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Thermo-Economic Evaluation of gas turbine plant with inlet air cooling: UBARI case study

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Abstract:

The efficiency of gas turbines is influenced by the climate conditions, The power output of gas turbines drops to a level that is less than estimated under high temperature and dry conditions which occur in UBAREI through the hot seasons, Atmospheric air temperature can be cooled by several cooling systems, for example, an evaporative cooler or an absorption chiller. This paper simulated thermodynamically the performance of the gas turbine unit at the site of UBARI (latitude 26.58 N º) Located around 1,000 km south of Tripoli city. This investigation was conducted for the SGT 2000 The thermodynamic equations of the suggested gas turbine model were solved using THERMOFLEX software. The results were obtained to study the thermal performance and economic analysis of the gas turbine unit without a cooling system, and compare them with the performance of each gas turbine unit equipped with an evaporative cooler and another equipped with an absorption cooler, Studied gas turbine parameters are power output, thermal efficiency, and heat rate. The results showed that at atmospheric air temperature equal to 313 K the evaporative cooler system provides an augmentation of 8.75% in power output and 2.6% in thermal efficiency. While an absorption chiller, system can achieve an increase of 13.58 % in power output and 3.5% in thermal efficiency.

Keywords: Gas turbine, Inlet air cooling, Evaporative cooling, Absorption chiller

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1. Introduction

Gas turbines are used in many countries in the world where they are used to produce power, operate aircraft, and for various industrial applications. There are more than 30 gas turbine units in Libya. The total capacity of these units is about 4,170 MW [1]. However, gas turbine units lose about 20% of their rated power in hot seasons. This means that about 834 megawatts are lost during the hottest months of the year. The city of Ubari is located in the southern region of Libya (latitude 26.58 North), which is characterized by a climate with low relative humidity and high temperature during the hot seasons, which affects the efficiency of gas turbines and leads to a decrease in production capacity and thermal efficiency in the hot seasons. In fact the power output drops by 0.54% - 0.90% for every 1 ºC (1.8 ºF) rise in air temperature [2]. The increase in air temperature also causes an increase in the gas turbine transfer heat rate and consequently operating cost. The gas turbines contain a compressor that supplies air to the combustion chamber at high pressure. These engines have a constant volume and their power output is directly proportional to the air mass flow rate. Since a compressor has a constant capacity for a volumetric flow rate of air and a given rotational speed, its volumetric capacity remains constant. Therefore, the mass flow rate of air entering a gas turbine varies with its mass, and it depends on the relative humidity and the temperature of the ambient air [3]. One of the methods used to solve this problem is the cooling of the compressor inlet air. different technologies are available, including evaporative cooling and absorption cooling systems. Several types of research have extensively studied the different turbine inlet cooling methods to increase gas turbine performance. Kakaras et al. [4] have made a computer simulation of the integration of absorption chiller technology for reducing the inlet air temperature in the gas turbine, For two test cases simple cycle gas turbine and a combined cycle plant. They concluded that the absorption chiller cooling system showed a higher gain in power output and efficiency than evaporative cooling for a simple cycle gas turbine. The combined cycle case also showed that the absorption chiller can significantly increase the power output, although there is a decrease in efficiency. In addition, Ameri and Hegazi [5] used a steam absorption chiller with an air cooler to cool the inlet air of the Chabahar gas turbine plant. This system provided an increase of 11.3% in power output; the economical studies have shown the cost of electricity is calculated to be 1.45 Cents/kWh which is less than the current price of electricity in Iran. This leads to a payback period 4.2 of years. Moreover, Alhazmy and Najjar [6] showed that spray coolers are more inexpensive than chiller coils. However, they are directly restricted by relative humidity and atmospheric temperature. Spray cooler can reduce air temperature by 3–15 ºC, increasing power by 1–7%, and efficiency by 3%, while chiller coils provide complete control for air temperature, and cooling coil improves the turbine output by 10% during cold humid conditions and by 18% during hot humid seasons. In addition, Jaber et al. [7] studied the effect of cooling gas turbine inlet air by using the evaporative and cooling coil. The results presented that power output is similar for both evaporative cooling and chiller system which is about 1.0–1.5 MW, but in the case of a chiller system, the power consumed by mechanical auxiliaries is higher, so the overall power output decreases. Farzaneh and Deymi [8] compared two common and one novel inlet air cooling methods using turbo-expanders. The net increase in electricity production for the turbo-expander system is around (18,338 MW h/year), and for the evaporative media system and mechanical chiller system is 1132 MW h/year and 2501 MW h/year respectively. The payback period for the turbo-expander method is lower than the other methods. El-Maghlany et al. [9] studied the performance of gas turbine without an inlet air cooling system and compared the performance of gas turbine connected with both evaporative cooler and absorption chiller separately. Results are given that at air ambient temperature equals to 37 ºC, the absorption chiller with regenerator can realize an increase of 25.47% and 33.66% in power and thermal efficiency respectively which saving 13% in power price, while the evaporative cooler provides only an increase of 5.56% and 1.55% in power and thermal efficiency respectively, and saving 3% in power price. As reported Carmona [10] conducted a thermal and economic analysis of the gas turbine using evaporative, were proved that there is still potential for evaporative cooling in humid and warm places, On the other hand, Ahmadzadehtalatape [11] has presented thermo-economic analysis which revealed that the payback period of using media evaporative, fogging and absorption refrigeration inlet air cooling systems were 1.4, 1.14 and 5.7 years، respectively. According to Marzouk [12], the economic analysis indicated that the payback period was 0.66 and 3.3 years for evaporative and vapor compression refrigeration inlet air cooling systems, respectively.

2. The climate of the site under study

The city of Ubari is located in the southwest of the state of Libya and has desert weather, where temperatures rise to high levels during the warm seasons. There is an oil field located in this city which has an industrial gas turbine with power generation of 19 MW, as well as Ubari city has a gas power plant with capacity of 640 MW. The atmospheric temperature is often higher than the standard condition 15 ºC during a year in Ubari city. The variations of the average temperature and the average humidity over a year are shown in Table 1.

These data are based on the statistical climatic conditions imported from program software (RETscreen) [13]. which is based on climate data from National Aeronautics and Space Administration NASA. According to these data, the maximum, and the minimum temperatures are 31.2 ºC, and 10.1 ºC respectively. The maximum relative humidity is 43.3% and the minimum is 16.9%.

Table 1: Variation of the average ambient temperature and average relative humidity in Ubari

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
average ambient temperature, ℃	10.1	12.4	17.4	23.0	27.7	31.1	31.2	31.0	29.3	23.9	17.2	11.7
average relative humidity, %	46.6	36.3	26.9	21.1	19.2	16.6	17.6	19.2	21.4	27.4	34.5	44.1

3. Gas turbine modeling

The system under study is (SGT-200-1S) shown in Fig. 1, this system is single shaft, industrial, and simple cycle gas turbine unit which consists of three main parts, compressor, combustion chamber and turbine, in order to cooling the inlet air, a cooling system is installed before the compressor.

Thermoflex software was used to simulate the air thermodynamic states from inlet to outlet, pressure and temperature for each state are calculated, and also the gas turbine Performance parameters are determined. The input data used in the study has been given in Table 2.

Table 2: technical parameters of selected gas turbine unit

Parameters	Value
Pressure ratio	11.53
Turbine inlet temperature, K	1297
Inlet pressure loss, kPa	0.98
Combustion chamber pressure loss, %	4
Fuel	CH_4
Fuel lower heating value, kJ/kg	50048
Exhaust gases volumetric flow rate, m^3/s	58

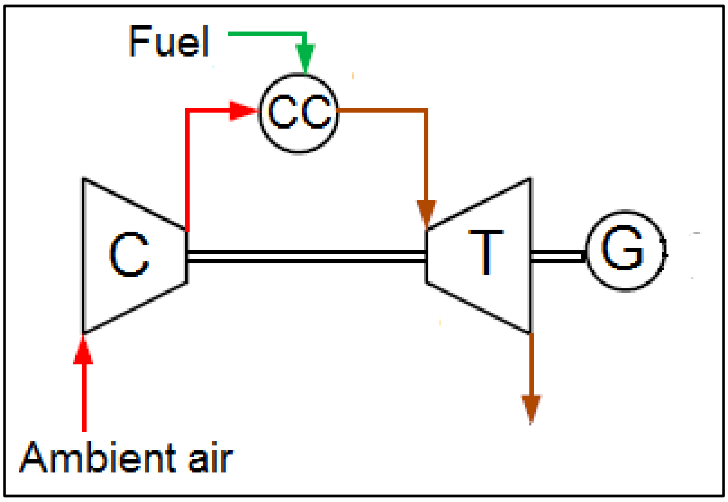

Figure 1 Schematic of the simple gas turbine cycle

a- Evaporative cooling system

The evaporative cooling is most appropriate for cooling air in hot dry regions, because it use the latent heat of vaporization to cool atmospheric temperature from the dry bulb to close the wet bulb temperature. This results in increasing mass flow rate and inlet air density. When the warm ambient inlet air comes in touch with the added spray of water, it transfers some of its heat to the liquid water and evaporates some of the water, which due to cools the inlet air. Evaporative systems have the lowest capital costs. Their primary disadvantage is that the range of cooling produced is limited by the wet bulb temperature, and in dry regions, the evaporative cooling consume large quantities of water, which included the major component of the system operating cost, two primary system of evaporative cooling types are commercially used wetted media and fogging. In this paper, we used the wetted media type Where Inlet air is exposed to a thin film of water on the extended surface of wetted media. The media may need to be replaced periodically every 4 to 8 years, depending on air quality, water quality and hours of operation.

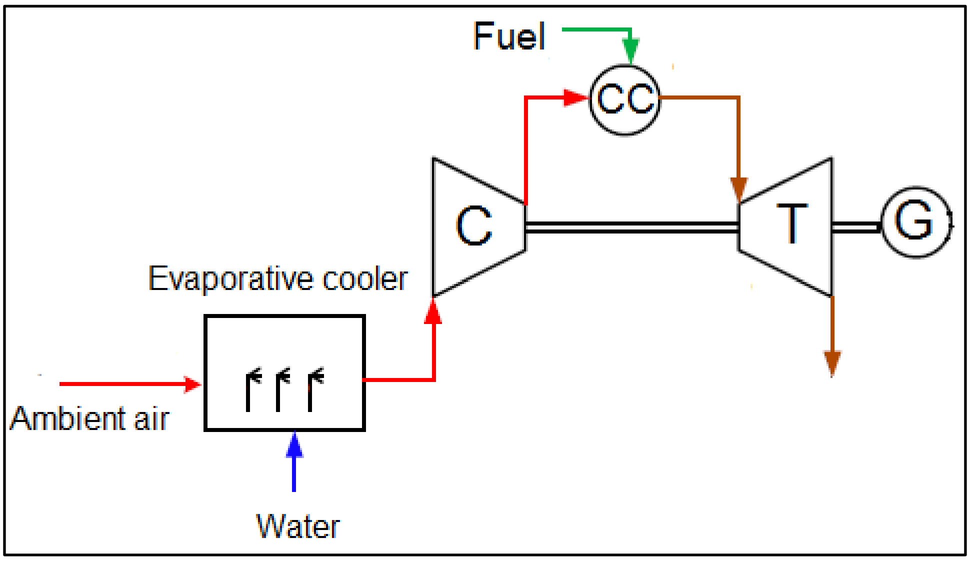

Figure 2 Schematic of the gas turbine cycle with evaporative inlet cooling

b- Absorption chillier system

The energy required to operate an absorption chiller is generally obtained by recovering heat from the turbine exhaust, and the cooled water is passed through a pipe of heat exchanger to decrease the air temperature. Absorption systems in gas turbine power plants can use a solution mixture of lithium bromide or ammonia and water.

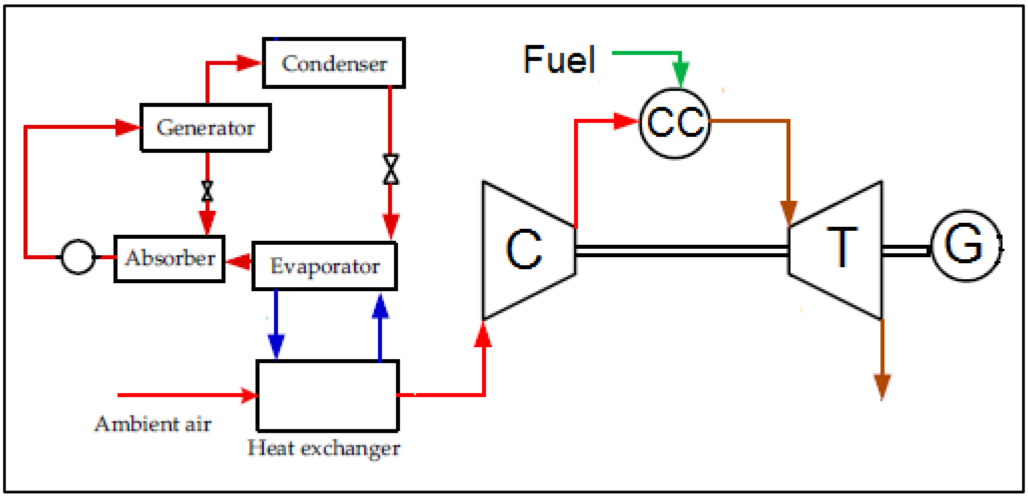

Figure 3 Schematic of the gas turbine cycle with absorption inlet cooling

4. Results

In the present study the power plant performance described by the power output, thermal efficiency, and heat rate, are evaluated. The results of the Thermoflex software were used to estimate both the performance of the Base-Case (without cooling intake air), inlet air cooling by evaporative cooling, and absorption chiller. Fig. 4 shows the net output power of the gas turbine with and without different inlet cooling systems. as showing the evaporative cooler provides great advantages when the air temperature is less than 300 K. At the temperature of standard conditions 288 K, the evaporative cooler system increases of power output is 3.65%, while at the hot temperature of 313 K the increased of power output is 8.75%. at using The absorption chiller the air passes over the cooling water pipes at the inlet air system, the air temperature decrease, And the absorption coolant at a low temperature of less than 290 K has a gas turbine output less than the base case, due to the consumption of a part of the power in operating the pumps of the absorption chiller system. While at a temperature of 313 K the power output increased by 13.58%. notice that when the air temperature is less than 300 K the power output of the gas turbine plant utilizing an evaporative cooler system is higher than the power output of the gas turbine with an absorption chiller system, and this is caused to that the compressor work is less with the evaporative cooler than with absorption chiller.

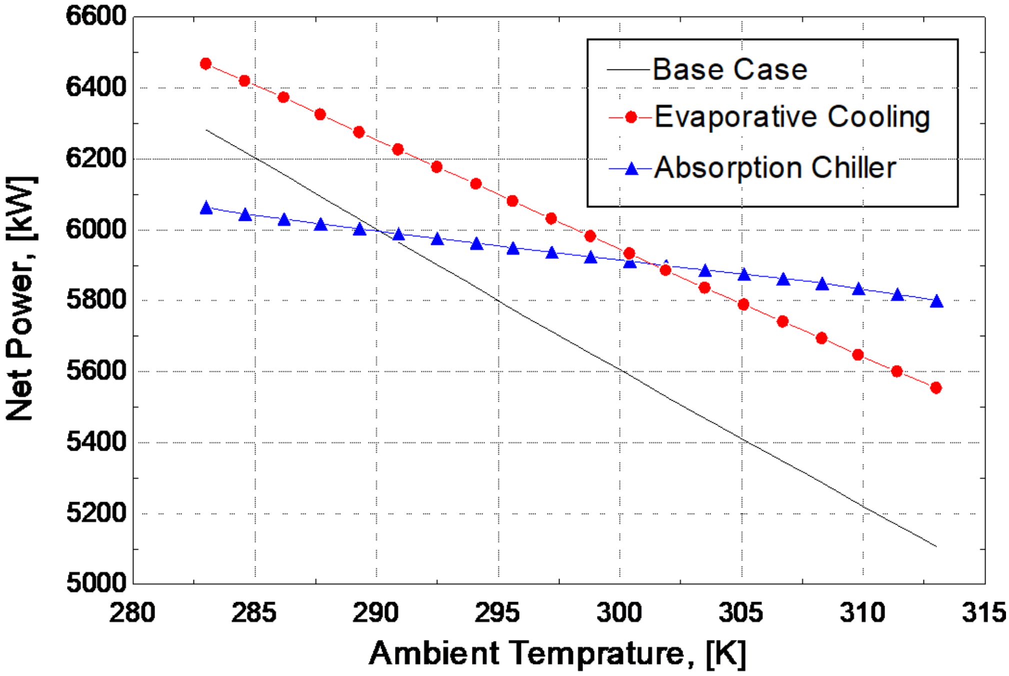

Figure 4 Effect of ambient temperature on the gas turbine power output

When the air ambient temperature rises the thermal efficiency of gas turbine decreased. Fig. 5 shows the thermal efficiency at different ambient temperatures for the three states (the base case, absorption chiller, and evaporative cooler). It is obviously that at standard conditions 288 K the evaporative cooler increase the thermal efficiency by 1.1 % , moreover, if the absorption chiller is used with the gas turbine, the thermal efficiency can be raised by 0.5 % at standard conditions, at a temperature of 313 K the thermal efficiency is increased by 2.6% and 3.5 % at utilizing evaporator and absorption respectively.

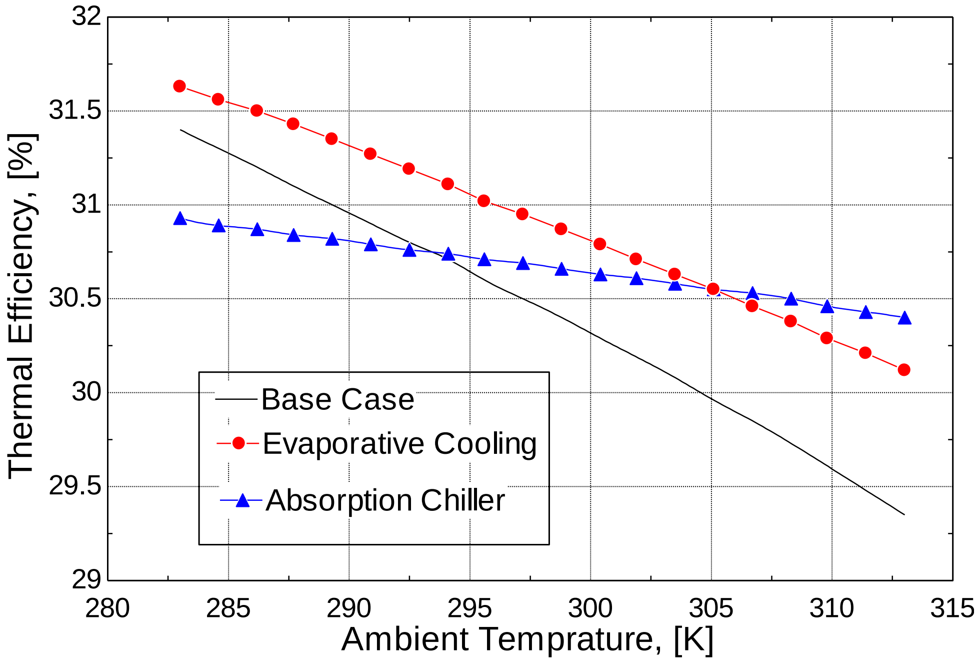

Figure 5 Effect of ambient temperature on the gas turbine thermal efficiency

Fig. 6 presents the gas turbine heat rate at different ambient temperatures for the base case, evaporative cooler, and absorption chiller. As shown in the lowest heat rate is achieved with the absorption chiller, where it's decreased by 3.4% at 313 K, while the highest heat rate occurs with the gas turbine base case, it increases as the ambient temperature increased. At 313 K, the evaporative cooler decreased the heat rate by 2.5%. The heat rate is one of the most important factors for the estimation of the performance and feasibility of gas turbine design, and it has a direct impact on the selection of the most appropriate turbine inlet cooling system.

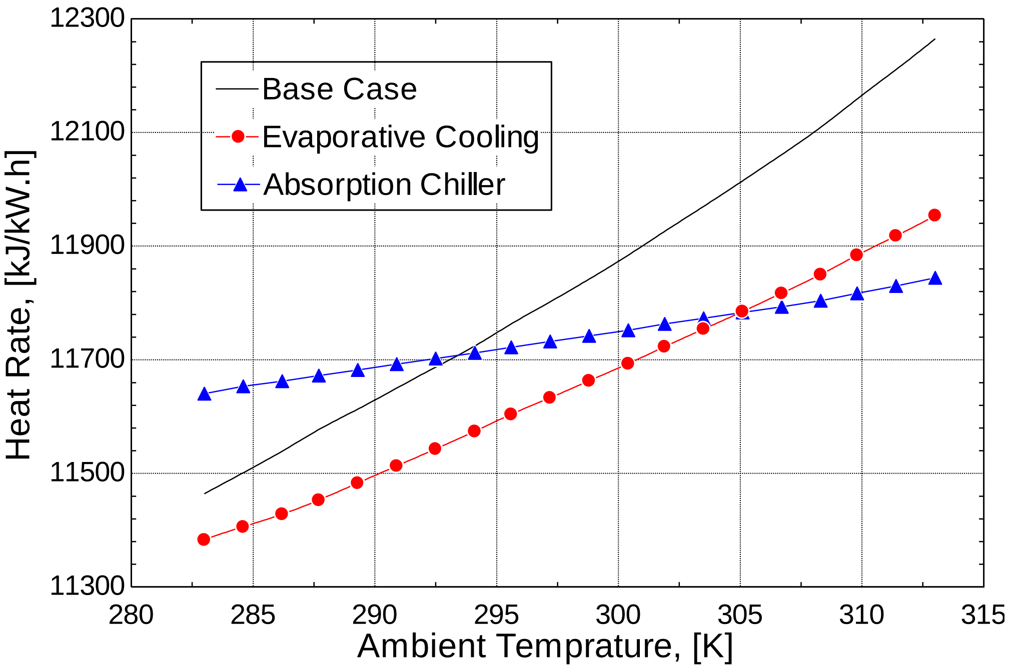

Figure 6 Effect of ambient temperature on the gas turbine heat rate

5. Economic Analysis

The feasibility of the inlet air cooling systems depends on their annual cost. where the total costs include operating costs and installation. Regarding operating cost, added annual profit AAP can be calculated from

$$AAP = S_a - C_a$$

Where

S_a is the added annual sale value of added energy

C_a is the added annual fuel and water costs.

The added annual sale value of added energy because of using inlet cooling systems can be calculated from

$$S_a = \Delta E \; Ta_e$$

The current tariff of electricity in Libya is Ta_e= 0.068 $/kWh [14]. The added annual cost because of using inlet cooling systems was estimated from

$$C_a = \Delta m_f \; LHV \; P_f + m_w P_w$$

where LHV is the low heating value of used natural gas, LHV = 44,472 kJ/kg and P_f is the price of natural gas fuel [15].

$$P_f = 6.426 \; \$/million.Btu$$

mw is the total water consumption and Pw is the water price (Pw = 0.31 USD/m^3) [16]. The evaporative and hybrid vapor-compression inlet cooling systems produced AAP of 9% 7.5% less than the average AAP, respectively. However, the two-stage evaporative hybrid absorption inlet cooling systems produced AAP of 3% and 6.5% higher than average AAP, respectively.

The initial invetment cost per added kilowatt C_i for evaporative and absorption system are 98 and 259 USD/kW respectively [11]

the total investment cost (USD) of inlet cooling systems was estimated from

$$C_{cap} = \; C_i \; P_{add}$$

Where P_{add} is the maximum monthly added power owed to inlet cooling, the payback period (PBP) was estimated from

$$PBP = C_{cap}/AAP$$

Table 2: Initial cost and payback period

SYSTEMS	P_{add}	C_i	C_{cap}	AAP	PBP
	kW	USD/kW	USD	USD/Year	Year
Evaporative	343	89	30527	13060.3	2.3
Absorption	322	259	83398	31947.8	2.6

6. Conclusion

absorption chiller and evaporative cooler systems were investigated for the SGT-200-a1 gas turbine under the weather conditions of Ubari city. Thermoflex software was used in this study to simulate the thermal performance of the gas turbine. This system can cool the inlet air below the wet-bulb temperature. The simulation data indicate that power output increases when the gas turbine utilizes evaporative cooler, and absorption chiller systems in hot conditions by 13.85% and 8.75%, respectively. The added annual profit of using the evaporative system is 59% lower than the absorption systems. The payback period of the evaporative system is 11.5% less the than the absorption systems.

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