. Becker, Challenges of using air conditioning in an increasingly hot climate, Int. J. Biometeorol. 62 (2018) 401–412.

[3] Ashish, "How Does an Air conditioner (AC) work?," 2022. [Online]. Available: https://www.scienceabc.com/innovation/air-conditioner-ac-work.html. [Accessed 25 08 2022].

[4] B. Rauniyar, H.S. Sodhi, Research on the Air Conditioning System, Suraj Punj J. Multidiscipl. Res. 8 (12) (2018) 179.

[5] N.A. Awang, H.M. Kamar, N. Kamsah, Energy saving potential of an air-conditioner-Ice thermal storage (AC-ITS) system, J. Adv. Res. Fluid Mech. Therm. Sci. 31 (1–10) (2017) 1–2.

[6] B. Si, "How does thermal energy storage (TES) system work?," 2015. [Online]. Available: https://www.linkedin.com/pulse/how-does-thermal-energy-storage-tes-system-work-bertin-si/. [Accessed 15 08 2022].

[7] G. Frankenfield, "How thermal energy storage works," DN Tanks, [Online]. Available: https://www.dntanks.com/what-we-do/thermal-energy-storage/how-tes-works/. [Accessed 10 08 2022].

[8] Y. Sun, S. Wang, F. Xiao, D. Gao, Peak load shifting control using different cold thermal energy storage facilities in commercial buildings: a review, Energy Convers. Manage. 71 (2013) 101–114.

[9] I. Sarbu, C. Sebarchievici, A comprehensive review of thermal energy storage, Sustainability 10 (1) (2018) 191.

[10] M.R. Sanzana, T. Maul, J.Y. Wong, M.O.M. Abdulrazic, C.-.C. Yip, Application of deep learning in facility management and maintenance for heating, ventilation, and air conditioning, Autom. Constr. 141 (2022).

[11] S. Salaudeen, Investigation on the performance and environmental impact of a latent heat thermal energy storage system, J. King Saud Univ. 31 (4) (2018).

[12] A. A.Al-Abidi, S.B. Mat, K. Sopian, M.Y. Sulaiman, C.H. Lim, A. Th, Review of thermal energy storage for air conditioning systems, Renew. Sustain. Energy Rev. 16 (8) (2012) 5802–5819.

[13] H.G. Lorsch, K.W. Kauffman, J.C. Denton, Thermal energy storage for solar heating and off-peak air conditioning, Energy Convers. 15 (1–2) (1975) 1–8.

[14] B. Nie, A. Palacios, B. Zou, J. Liu, T. Zhang, Y. Li, Review on phase change materials for cold thermal energy storage applications, Renew. Sustain. Energy Rev. 134 (2020).

[15] P.M. Congedo, C. Baglivo, L. Carrieri, Application of an unconventional thermal and mechanical energy storage coupled with the air conditioning and domestic hot water systems of a residential building, Energy Build. 224 (1) (2020).

[16] A. Mehari, Z.Y. Xu, R.Z. Wang, Thermal energy storage using absorption cycle and system: a comprehensive review, Energy Convers. Manage. 206 (2020).

[17] I. Dincer, On thermal energy storage systems and applications in buildings, Energy Build. 34 (4) (2002) 377–388.

[18] B.B.P. Lindsay, J.S. Andrepont, Evolution of thermal energy storage for cooling applications, ASHRAE J. 61 (10) (2019) 42-44,46,48,50,52,54,56-59.

[19] A. Sciacovelli, Y. Li, H. Chen, Y. Wu, J. Wang, S. Garvey, Y. Ding, Dynamic simulation of Adiabatic Compressed Air Energy Storage (A-CAES) plant with integrated thermal storage – Link between components performance and plant performance, Appl. Energy 185 (1) (2017) 16–28.

[20] Y. Zhang, R. Wang, Sorption thermal energy storage: concept, process, applications and perspectives, Energy Storage Mater. 27 (2020) 352–369.

[21] R. Stropnik, R. Koželj, E. Zavrl, U. Stritih, Improved thermal energy storage for nearly zero energy buildings with PCM integration, Sol. Energy 190 (2019) 420–426.

[22] E. Guelpa, V. Verda, Thermal energy storage in district heating and cooling systems: a review, Appl. Energy 252 (2019).

[23] R. Tang, S. Wang, Model predictive control for thermal energy storage and thermal comfort optimization of building demand response in smart grids, Appl. Energy 242 (2019) 873–882.

[24] P. Kohlhepp, H. Harb, H. Wolisz, S. Waczowicz, D. Müller, V. Hagenmeyer, Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: a review of international field studies, Renew. Sustain. Energy Rev. 101 (2019) 527–547.

[25] P.M. Congedo, C. Baglivo, L. Carrieri, Hypothesis of thermal and mechanical energy storage with unconventional methods, Energy Convers. Manage. 218 (2020).

[26] S. Huang, A. Khajepour, A new adiabatic compressed air energy storage system based on a novel compression strategy, Energy 242 (2022).

[27] A. Cruse, Doing Something About the Weather: a Case for Discomfort, Constructing Building Enclosures, Taylor & Francis Group, 2020.

[28] H. Nguyen, Y. Makino, Y. Lim, Y. Tan, Short-term prediction of energy consumption of air conditioners based on weather forecast, 2017 4th NAFOSTED Conference on Information and Computer Science, 2017.

[29] A. Allouhi, Y. El Fouih, T. Kousksou, A. Jamil, Y. Zeraouli, Y. Mourad, Energy consumption and efficiency in buildings: current status and future trends, J. Clean. Prod. 109 (2015) 118–130.

[30] N. Ranjbar, S.A.Z.S. Salim, N.M. Yusoff, F. Yakub, A. Hagishima, Short-term measurements of household electricity demand during hot weather in Kuala Lumpur, Int. J. Electr. Comput. Eng. 7 (3) (2017) 1436–1443.

[31] B. Anderson, X. Lin, A. Newing, A.S. Bahaj, P. James, Electricity consumption and household characteristics: implications for census-taking in a smart metered future, Comput. Environ. Urban Syst. (2016).

[32] C.-.L. Hor, S.J. Watson, S. Majithia, Analyzing the impact of weather variables on monthly electricity demand, IEEE Trans. Power Syst. 20 (4) (2005) 2078–2085.

[33] E.A. Adjei, S. Omer, S. Amos-Abanyie, Impact of weather dependent variables on cooling and dehumidification loads of air-conditioned office in warm-humid, J. Build. Perform. 12 (1) (2021).

[34] E.A. Adjei, S. Riffat, S. Omer, 285: Impact of weather dependent variables on minimizing dehumidifying load on air conditioned office, 14th International Conference on Sustainable Energy Technologies, 2015.

[35] M. Shehadi, Review of humidity control technologies in buildings, J. Build. Eng. 19 (2018).

[36] D. Sánchez-García, C. Rubio-Bellido, M. Tristancho, M. Marrero, A comparative study on energy demand through the adaptive thermal comfort approach considering climate change in office buildings of Spain, Build. Simul. 13 (2020) 51–63.

[37] R.C. Sarker, S. Gato-Trinidad, M. Imteaz, Temperature and Rainfall Thresholds corresponding to water consumption in Greater Melbourne, Australia, in: Proceedings of the 20th International Congress on Modelling and Simulation, Adelaide, Australia, 2013.

[38] S.L. Zubaidi, S.K. Gharghan, J. Dooley, R.M. Alkhaddar, M. Abdellatif, Short-term urban water demand prediction considering weather factors, Water Resour. Manage. 32 (2018) 4527–4542.

[39] S.L. Zubaidi, K. Hashim, S. Ethaib, N.S.S. Al-Bdairi, H. Al-Bugharbee, S.K. Gharghan, A novel methodology to predict monthly municipal water demand based on weather variables scenario, J. King Saud Univ. - Eng. Sci. 34 (3) (2022) 163–169.

[40] C.R. Upshaw, J.D. Rhodes, M.E. Webber, Modeling peak load reduction and energy consumption enabled by an integrated thermal energy and water storage system for residential air conditioning systems in Austin, Texas, Energy Build. 97 (2015) 21–32.

[41] K. Shan, C. Fan, J. Wang, Model predictive control for thermal energy storage assisted large central cooling systems, Energy 179 (2019) 916–927.

[42] A. Akuoko-Asibey, L.C. Nkemdirim, D.L. Draper, The impacts of climatic variables on seasonal water consumption in Calgary, Alberta, Can. Water Resour. J. 18 (2) (1993) 107–116.

[43] T.J. Erinle, A.O. Akinola, O.M. Adesusi, I.A. Agbamu, Experimental evaluation of air-conditioning system, Assump. University-eJ. Interdiscipl. Res. (AU-eJIR) 6 (1) (2021) 1–17.

[44] O. Kaynakli, M. Mutlu, I. Atmaca, M. Kilic, Investigation of humidity effects on the thermal comfort and heat balance of the body, in: Progress in Exergy, Energy, and The Environment, SpringerLink, 2014, pp. 421–434.