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Enhancing the sustainability of Chiller systems against annual temperature rise: A review

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Abstract

Global warming which is accompanied by annual temperature rise represents a significant challenge reaching various majors, Air conditioning systems were no exception but two relatively opposite demands are often assessed which are; improving the indoor conditions and reducing the energy consumption. The commercial and practical data for the systems shows a dramatic decrease in the coefficient of performance against ambient temperature rise, which in turn decreases the efficiency of the cooling plant year after year resulting in an insufficient cooling at some point for the existing systems. Also, the sustainability of these systems decreases due to the side effects of the climate change which results in more extreme load periods, intense solar heat flux and higher temperature differences, So, This review presents thermal load increment according to past, present and future climate data for active cooling systems, listing their energy consumption for different climate zones, discusses the major countermeasures for climate change adaptation, and introducing the currently developed approaches for enhancing COP of air conditioning systems for various components. From this review it can be concluded that the main drawbacks in the previous enhancements are either the over complexity of the system, decreasing the thermal efficiency against increasing the COP when implementing additional thermal components of renewable energies, or the over-space needed for the systems which is not suitable with the system size and finally the common issue is that the enhancement is limited to finite system size range and specific environmental conditions.

Keywords: *Air conditioning; Climate models; Thermal comfort; Sustainability; Nanoparticles; Renewable energy.*

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1. Introduction

Global warming represents one of the most significant challenges we already facing resulting into a direct impact on the climate change rate, Numerous researchers conducted a study on the its effect on both cooling and heating loads (Abolhassani, 2023), these studies shows a rapid increase in the energy demands to achieve the required set points, the effect of these changes and increment that varies from one climate zone to another.

The assessment of thermal load increment on the active cooling systems for buildings are approached using the predicted climatic data in the future years. These data include humidity, dry bulb ambient temperature, wet bulb, solar heat flux and extreme load periods, increasing the cooling demand means increasing of energy consumption and using equipment to cover larger load, or deterioration of performance of the existing equipment through time as the demand became more than that they were assigned to accompanied by decrease in reliability. The effect is also extended to net-zero energy buildings developed recently which produce energy as they consume, and they may deviate from the net zero target in the future due to change of heating of cooling demand (Abolhassani, 2023) (Rey-Hernandez, 2018). Climate change has several environmental impacts, the one we are concerned with most is the rise of ambient temperature throughout previous years and in the future decades, as it causes increasing in the thermal load requirement by a considerable amount which means extra reliability on air conditioning systems, increasing peak load duration, more power consumption and most of all, causing an undersized state for some existing cooling districts (Yau, 2011), Weather database are generated using either a statistical approach or a simulation one (Yau, 2011), the first is utilized to record the data over the past years extracting the changes occurs and hence generate equations that fits the curves, and the latter is used by software using numerical methods with help of the generated equations in order to simulate the climate over next decades and predict values of air properties. This study presents the analysis of ambient temperature growth versus the operational performance of AC systems, methods for tracking the performance, previous research tracks for the active cooling systems, approaches towards improvements including renewable energy system integrations, Finally the main limitations of the previous tracks and highlighting the main recommendations towards implementing a sustainable efficient air conditioning system.

2. Analysis of ambient temperature growth versus the operational performance of AC systems

Global warming represents one of the most significant challenges we already facing resulting into a direct impact on the climate change rate, Numerous researchers conducted a study on the its effect on both cooling and heating loads (Abolhassani, 2023), these studies shows a rapid increase in the energy demands to achieve the required set points, the effect of these changes and increment that varies from one climate zone to another, The assessment of thermal load increment on the active cooling systems for buildings are considered as potential spots for the future consequences (Mostafa, 2011).

2.1. Mean temperature difference per decade

The rate of evolution of temperature per decade for regions have been investigated by researchers using variety of climate models, scenarios and algorithms (Abolhassani, 2023), Mean annual temperature rise for a variety of climate zones for the past few decades are included in (ASHRAE CLIMATE, 2009). While for the near and far future periods are shown in Table 1 for some climate zones.

Table 1. Mean Annual temperature rise for some locations representing variety of climate zones

Place	Climate Region	Period	Mean T/decade	Climate Model
Hongkong (China) (Chan, 2011)	1A	2046-2065	+ 0.9	SRA1B
Naha (Japan) (Shibuya, 2016)	2A	1990-2040	+ 0.22	RCM 20
Phoenix (USA) (Wang, 2017)	2B	2020-2050	+ 0.8	HadCM3
Curitiba (Brazil) (Invidiata, 2016)	3A	2020-2080	+ 0.77	GCM
Valencia (Spain) (Cellura, 2018)	3B	2018-2090	+ 0.6	RCP 8.5
Los Angles (USA) (Invidiata, 2016)	3C	2020-2050	+ 0.43	HadCM3

Egypt, which is located in the north Africa region and middle east, was found to experience a rise in the daily maximal and minimal temperatures by 1.3 ± 0.1 ºC and 1.3 ± 0.3 ºC respectively, relative to 1960 (Mostafa, 2011). Hourly mean dry bulb temperatures (T_{db}) difference relative to 2009 as a baseline were plotted for the years 2020, 2050 and 2080 for Cairo, Ismailia and Asyut in Egypt, illustrated in Figure 1 as follows.

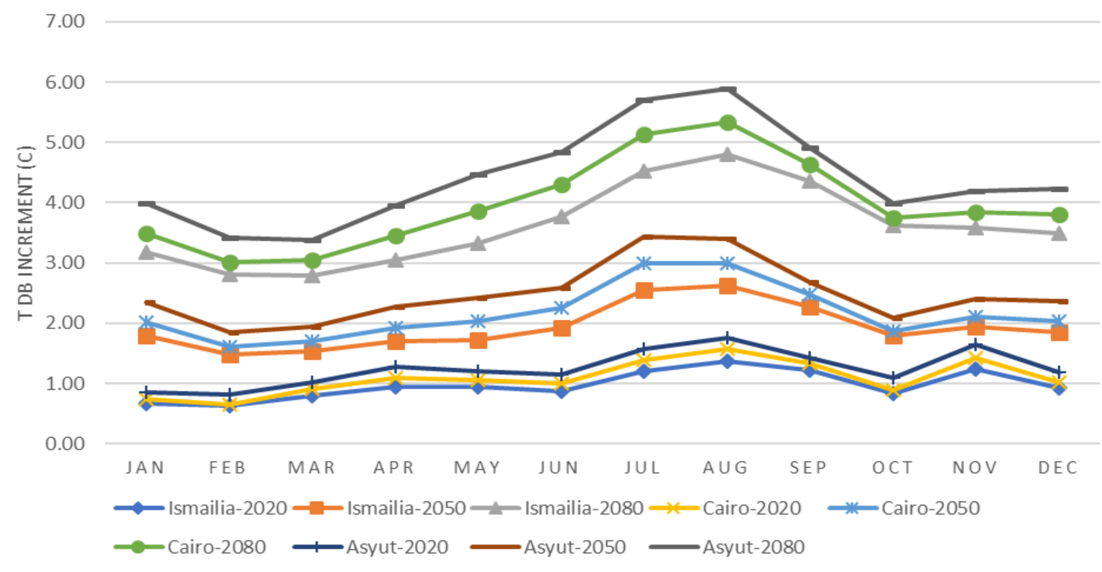

Figure 1: Increment of Daily average T_{db} in Egypt in 2020, 2050 and 2080
Source: Researcher

The meteorological 2009 data was obtained from (ASHRAE climate 2009), and HadCM3 was used a climate change model for investigation by the means of the program package CCWorldWeatherGen. The plot shows that at peak summer time in August, T_{db} increased by 1.36, 1.57 and 1.75 ℃ for Ismailia, Cairo and Asyut respectively by 2020 which are the largest annually, also by 2050, the same regions will experience 2.62, 2.99 and 3.4 ℃ respectively, these rates will directly affect the thermal loads on current air conditioning systems in various ways which will be highlighted in the next sections.

2.2. **Increment of cooling loads**

Several methods are presented in ASHRAE Handbook of fundamentals in order to calculate the peak heat gain of a building, these methods include Radiant time series method (RTSM), Heat balance method (HBM) and Cooling load temperature difference methods (CLTD) (ASHRAE Handbook of Fundamentals, 2022).

According to past, present and future climatic data, Rate of change of thermal loads for various climatic zones worldwide were investigated, showing relatively high values such as Belen Brazil in A2 zone in which the cooling load will increase by more than 60% percent by the arrival of year 2050 (Abolhassani, 2023) (Chan, 2011), and for Phoenix USA in B2 climate zone by nearly 20% increment for residential cooling loads (Shen, 2017). Air conditioning of spaces accounts for high percentage of energy consumption, Gjoka et al. stated that about 40% percent of the residential energy is consumed in space conditioning in Australia (Gjoka, 2023), meanwhile Chu et. al pointed out that the same percentage is consumed for China data centers by 2019 (Chu, 2023), on the other hand, in harsh hot climates, 60% of the energy consumption is accounted for the cooling systems (Alajimi, 2020), For air cooled air conditioning, refrigerant compressor occupies about 68% of energy consumption by the unit, while this percentage becomes 54% for water cooled ones and 18% for water pump (Gjoka, 2023).

Cooling coil has to overcome the gain from four main energy sources (Vallejo-Coral, 2019), transmission & solar loads, Ventilation, Occupants and Miscellaneous loads, the breakdown percentages varies according to numerous factors such as insulation type, number of air changes, building application and orientation, but according to market data, the nominal capacity of HVAC equipment decrease significantly with the increment of the ambient temperature, Figure 2 shows the relation between outdoor temperature and chiller capacity at 5, 6 and 7 ̊C LWT (leaving water temperatures) for 30RA Carrier air cooled chiller according to manufacturer manual.

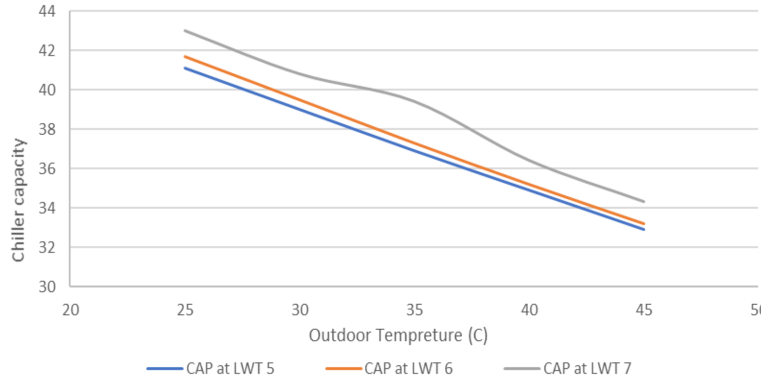

Figure 2: Performance chart for 30RA Carrier air to water chiller against ambient temperature rise
Source: 30RA Carrier air cooled chiller manufacturer manual

2.3. **Measures for preservation of Active cooling equipment**

Active cooling systems involves many types and the commonly used ones are district cooling DC water cooled chiller based which proved to be less in energy consumption compared to roof top units RTU and variable refrigerant volume units VRV (Vallejo-Coral, 2019), Chilled water system are categorized into vapor compression and vapor absorption chillers then they are further categorized based on condenser system into air-cooled, water cooled and evaporatively cooled (Chawathe, 2020), In absorption chillers, the waste energy is recovery into cooling energy so that they are good investment in plants with high cooling capacities and considerable wasted energy (Sahin, 2021).

A number of strategies were implemented by researchers to make the cooling process more efficient, this also extends for the preservation of the long lead air conditioning equipment to give their desired output (Giovannini, 2023), these measures are summarized as follows:

1. Increasing thermal resistance for construction items.
2. Changing the thermal capacity for cooling means.
3. Enhancing short wave reflectivity and green roofs.
4. More dependency on natural ventilation.
5. Controlling the condenser pressure according to operation conditions.

3. Methods for performance traction

Recently, Chiller system applications development have become attractive approach to tackle the air conditioning related issues for buildings (Sathesh, 2023), these systems have numerous power driven parts, including pumps, fans, compressors and controllers which present according to their purposed functions in the cycle components such as cooling tower, chiller, air handling units and pipelines, the ratio between the achieved cooling effect to the total electric power consumed to achieve this effect is called Coefficient of Performance COP. It is also noted that typical COP values may vary from one researcher to another because of the way of total power estimation, some take it as the sum of compressors power as they occupy the largest percentage (Chawathe, 2020), while others take it as the sum of power consumed by compressors, pumps and fans (Yu, 2019). Tracking and analyzing of these performance parameters can take place by three methods (Pan, 2021), either by fitting the existing data, the second one is by developing a thermodynamic model (Tian, 2021), or the third by using a mathematical model developed by artificial intelligence (Pieper, 2021) , In which, by choosing a model followed by training through suitable parameters, an error within ±5% from experimental data is observed which makes it a promising approach (Tian, 2021).

Values of COP varies from one cooling system to another depending on their working mechanism and behavior towards inside and outside conditions, reported values for each type are shown in Table 2, It can be deduced that water- or air-cooled chillers are advantageous in terms of performance, also there are wide ranges of values for them depending on the implemented compressor type and cooling capacity (Tian, 2021), while the lowest values are accounted for absorption chillers (Chawathe, 2020). It is worth to mention that; the working fluid type affects COP for absorption chillers though the two most used ones are Li-Br water and Ammonia solutions (Sahin, 2021).

Table 2. Typical ranges of COP for different cooling systems

Cooling System	**Roof Top** (Alajimi, 2020)	**VRF (**Alajimi, 2020)	**Air cooled chiller (**Yu, 2014)	**Water cooled chiller (**Yu, 2014)
COP	2.5	3.3	2.4 - 3.06	3.8 – 6.39

In addition to the system and working fluid types, COP is also affected by ambient temperature changes, Lin et al. reviewed this effect on a number of systems (Lin, 2019), they reported that for ambient increase from 45° to 46°C, COP for window type system is reduced from 2.75 to 2.69, while for ambient increase from 35° to 49°C, COP of air cooled chiller reduced by 17.5% and for evaporative cooling condenser at temperature increase from 23.8° to 44.5°C, it decreases from 2.167 to 1.669

4. Scopes of previous research tracks

Assessments made by researchers to optimize and enhance these systems followed various approaches, Some focused on the outdoor condensing unit through either thermophysical analysis of refrigerant for design optimization or the coil itself , another group investigated the dehumidification process to seek improvement of latent heat transfer, some worked on improving thermal characteristics and adaptation of cooling coils, while others optimized the performance of units from working fluids' point of view, number of their findings are listed below in Table 3.

Table 3. Overview on previous research tracks and their main findings

Investigation Field	Researcher	Objective	Approach	Driving Parameter	Findings
Condenser Unit	(Charun, 2013)	Thermophysical analysis for 2-phase state of refrigerant in coil	Experimental	Geometric indexes of coil geometry and 2-phase length	Consistence of ±12% and can be used for coil design
	(Lee, 2012)	Improving performance by novel condenser coil configurations	CFD	Velocity & overall heat transfer rate	Performance is improved by 5.3% for variant coil designs
	(Lin, 2019)	Studying effect of coil fouling at different ambient temperatures on operation performance	Experimental	Ambient temp. & coil fouling versus work done & COP	Ambient temperature change affects significantly COP of the unit
Dehumidifier	(Nada, 2020)	Enhancing thermal properties of dehumidifying coils by strip fins	Experimental	Heat transfer coefficient and dehumidification rate	Adding fins and increasing flow rate caused dehumidification to increase
	(Liang, 2009)	Examining dehumid. effects on superheated region of refrigerant in coil	Experimental	Mass flow rates of both air and condensate	Assuming dry air in SPR can lead to error of 3 to 7% in water vapor amount
	(Delfani, 2010)	Dehumid. Investigation using air to air heat exchanger	Experimental	Latent and sensible heat values	Applicability of the heat exchanger in high humid. content areas
	(Yang, 2020)	Novel dehumid. control using two sectioned evaporator coils	Modelling & Experimental	Controlling Sensible heat ratio SHR	Dehumid. control over a wide range using less coils surface areas
Cooling Coil	(Weng, 2020)		Modelling & Experimental	Cooling capacity and SHR	Using variations od air mass flow rate, different combinations of cooling capacity and SHR are obtained
	(Sekhar, 2018)	Improving thermal comfort using adaptable cooling coil	Computational evaluation	Cooling capacity and SHR	Adaptable coil shows better performance into reducing overcooling effect and relative humidity
	(Yu, 2017)		Simulation & Experimental		Noticeable performance for heavily oversized coils but not promising results for commercial large-scale use
	(Ning, 2016)	Developing control for HVAC with double circuit cooling coil	Modelling & Experimental	Adjusting chilled water flow rate & temperature independently	Energy saving potential by 60% under high sensible low latent loads
Refrigerant & working Fluids	(Saleh, 2016)	Working fluid thermal analysis to determine best COP candidates	Computational evaluation	Cooling capacity, temperature differences, COP and mass flow rate	For examined fluids, R600 had highest COP & was superior candidate for low-grade thermal energy retrieve
	(Zhou, 2022)	Comparison of binary & ternary water solutions with lithium & ammonia at different proportions	Experimental	Cooling capacity and logarithmic mean temperature difference	Working fluid with higher water mass fraction has better mass and heat transfer performance and COP changes with water mass fraction

5. Approaches towards the improvement of active cooling components and thermal comfort

Four main tracks were implemented to achieve this mission, the first one is by energy management and optimization of the basic cycle against the varying operating and demand conditions, which were adopted by various researchers in order to increase the systems' COP of the conventional systems, Chen et al. investigated the optimum energy and cost saving chiller system by developing a weather-based one and they found that the COP increased by 0.5 units and they encouraged applying this strategy on the inner demand side in addition to the weather side in future (Chen, 2022), Zulkafli et al. worked on the same scope by establishing a linear programing model for the chiller- AHU system to accommodate the dynamic change of cooling load with ambient temperature change at a fixed set point, The model was established used the local temperature data, empirical relations and correlation analysis to predict the power consumption, this showed a greater coefficient of performance by about 7% to 10% and a reduction in the power consumption by 3% (Zulkafi, 2023), while a predictive model control for AHU which gives the optimum inputs achieved a cost reduction by 6.2% (Wang, 2022), Integration of a complementary system to the main one represents the second approach towards enhancing the performance (Nguyen, 2023), some worked on this approach although the contribution in this track is limited by avoiding complexity and extra energy demand, Heidarinejad et al. studied the effect of integrating a spray-nozzle system at various orientations to a condenser of an air-cooled chiller shown in Figure 3 using Eulerian-Lagrangian approach simulated by ANSYS Fluent 16.0, their results suggested that for 90° orientation yields maximum COP for increase of 10.6 (Heidarinejad, 2019).

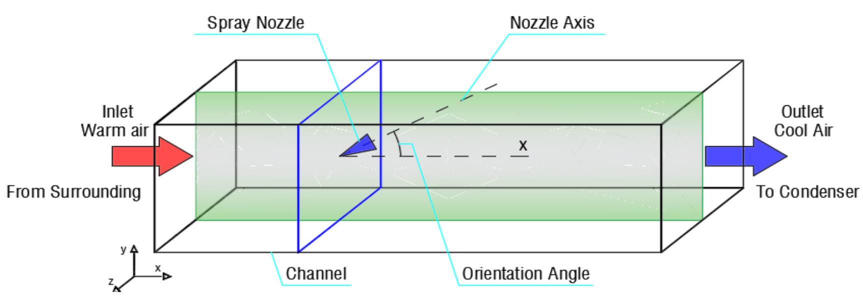

Figure 3: Illustration for spray nozzle system used by (Heidarinejad, 2019)
Source: Researcher

The third track was by the reconfiguration of basic cycle components in a way that serves a better energy management (Wang, 2022), They identified maximum potential to improve screw chiller systems' performance by applying series loops of water for multiple screw chiller systems (Wang, 2022), Figure 4 shows basic parallel chiller connections for (n) chillers which was used by Yu et al (Yu, 2019) versus series connection used by C. Wang et al. (Wang, 2022) who recognized COP to reach 7.22 with an increase by 26.02% in COP relative to single screw chiller unit by energy and exergy analysis, they also deduced that the improvement of COP decrease with the increase of the added chillers so it is not suggested for energy saving to design multi chiller systems with more than four chillers (Wang, 2022).

The working fluids were no exception for the research investigation fields, and this is what the fourth track about, which can be categorized into two main sectors; the refrigerant or the water-based cycle, Velasco et al. used R513A as against R134a but it resulted into a lower efficiency due to the high vapor density of R513A (Velasco, 2021), Tube et al. used R22 and R407C in capillary tubes as expansion devices and the study aimed to suggest the optimum dimensions giving highest COP (Tube, 2023), while a novel comprehensive approach was implemented by Akbari et al. to select the most appropriate working fluid for vapor compression systems and found that R600a needs the lowest conductance while R512a consumes lowest compressor work and it is better than R22 economically and environmentally (Akbari, 2018), Papadopulos et al. made an assessment for absorption systems using 75 different mixtures (Papadopulos, 2020),The goal was to identify the suitable candidates from economic, environmental and safety perspectives. S. Kumar et. al. evaluated the performance of vapor compression refrigeration system using aluminum oxide nanoparticles added to R600a refrigerant resulting into COP improvement by (3.68% – 11.05%) (2021), Addition of nanoparticles to water base fluid water also had its portion from the studies in refrigeration field, Gürbüz et. al. made a thermoeconomic analysis on diffusion absorption refrigeration by implementing nanoparticles like TiO_2 and hybrid ones like $ZnOAl_2O_3$ and $MgOAl_2O_3$ which gave the highest cooling capacity at 1 wt.% (Gürbüz, 2022).

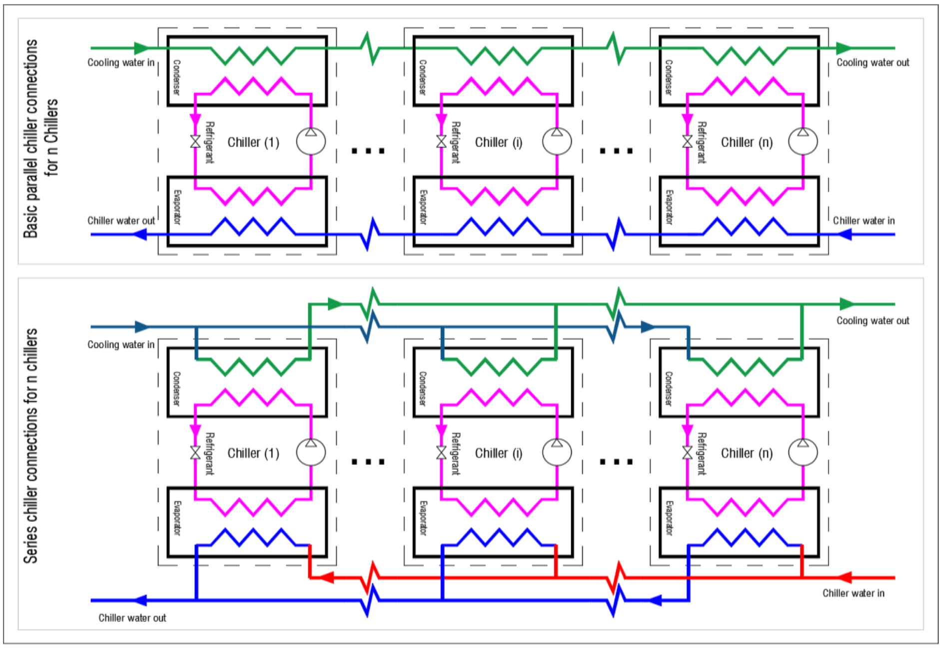

Figure 4: Illustration for Basic parallel connection used by (Yu, 2019) versus series chiller connection used by (Wang, 2022) Source: Researcher

6. Implementation of renewable energy to chilled water air conditioning systems

Integration of renewable energy sources with district cooling plants used for air conditioning had also its share of studies through the last decade and still ongoing (Rezaie, 2012), The main technologies which can be integrated with cooling applications are solar thermal energy, photovoltaic energy, biomass energy and geothermal energy (Inayat, 2019), Utilization of renewable energy in this field has either one of two ways, the first one is to use the energy source directly for heating or cooling through heat exchangers (Kalkan, 2012), and the other is to use the renewable energy source for generation of electricity which in turn used for driving the compressors and fans used in conventional cooling system, a brief on contributions regarding integration of renewable energy applications with cooling systems is shown in Table 4.

Table 4. contributions regarding integration of renewable energy applications with cooling systems.

Renewable Energy	Researcher	Investigation Field	Geographical Place	Main Findings
Biomass and Geothermal Energies	(Moretti, 2013)	Used in cooling and heating solutions in 2 existing buildings	Umbria-Italy	reduction of electricity consumption but the long-term stability was not investigated
Solar Energy	(Mammoli, 2010)	Utilization in cooling applications	New Mexico	Achieved 18% supply for the total cooling requirement
Solar Energy with battery storage	(Wang, 2015)	Battery storage vs cold storage vs no storage for chillers	Brisbane, Shanghai and Madrid	The sensitivity of the primary energy savings ratio (PESR) of cold storage is lower than that of the battery's and more future investigation is needed for the enhancement of heat transfer to accelerate the phase change process
Thermal driven renewable energies	(Elnagar, 2023)	Flexibility, integration, performance, typology, technology readiness for 20 systems	-	Thermal driven systems are still steps behind the electrical ones due to lack of Technology maturity, but thermal energy driven systems have more flexibility to be driven by different energy sources
Single & double effect Solar Systems	(Ali, 2008)-(Nkwetta, 2016)	Implementation is lithium bromide absorption chiller	Germany	COP ranged from 0.37 to 0.81 and the required collector area was 4.23 m^2/kW_{cold} (Ali, 2008)

Renewable Energy	Researcher	Investigation Field	Geographical Place	Main Findings
Single & double effect Solar Systems	Ghaith et. al (2014)	Implementation is lithium bromide absorption chiller	UAE	156 Kwh was saved per year and this can achieve a payback in a period of 4 years
Solar Collectors	Yin et. al (2012)	Utilization for 50 kw capacity cooling system	Shanghai	The system used 96 m2 solar collectors and achieved cooling increase by 23.5%, Yet these systems are not widely used due to the complexity and large space usage for the small capacities (Jaruwongwittaya, 2010)
Solar flat plates with evacuated tubes	Angrisani et. al (2016)	Utilization in cooling applications	-	a good contribution on CO2 emission basis that was reduced by 23%, but on economical side it was not competitive yet against natural gas and electricity

It is worth to mention that life cycle assessments for solar cooling plants were important to be made, Buonomo et. al used Simapro v.9 to analyze a 250 m^2 solar thermal field for a solar cooling plant through a life time of 20 years (Buonomo, 2022), but the study focused on the impact of solar fraction on emissions not economic side.
Cogeneration plants using solid wastes for application of cooling was also an approach for research, Udomsri et. al investigated the potentials surrounding this type of cooling plants and showed a fuel reduction of 1 MWFuel / MWCooling on small units' scale and some attractive ecofriendly features (Udomsri, 2011), and these systems still need some improvements to be more feasible, sustainable and economic wise, through exploring the performance of large number of combined systems in number of places in the world, Al Nini et. al showed that they need to improve the energy storage methods, implementing more smart grid technologies and exploring synergies between these systems to overcome the current associated problems in-between (Al Nini, 2023).

7. Limitations and drawbacks

From the previous review some drawback always faces the researchers in this field, which can be listed as follows; first, the overcomplexity of the modifications which decreases the reliability and sustainability of these systems, Secondly, the resulting improvement rates doesn't fit with the required costs so it cannot be commercialized, Third, even the high enhancement rates don't account for all load ranges and conditions, besides, for implementing renewable energy systems, although the COP increases as the power consumed is substituted with a renewable source, the thermal efficiency decreases because the number of thermal components increase, another drawback is the high initial cost, long term payback period, the large space requirements, the need for energy storage system to deal with the variable loads and finally the high maintenance cost.

8. Conclusion

Researches and innovations in the active cooling systems, especially the chillers, are still in progress until now, taking in account the drawbacks in the previous contributions, going towards a more efficient, sustainable, eco-friendly and commercial systems, the pace of work has increased lately, because of the global warming effects and the ambient temperature rise whose rate is increasing through decades. In order to take the lead toward a feasible and sustainable novel active cooling system, the following recommendations are to be considered:

- The innovation introduced shall be applicable for all cooling ranges for a specific application not limited to a specific load only and excluding others.
- Analysis of systems shall be made over different climate regions to determine the recommended conditions for operation and the restrictions.
- The global temperature increase from global warming shall be considered through the next decades.
- The current urban expansions increase the need for solutions which doesn't depend on specific geographic resources for renewable energy.
- Avoiding the overcomplexity of the systems which comes from adding more parts into the cycle.

Improving the thermal behavior of air conditioning systems shall be the prime approach for enhancement, as it will reduce the system size, applicable for a wide operational range and can be commercialized easily, this also shall be a priority in order to overcome the global temperature increase from the global warming and make durable systems that can serve efficiently along its life time period.

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