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Energy saving potential, environmental and economic importance of evaporative cooling system: A review

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ABSTRACT

Energy consumption all over the world is increasing rapidly and one factor driving energy cost in buildings is peak electricity demand, much of which comes from cooling. With the rise in living standards, air-conditioning system has become more popular and even a necessity in life to create comfortable environment. Air-conditioning plays an essential role in ensuring occupants thermal comfort, vapour compression refrigeration-based air conditioners are being used for comfort cooling in residences, offices and commercial buildings throughout the world. These systems consume substantial power and energy and produce harmful effect on environment by damaging ozone layer. The rapid growth of world energy consumption has raised serious concerns over the depletion of energy resources and the associated environmental impact of global climate change. Decreasing the energy consumption of heating, ventilation and air conditioning (HVAC) systems is becoming increasingly important due to rising cost of fossil fuels and environmental concerns. This study reviews the energy savings potential and environmental benefits of using evaporative cooling technology under climatic conditions and it shows that evaporative cooling technology requires the minimum energy required in cooling.

Key words: Blood Pressure, Heart rate, Oscillometric, Analog-to-digital converter, Microcontroller

1. INTRODUCTION

The rapid growth of world energy consumption has raised serious concerns over the depletion of energy resources and the associated environmental impact of global climate change. Over the last two decades, the world primary energy consumption (fossil fuels) has increased by 49% and carbon dioxide emissions by 43% [1]. Energy demand worldwide for buildings cooling has increased sharply in the last few decades, which has raised concerns over depletion of energy resources and contributing to global warming. The highest share of building energy use is mainly due to space air conditioning using traditional HVAC systems.

Energy saving is a high-priority in developed countries. For this reason, energy-efficient measures are being increasingly implemented in all sectors. The residential sector is responsible for an important part of the energy consumption in the world. Most of this energy is used in heating, cooling, and artificial ventilation systems.

In 2004, energy consumption of buildings in EU countries accounted for 37% of total energy use, higher than those for industry (28%) and transport (32%). In the UK, the proportion of energy consumption in building was 39%, which is slightly higher than the European ([2]. In developed countries, the energy consumption in heating ventilation and air conditioning (HVAC) systems has accounted for 50% of the energy consumption in buildings and 20% of total energy consumption. The building sector consumes a large amount of the total primary energy compared to other sectors. Energy consumption in buildings stands at between 30–40% of the total primary energy use globally For example, in the developed countries such as USA, 41% of primary energy was consumed by residential and commercial buildings compared to 30% and 29% by industrial and transportation sectors respectively, while in the developing countries such as Kingdom of Saudi Arabia where air conditioning is required for the majority of the year, 70% of primary energy is consumed by the building sector to provide comfortable indoor climatic conditions for occupants [3-4]. Today, the demand for energy is growing rapidly, and the world is hungry for energy. World energy consumption pattern showed that fossil fuels including oil, coal and gas are being consumed significantly higher than the environmentally friendly renewable energy sources as shown in Figure 1. This will result in increased CO_2 emission to the environment and subsequent climate change.

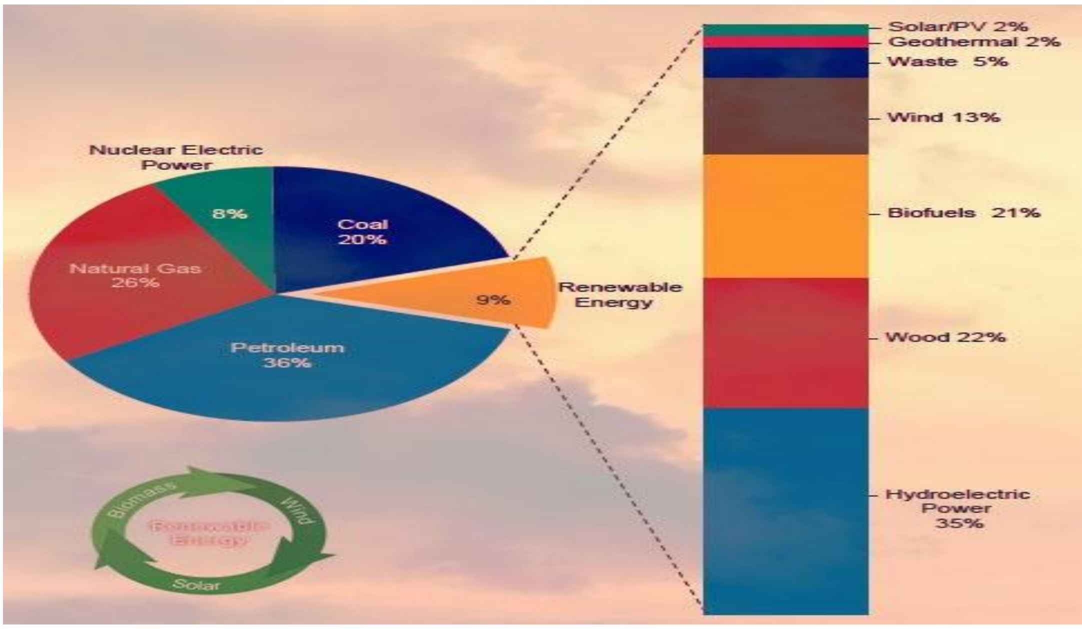

Fig. 1 Graphical representation of the world energy consumption source: Renewable Energy Sources [5]

The growth in air conditioning systems in the world is mainly driven by an increase in living standards, affordability, population growth and cheap electrical energy in some regions such as the Middle East. This has put severe strains on electricity grids in many countries, which in turn negatively impact the environment by emitting more greenhouse gases. Majority of the energy consumption in building for cooling or heating is derived from fossil fuels. It is therefore very vital to provide a less energy intensive system for space cooling which will replace or minimize dependency on the conventional vapour compression air conditioning systems. To meet the need of increasing air conditioning appliances without the use of conventional air conditioning that consumes substantial amount of electricity energy, it is necessary to develop sustainable cooling systems that are CFC-free. Evaporative cooling systems utilize the latent heat of water evaporation, i.e. a kind of natural energy existed in the atmosphere, to perform air conditioning for buildings. These systems consume 20% of electrical energy by vapour-compression air conditioning, equivalent to reducing nearly 44% carbon dioxide emissions produced by vapour-compression air conditioning. Given the global significance of cooling building space and the recognized energy saving benefits of evaporative cooling over more conventional methods, understanding the energy saving potential and environmental benefit of such system is necessary to help understand its importance in achieving regional emissions reduction and energy savings goals.

2. PRINCIPLES OF EVAPORATIVE COOLING

Evaporative cooling is a process that reduces air temperature by evaporation of water into the airstream. As water evaporates, energy is lost from the air causing its temperature to drop. The amount of cooling available from evaporative cooling depends on the temperature and water content (humidity) of the air being cooled. Drier air is able to absorb more moisture than humid air, so evaporative cooling performs best in warm, arid climates. When warm, dry (unsaturated) air is pulled through a water soaked pad, some of the water evaporates. This happens because the temperature and the vapor pressure of the water and the air attempt to equalize. As the water molecules become a gas (evaporate), they “absorb” heat from the surrounding air and lower its temperature. The heat is still present; however, it has just been “captured” in the form of water vapor within the air (humidity). The air is cooled in the process and the humidity is increased. The evaporative cooling technology is an energy-efficient alternative to compressor-based cooling. In dry and arid regions, evaporative cooling can meet most or all building cooling loads using one-fourth the energy of conventional equipment. The evaporative cooling process is extremely energy efficient, generally requiring only a pump to keep the evaporative media wet, and a fan to deliver conditioned air.

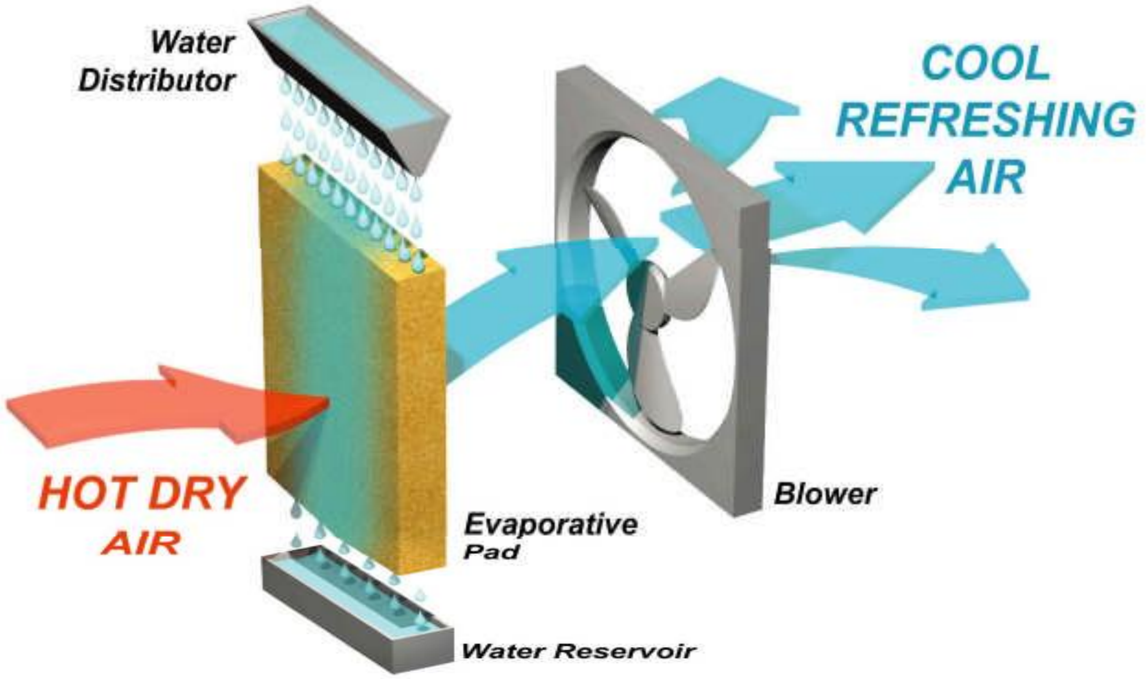

Fig. 2 Basic evaporative cooling process [6]

3. Methods of Evaporative Cooling System

Basically evaporative cooling can be direct, indirect or combination of direct and indirect. The combination types are also called hybrid or integrated types. There are three main methods of achieving evaporative cooling and the choice of each depends on the type of application required.

A. Direct Evaporative Cooling

In direct evaporative cooling air and moisture get direct contact with each other. Air transfers its sensible heat energy to water molecules and water gets evaporated and mixes with warm air. As the hot dry air loses its sensible heat and simultaneously absorbs the water vapour it gets converted into cool moist air. In direct evaporative cooling the dry bulb temperature is lowered but the wet bulb temperature remains unchanged. In operation, a blower pulls air through a permeable, water-soaked pad. As the air passes through the pad, it is filtered, cooled, and humidified. A recirculation pump keeps the media (pad of woven fibers or corrugated paper) wet, while air flows through the pad.

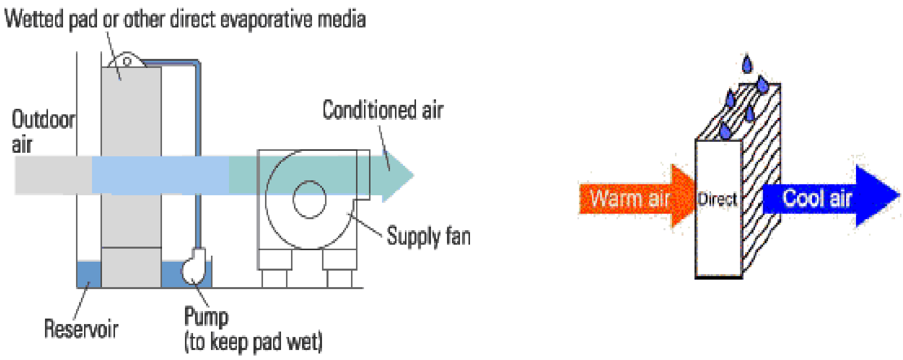

Fig. 3 Direct Evaporative Cooling [7]

B. Indirect Evaporative Cooling

Indirect evaporative cooling process involves two air streams, one primary or product air stream and the other secondary or working air stream. The working air stream is cooled by water using direct evaporative cooling and it is passed through the heat exchanger where, it cools the primary air without coming in direct contact. This reduces DBT and WBT of primary (product) air. Due to the heat transfer between secondary and primary air through heat exchanger, the secondary (working) air becomes hot. The minimum dry bulb temperature of the product (primary) air which can be reached is the wet bulb temperature of the secondary (working) air. The effectiveness of the indirect evaporative cooling is determined mainly by the efficiency of the heat exchanger.

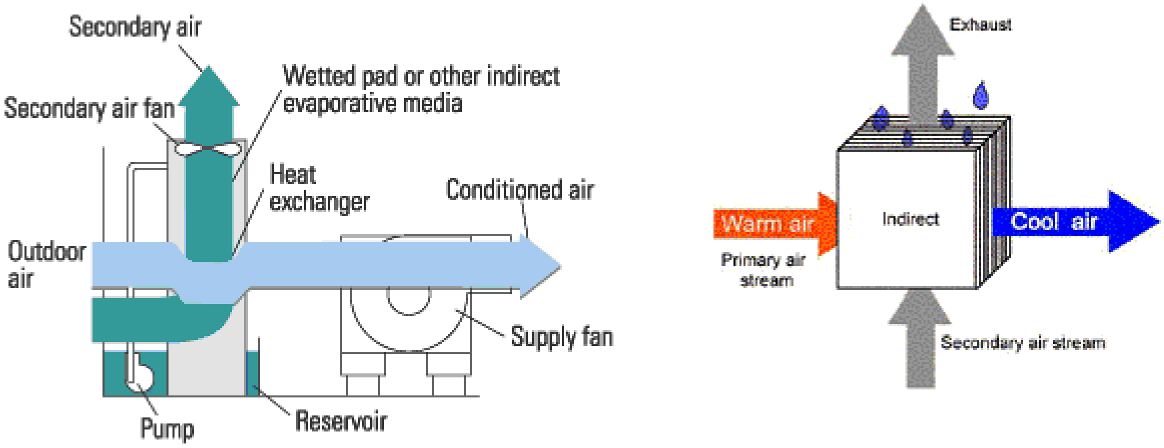

Fig. 4 Indirect Evaporative Cooling [7]

C. Indirect / Direct Evaporative Cooling

This is a combination of the direct and indirect system. The primary air is cooled first with indirect method and then cooled further with direct evaporative cooling as illustrated in Figure 5.

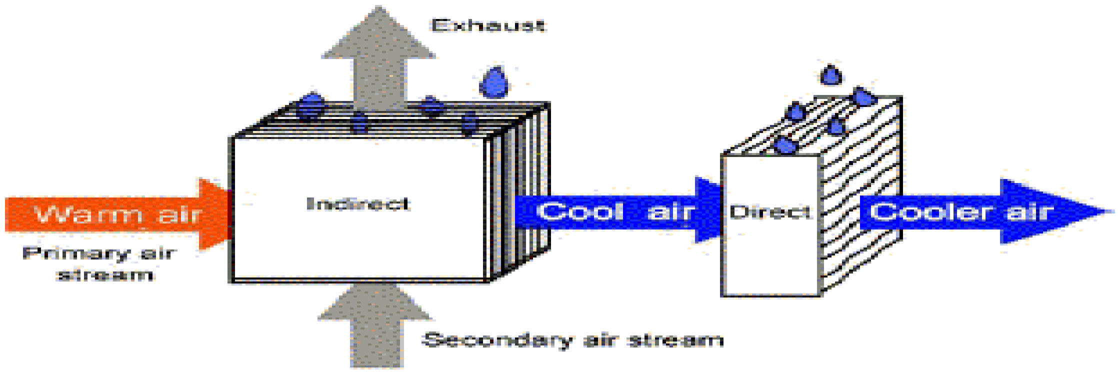

Fig. 5 Indirect/direct evaporative cooling system [7]

D. Energy Performance of Evaporative Air Conditioners.

The following parameters are used for evaluating the performance of evaporative air conditioners:

- **Saturation Efficiency (Cooling Effectiveness) and Enthalpy Change in Air**

Saturation efficiency (η_{sat}) is an index used to assess the performance of a direct evaporative cooler. Cooling efficiency in percentage can be defined as expressed in Eq. (1) [8-9]:

$$\eta_{sat} = [\ (t_d - t_c) / (t_d - t_{wb})] \times 100 \qquad (1)$$

where T_d and T_{wb} are the dry and web bulb temperatures of the ambient air and T_c is the dry bulb temperature of the cooled air in ^oC. The enthalpy change in air ΔH, can be calculated as follows:

$$\Delta H = MC_{pa}\ (T_d - T_c) \qquad (2)$$

where C_{pa} is the specific heat of moist air in kJ $kg^{-1}K^{-1}$; and M is the air mass flow rate in kg s^{-1}.

- **Cooling capacity of an evaporative air conditioner**

As evaporative air conditioners pumps 100% outside air to the space to be cooled, cooling is achieved through replacing the expelled air from the room by inlet air from the air conditioner. Therefore, the cooling capacity of an evaporative air conditioner can be defined as:

$$C_c = \rho A_v\ C_{pa}\ (T_d - T_c) \qquad (3)$$

Where C_c : cooling capacity (kW), ρ: density of standard air (1.20 kg/m3 for standard air) A_v: air volume flow rate corrected to standard temperature and pressure (m^3/s), C_{pa}: Specific heat capacity of moist air at constant pressure (1.024 kJ/kg, based on a humidity ratio of 10 g/kg)

If the air delivered by the air conditioner is at a temperature equal or greater than the air being expelled from the space, then evaporative air conditioning is ineffective. Consequently, cooling is only achieved when C_c has a positive value. The cooling capacity of an evaporative cooler is dependent on the inlet air dry and wet bulb temperatures as well as the air flow rate and evaporation effectiveness of the cooler. No cooling can be achieved if the air produced by the cooler is at a higher temperature than the desired temperature of the air being exhausted from the room. In order to evaluate a rated cooling capacity, the dry and wet bulb temperatures of the outside air must be fixed. The evaporative cooler evaporation effectiveness (or efficiency) must be evaluated experimentally at these conditions. Once the rated cooling capacity has been established, a rated Energy Efficiency Ratio‖ can be determined as a measure of rating the cooling effect being produced per unit electrical power being consumed.

- Energy Efficiency Ratio (EER)

Energy efficiency ratio (EER) was developed by the industry to evaluate the rate of energy consumption for air conditioning units [10]. The EER represents a measure for rating air conditioning units. The energy efficiency ratio EER is defined as the net thermal energy removed from air for cooling purposes per watt of energy expended. That is

$$EER = \frac{\Delta H}{P} \quad (4)$$

Where,

P is input electrical power in kW of the exhaust fan and water pump.

The value of EER is calculated by determining the difference in the enthalpy of the inlet and outlet air streams through the cooling pad and the input power.

- Seasonal Energy Efficiency Ratio (SEER)

In addition to the parameters above a single rating tool is necessary for rating the energy consumption of different evaporative conditioners. The rating parameter will enable direct comparison of different models. Keeping in mind the performance sensitivity of evaporative air conditioners to the outdoor temperature and humidity, a new parameter based on the annual performance of a particular unit in a specific location for providing the energy rating of evaporative air conditioners was proposed. Using the test results (air supply rate, total electrical power consumption and evaporation effectiveness) which are insensitive to temperature and humidity variations, the hourly cooling capacity C_c for a specific unit can be evaluated in a particular location for all hours of the year when cooling is required. This will enable the evaluation of a new performance parameters which takes into consideration the overall annual performance in a specific location, namely the Seasonal Energy Efficiency ratio, SEER, where

$$SEER = \frac{\text{Total anual cooling capacity (kwh thermal)}}{\text{Total anual electric energy consumption (kwh electric)}} \quad (5)$$

The SEER value is location specific. However, it is comparable with the EER values quoted for other cooling systems as the latter gives an indication of the cooling effect produced per unit electrical energy consumption at the standard test conditions.

Wasin *et al.*, [11] presented an estimate of the energy consumption of evaporative air conditions in different parts of Australia. The total annual electricity consumption to provide cooling during all hours when the outside temperature is above 27°C was calculated.

Table 1 below demonstrates the low energy consumption and cost associated with the use of these cooling systems.

Table -1 Estimates of energy performance of evaporative air conditioners for different unit sizes and Australia locations [11]

Location	Total Anual Electricity Consumption (Kwh)		Seasonal Energy Efficiency ratio	
	9630 (m^3/h)	16000 (m^3/h)	9630 (m^3/h)	16000 (m^3/h)
Adelaide	684.4	895.7	29.9	39.0
Brisbane	463.3	606.3	16.3	21.3
Canberra	235.7	308.5	33.3	43.5
Hobert	29.2	38.2	29.8	38.9
Melbourne	281.1	367.8	26.3	34.4
Perth	679.6	889.3	26.9	35.1
Sydney	223.6	292.6	20.7	27.0

Table 1 above also introduces a new parameter for evaluating the energy performance of evaporative air conditioning systems, namely the Seasonal Energy Efficiency Ratio (SEER) which is the ratio of annual cooling output of the air conditioner during the cooling season and the total annual electrical energy usage to produce the cooling requirements. This ratio is a good measure of the electrical energy effectiveness of cooling production under different climatic conditions. It is a more comprehensive measure in comparison with the Energy Efficiency Ratio (EER) commonly used for rating refrigeration system performance as the latter is a measure of the performance at specified thermal test conditions only and does not take into consideration the impact of temperature and humidity variation throughout the cooling season. The total annual electricity consumption is the energy consumed by the evaporative coolers that supply air volume flow rates of 9630 m^3/hr and 16000 m^3/hr during the whole cooling season.

Furthermore, the amount of energy consumption for cooling purposes has been calculated based on hourly weather conditions in a typical hot day and a typical summer day from two available climate data sources for Adelaide: (1) data supplied by ACADS-BSG (a specialist building services Simulation Company) and (2) climate data from Australian Climate Data Bank (ACDB). The typical hot day in this report refers to a day in which the 3:00pm dry-bulb temperature is only exceeded on 10 days per year. The typical summer day refers to a day, in which the 3:00pm dry-bulb temperature equals the average 3:00pm temperature of the summer days requiring cooling. In the calculation, cooling is assumed to be switched on at full speed during hours when the outside temperature exceeds 27 ^{0}C and represents the maximum energy consumption on those days. The total energy consumption and the average energy consumption and energy efficiency ratio are shown in Table 2.

Table -2 Estimates of energy consumption of evaporative air conditioners on typical days in Adelaide [11]

Conditions	**Source of climate data**	**Period requires cooling**	**Total cooling capacity for various air flow rates (kw)**		**Average cooling capacity for various air flow rates (kw)**		**Average EER for various air flow rates**		**Total electricity consumed for various air flow rates (kwh)**	
			9360 (m^3/h)	**16000 (m^3/h)**	**9360 (m^3/h)**	**16000 (m^3/)**	**9360 (m^3/h)**	**16000 (m^3/h)**	**9360 (m^3/h)**	**16000 (m^3/h)**
Adelaide typical hot day	ACADBSG	6.00am - 12.00pm	445.8	762.0	23.5	40.1	29.0	37.8	29.0	37.8
	ACDB	11.00am - 11.00pm	278.4	476.0	21.4	36.6	26.4	34.5	26.4	34.5
Adelaide typical summer day	ACADBSG	10.00am - 7.00pm	221.5	378.6	22.1	37.9	27.3	35.7	27.3	35.7
	ACDB	11.00am - 8.00pm	250.7	428.5	25.1	42.8	30.9	40.4	30.9	40.4

E. Regulatory Approaches

This involves the regulating the amount of energy for cooling according to locality.

- **California Appliance Efficiency Regulations**

The California Appliance Efficiency Regulations include a procedure for evaluating and rating the energy performance of evaporative coolers. This is achieved by evaluating the Evaporative Cooler Efficiency Ratio (ECER). ECER is evaluated by Equation 6. The conditions specified for the evaluation of ECER are intake dry and wet bulb temperatures of 32.8 and 20.6°C (91 and 69°F) respectively for testing the evaporation efficiency and assumed room outlet air temperature of 26.7°C (80°F).

$$ECER = 1.08 \times (t_{room} - (t_{db} - \eta_{sat} \times (t_{db} - t_{wb}))) \times Q/W \quad (6)$$

Where

t_{room} = room dry-bulb temperature, ^{0}C

t_{db} = outdoor dry-bulb temperature, ^{0}C

t_{wb} = outdoor wet-bulb temperature, ^{0}C

η_{sat} = saturation effectiveness divided by 100

Q = air flow rate, cfm

W = total power, W

No water consumption requirements are included in the Regulations.

- **Iran Labeling Program**

Iran is the only country that currently conducts a mandatory comparative labeling program for energy consumption of evaporative air conditioners (see example of the label and rating, Figure 6 and Table 3). It shows efficiency grades from 1 (most efficient - the shortest bar, which appears in green on the original label) down to 7 (least efficient - the longest bar, which appears as red). The aim of the Iranian program is to encourage local manufacturers to improve the energy efficiency of their products. Studies conducted in cooperation with manufacturers revealed that there are a variety of design changes possible, such as the use of more efficient fans and motors, pad density and improved water circulation rate. These changes would make a considerable impact on energy consumption without requiring major investment.

Table -3 Energy Efficiency Thresholds for Iranian Energy Label (Iran Energy Efficiency Organization)

Rating	EER Value
1	EER≥ 65
2	58≤EER<65
3	50≤EER<58
4	42≤EER<50
5	34≤EER<42
6	26≤EER<34
7	EER<26

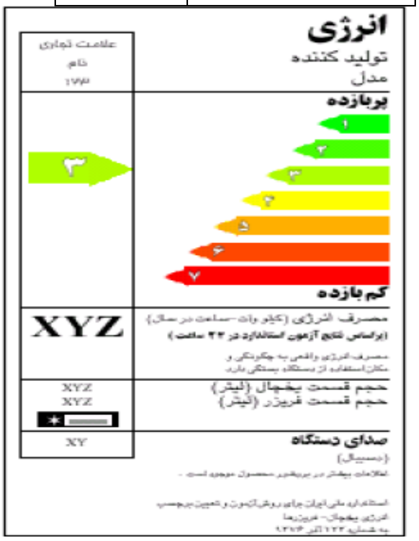

Fig. 6 Example of the Iranian energy label (Iran Energy Efficiency Organization) [12]

F. Energy Savings of Evaporative Cooling System

Energy saving potential associated with the evaporative cooling systems was studied by a number of researchers. Chen *et al.*, [13] carried out a case study for applying the Regenerative Indirect Evaporative Cooling System (RIECS) to an all-fresh-air hybrid air-conditioning system of a wet market in Hong Kong. The condense water from an air-handling unit (AHU) is collected and used as cooling medium sprayed onto the heat exchanger of an IEC equipment. At the same time, the contaminative and exhausted air from the wet market returns to the IEC equipment to cool the intake fresh air, so that the fresh air pre-cooling before it enters to the AHUs is realized. The energy saving and economic efficiency were analyzed and compared among RIECS, rotating heat recovery wheel system and the A/C system without heat recovery. The results show that RIEC system has the largest annual energy saving potential with a payback period of 2.9 years, which shows a great potential of its application in Hong Kong.

Moien and Ghassem [14] worked on increasing effectiveness of evaporative cooling using pre-cooled nocturnally stored water for two stage evaporative cooling for four cities. He found that multistep system is economical and has higher effectiveness than conventional two stage evaporative cooling system. He also found energy saving potential varies between 75% to 79% compared to vapour compression refrigerated system. Ebrahim [15] used direct evaporative cooling to improve performance of condenser of window air conditioner. He found that new system gives reduced power consumption by 16% and COP stepped up by 55%.

Maheshwari and Al-Ragom [16] presented an analytical investigation using the field testing results of an IEC unit with capacity of 1180 l/s air-flow rate and the recorded weather data in coastal and inland locations in Kuwait. The cooling outputs and power consumptions of the IEC and the packaged refrigerated air-conditioner of the same capacity were estimated; there results indicated that the IEC unit, when being used in the inland and coastal regions of Kuwait, could obtain 12,418 kWh and 6320kWh of seasonal energy savings compared to the same sized conventional mechanical vapour compression refrigeration based air conditioner.

Heidarinejad *et al.*, [17] investigated a two-stage IEC/DEC system used in various climate regions in Iran, with particular focus on the issues of thermal comfort, power saving and water consumption. The study indicated that more than 60% of power saving could be obtained by using this system in comparison with the conventional mechanical vapour compression systems with the same capacity; while the water consumption by the former was 55% higher.

Based on this study, Delfani *et al.*, [18] experimentally investigated the performance of the IEC to pre-cool air for a conventional mechanical vapour compression system (pack- aged air conditioner) for four cities in Iran. Two air simulators were designed and used to simulate indoor heating load and outdoor design conditions. By using the experimental data and an appropriate analytical method, the performance and energy reduction capability of the combined system during the cooling season operation was evaluated. The results indicated that the IEC unit could take up around 75% of total cooling load and save around 55% of electricity consumption compared to the sole use of the packaged unit air conditioner.

Frank Bruno (2011) worked on noval due point evaporative cooler for commercial residential applications. He obtained average EER in the range of 7.22 to 11.5. The lowest temperature achieved by cooler is 14.7ºC and average temperature delivered was 17.3ºC. The Wet bulb effectiveness range from 93% to 106% and Dew point Effectiveness range from 65% to 83%. Annual energy saving range from 55% to 60%.

Khandelwal *et al.,* [19] studied the energy saving in a building using regenerative evaporative cooling system. There result indicated significant potential for energy savings up to 15.69%, where as simple evaporative cooling system provided 12.05%.

El-Dessouky *et al.,* [10] developed a membrane air dryer and coupled with conventional direct/indirect evaporative cooler. The dryer removes the moisture from the incoming air before passing through the evaporative cooling system. When they combined the system with mechanical vapour compression system, about 50% savings in electricity was obtained.

Taufiq [20] conducted an energy analysis of evaporative cooling for reducing energy use in a building. They developed correlations between the relative humidity, ambient temperature and energy efficiency. They concluded that evaporative cooling system is a feasible technology that can reduce mechanical cooling and energy requirement.

In other to gain an understanding of the extent to which annual and peak energy reductions are realistically possible, Bo Shen *et al.*, [21] study the effect of pre-cooling technology on energy savings and peak energy reduction in three building types (medium office, secondary school, and supermarket) in 16 locations within the U.S. with four levels of pad effectiveness and show the effect for HVAC systems using either refrigerants R22 or R410A.

Energy Plus simulations are conducted with an improved algorithm for estimating the condenser pre-cooling wet bulb efficiency. Computer algorithms were developed for use with Energy Plus to simulate the performance of commercial units under a variety of operating parameters. Performance maps were generated and estimated energy savings and peak demand reductions were calculated. Annual savings are calculated on the basis of installing condenser pre-cooling pad on an existing rooftop air conditioner. Actual savings may be more because condenser pre-cooling generally increases cooling capacity and hence the replacement unit may be downsized and cost less than the equipment it was replacing. For retrofit applications, the pad is directly added to the original rooftop unit sizes selected by Energy Plus as equipment upgrades. Condenser Pre-cooling is used to increase the efficiency of refrigerated air systems by pre-cooling the air, which is drawn through the outdoor air-cooled refrigerant condenser. This additional temperature reduction at the condenser will decrease the energy required by the compressor and effectively increase the capacity of the unit, or alternately, a smaller and less costly unit can be specified. An added advantage is that the direct pre-cooler will reduce head pressures and thus extend compressor life. Evaporative condenser pre-cooling expands the availability of energy saving, cost-effective technology options.

The effect of refrigerant type can be understood by noting that R410A condensing pressure operates near the critical region (where the refrigerant liquid and vapor become identical) and any lowering of the condenser temperature (as would be the case of evaporative cooling) causes the two-phase isotherm to move downwards from the apex of the critical region enabling the system to increase its cooling capacity and efficiency. In other words, the refrigerant operates over a larger enthalpy change across the two-phase region, resulting in improved overall condenser heat transfer effectiveness, and hence can reject more heat to the ambient for the same mass flow rate. Consequently, precooling has a more beneficial effect on energy savings for R410A systems, as compared with R22 units.

If pre-cooling is deployed at all ambient temperatures during the cooling season, then the percent energy savings relative to using no pre-cooling at wet bulb efficiency of 0.7 and equipment COP of 3.0 is shown in Fig.7. We observe that annual operating cost savings are increased due to pre-cooling for all three types of buildings particularly in the hot dry climates (Phoenix, Albuquerque) but less pronounced in wet climates (Seattle), and that cost savings with R410A are significantly greater than it is for the older R22 refrigerant. Hot dry climates are amenable to water evaporation and hence such climates benefit from this technology.

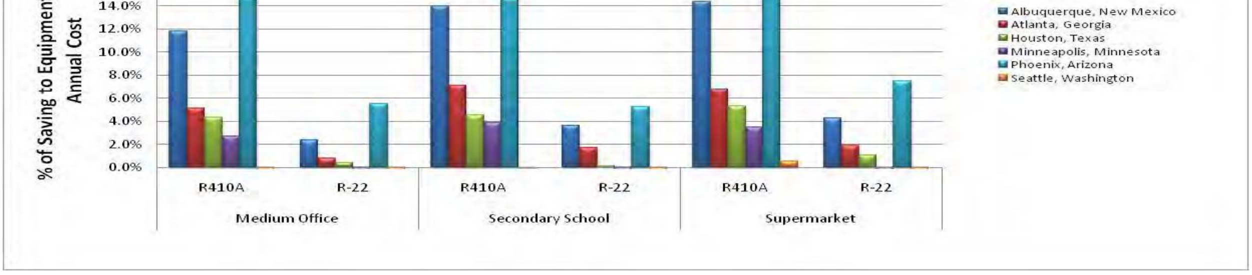

Fig. 7 Percentage of energy savings due to pre-cooling relative to no pre-cooling when water is sprayed at all ambient temperatures and wet bulb efficiency of 0.7, and COP = 3 [21]

From the result of their study they concluded that evaporative cooling can expand the availability of energy saving and provides the opportunity for annual energy savings and peak demand reduction, with significant potential in hot, dry climates.

Ayman and Adel [22] evaluated the energy savings potential of indirect evaporative cooling (IEC) as fresh air pre-cooling in hot climatic conditions in Saudi Arabia. A commercial IEC unit was pilot-tested in a building located in Ras Tanura refinery. Energy saving calculation method (equation 7) for hybrid IEC/DX-based AC system was performed and a generalized energy saving chart (table 4) was generated for a range of dry bulb temperatures and wet bulb temperatures from 120 F to 75F and from 90 F to 69F respectively.

$$\text{Saving} = 1 - (EER_{DX} / EER_{Hybrid}) \quad (7)$$

$$EER_{Hybrid} = [(EER_{IEC} \times Q_{IEC}) + (EER_{DX} \times Q_{DX})] / Q_{Total} \quad (8)$$

Where:

EER_{DX} = energy efficiency ratio of the DX- based AC system
EER_{IEC} = energy efficiency ratio of the IEC system
EER_{Hybrid} = energy efficiency ratio of the Hybrid
Q_{IEC} = cooling capacity of the IEC system
Q_{DX} = cooling capacity of the DX- based AC system
$Q_{Total} = Q_{IEC} + Q_{DX}$

Table -4 IEC energy saving in fresh air pre-cooling application [22]

Wet Bulb (F^o^) / Dry Bulb (F^o^) / Saving (%)

DB \ Wb	90	89	88	87	86					73	72	71	70	69
120	43%	44%	45%	47%	48%									
115	38%	40%	41%	43%	44%									
110	34%	35%	36%	38%	39%									
105	30%	31%	32%	33%				35%	57%					
100	27%	27%	28%				48%	50%	53%					
95	25%	25%				[illegible]	41%	44%	47%	50%	53%			
90		26%				31%	33%	36%	39%	42%	46%			
85						25%	26%	28%	30%	32%	35%	39%		
80						24%	24%	23%	23%	24%	25%	27%	30%	
75									25%	23%	22%	21%	19%	25%

Table 4 shows an example of the powerful benefit of determining the percentage energy saving of deploying IEC for fresh air pre-cooling as opposed to using DX only, for a given dry bulb and wet bulb temperatures. The table is specific to an installation deploying IEC unit with 80% effectiveness and a DX unit with EER of 11.

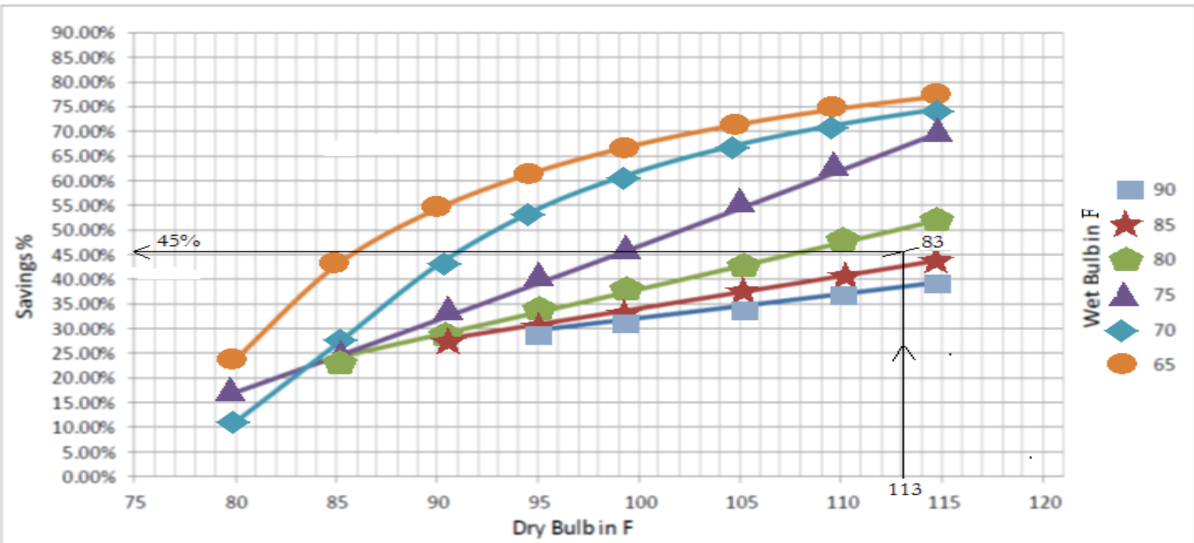

Fig. 8 IEC energy saving in fresh air pre-cooling application [22]

Given the fact that many HVAC designers prefer to work with sizing charts, table 4 was used to generate an energy savings chart as shown in figure 8. The chart has a combination of straight and curved lines for wet bulb temperature. The straight lines represent the IEC/DX hybrid operation and the curved lines represent the IEC operation only when the outdoor wet bulb temperature is low enough to allow IEC to be sufficient to carry the entire cooling load required for fresh air pre-cooling.

G. Economic Evaluation

The evaporative cooling has several economic advantages when compared with mechanical compression refrigeration system. The advantages of evaporative cooling over mechanical compression systems are mainly due to low initial investment, low installation and maintenance costs, and reduction in insulation requirement and can be used by micro and small scale enterprises dealing with fruit and vegetable marketing. In general, the cost of mechanical refrigeration system for fruits and vegetables storage by small to medium scale entrepreneurs is obviously very high and this adiabatic cooling technology could help to encourage the entrepreneurs. The feasibility and economics of reducing the indoor temperature and raising the relative humidity of the evaporative cooled fruit and vegetables storage chamber by using direct evaporative cooling was investigated by Tilahun [23]. He built an experimental forced ventilation evaporative cooler for the study. The economic computation was based on the number of months that each fruit or vegetable is available in market. It was found that the evaporative cooling system was capable of significantly ($P < 0.001$) reducing the temperature and significantly ($P < 0.001$) increasing the relative humidity as required for short time storage of selected fruits and vegetables.

Taking the same sized conventional air conditioner (AC) as the reference, Navon and Arkin [24] investigated the economic benefit and thermal comfort relating to utilization of a combined DEC/IEC system in a residential building in Israel. The life cycle cost was calculated by using the annual equivalent costs (AE) of the DEC/IEC and AC, as well as the estimated initial cost of the DE/ IEC system. The results indicated that the economic benefit relating to use of the DEC/IEC is very promising owing to its significant electricity cost saving over the conventional AC.

Duan [25] carried out a preliminary economic analysis of the prototype dew point air conditioner in order to understand its commercial viability within the Europe and China. The results of his analyses were summarized in the table 5 and 6 below.

Table -5 Operating cost of the cooling systems at several cities in Europe and China [25]

City	London	Bern	Cyprus	Lisbon	Athens	Beijing
Average cooling load, W/m^2	30	40	45	50	55	65
Operating cost – dew point system, euro	26.46	36.8	41.4	46.0	50.6	59.8
Operating cost – mechanical compression system, euro	115.2	153.6	172.8	192.0	211.2	249.6

Table -6 Economic benefit of the dew point systems relative to the conventional mechanical compression system [25]

City	London	Bern	Cyprus	Lisbon	Athens	Beijing
Payback period, year	1.88	1.42	1.26	1.14	1.05	0.91
Life cycle net energy bill saving, euro	2534.7	3410.7	3849.4	4286.8	4722.8	5447.1

H. Environmental Considerations

This section compares the environmental impact of EAC’s to refrigerated cooling. EAC's use water as the coolant working fluid, while refrigerated A/C's (also known as vapor compression cycle) use different types of Freon® type of coolant as organic working fluids. These refrigerant working fluids are also known as CFC's (chloroflurocarbons) and HCFC's (hydrogenated chloroflurocarbons). The two most important environmental considerations in favor of using EAC's are the reduced CO_2 and other power plant emissions, and the reduction of use of CFC's and HCFC’s, which have been proven to reduce the earth's ozone layer. Around the globe EAC residential units directly obviate at least 118 million pounds of HCFC-22. These residential coolers save approximately 60 million barrels of oil annually and 27 billion pounds of annual CO_2 emissions in lieu of using vapor-compression air-conditioning systems. Also the 4 million EAC units in operation in the United States provide an estimated annual energy savings equivalent to 12 million barrels of oil and an annual reduction of 5.4 billion bounds of CO_2 emissions. They also avoid the need for 24 million pounds of refrigerant traditionally used in residential VAC [refrigeration] systems [26].

Jaber and Ajib [27] designed an indirect evaporative air-conditioning for the typical Mediterranean residential buildings. They reported that most of the cooling load of the buildings could be matched by using an IEC unit with the air flow rate of 1100 l/s. If such a IEC system were mounted in 500,000 Mediterranean residential buildings, as the replacement of conventional mechanical vapour compression refrigeration systems, the estimated annual energy saving and CO_2 emission reduction would be around 1084 GW h and 637,873 t per annum, respectively. The payback time of the implementation would be less than two years.

In his (Duan, [25]) preliminary economic analysis of the prototype dew point air conditioner, in which he worked out the annual electricity power saving of the dew point system over the conventional mechanical compression cooling system, in terms of kWh per annum, he was able to convert the figures into carbon emissions reduction by using the following equation:

$$Em_{co2} = f_{c,c}En_a / 1000 \quad (9)$$

The results derived from the calculation are presented in Table 7. For 100 m^2 building space, using a 8 kW rating dew point cooling unit, its annual CO_2 emission reduction will be in the range 0.323 to 0.7 tons. Considering that each year there will be 5 million m^2 of European building using this technology, the estimated annual carbon emissions reduction will be as high as 35,000 tons.

Table -7 Environmental benefits of dew point system relative to conventional mechanical compression system [25]

City	London	Bern	Cyprus	Lisbon	Athens	Beijing
Carbon emissions reduction for 100 m^2 building space, tons	0.323	0.430	0.484	0.538	0.591	0.700
Carbon emissions reduction for 5 million m^2 building space, tons	16,150	21,500	24,200	26,900	29,550	34,991

3. CONCLUSION

A review on energy saving potential, environmental and economic importance of evaporative cooling system has been undertaken. From this study, the following are evident:

a) With the ongoing energy crisis and pollutant emission, use of evaporative cooling has much advantage. It is inexpensive, energy efficient and potentially attractive. Evaporative cooling provides the opportunity for annual energy savings and peak demand reduction, with significant potential in hot, dry climates.

b) The environmental benefits of evaporative cooling technology are impressive when compared to vapour compression in terms of low electrical power consumption, low noise from components and reduced CO_2 emission. Evaporative coolers also provide excellent ventilation as they use 100% fresh air from outside and could achieve up to 75% energy savings compared to all types of refrigeration cycles.

c) Rating evaporative air conditioners for the efficiency of water and to be able to evaluate the amount of water needed for the process is possible.

d) No water rating system for evaporative air coolers is in use recently or available in literature.

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