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Techno-economic assessment of a solar powered absorption chiller coupled with shallow-geothermal ground loop

F. Altwijri[a,b,*], M. Aldubyan[c], A. Chiasson[a]

[a]Department of Mechanical and Aerospace Engineering, University of Dayton, Dayton, Ohio, 45469 USA
[b]Mechanical Engineering Department, College of Engineering, Qassim University, Qassim 52571, Saudi Arabia
[c]King Abdullah Petroleum Studies and Research Center (KAPSARC), Riyadh 11672, Saudi Arabia
** Author to whom correspondence should be addressed.*

Abstract

Almost 65% of the energy consumed by the building sector in the Kingdom of Saudi Arabia (KSA) goes to air conditioning systems [7]. This high electricity demand can be greatly reduced if a clean energy resource is adopted. This study suggests that replacing conventional components of vapor compression chillers in commercial HVAC systems with renewable resources is technically applicable, economically viable, and environmentally sustainable. It presents a thermo-economic assessment of a solar-driven absorption chiller coupled with geothermal loop simulated for Saudi Arabian weather condition. In this system, solar thermal collectors along with a thermal energy storage tank are used to provide sufficient heat input for the absorption chiller over the course of the day while the geothermal loop operates in the system as a heat sink. The solar collectors and geothermal loop replace furnaces and cooling towers, respectively, in absorption chillers. A computer-based software was employed to simulate the 20-year thermal behavior of the suggested system. The model shows that a 3.5-ton absorption chiller coupled with a 23m^2 evacuated tube thermal collector and 23 boreholes is able to meet the cooling load of a small-size commercial building located in Riyadh, Saudi Arabia. This system can reduce the annual electricity consumption of the building by up to 51% and reduce the annual CO2 emissions by 9.2 metric tons. Despite its technical viability and environmental benefits, the economic analysis shows that the solar-driven absorption chiller coupled with geothermal loop is not economically feasible due to the high initial cost of the drilling. However, when a conventional cooling tower is used instead of the geothermal loop, a payback period of 10.5 years can be achieved.

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* Corresponding author. E-mail address: faisaltwijri@gmail.com (F. Altwijri)

1. Introduction

The rapid increase in energy consumption around the world has become the ultimate concern for many countries, triggered by concerns about the reliability and environmental impact of currently used energy resources. As a result, beginning in the 1980s, people started looking for sustainable and clean resources for tomorrow's energy [1]. Renewable energy resources are arguably an appropriate replacement for fossil fuels in that they are sustainable, clean, and, in many cases, economically attractive.

Despite being an oil-rich country, Saudi Arabia is suffering from the recent dramatic growth in electricity demand, especially in the building sector, which in 2017 only consumed around 77% of the total annual energy generated in Saudi Arabia [2]. The extremely hot weather conditions in the majority of Saudi regions have a significant impact on electricity consumption and peak demand, especially in the summer(Figure 1) [2][3].

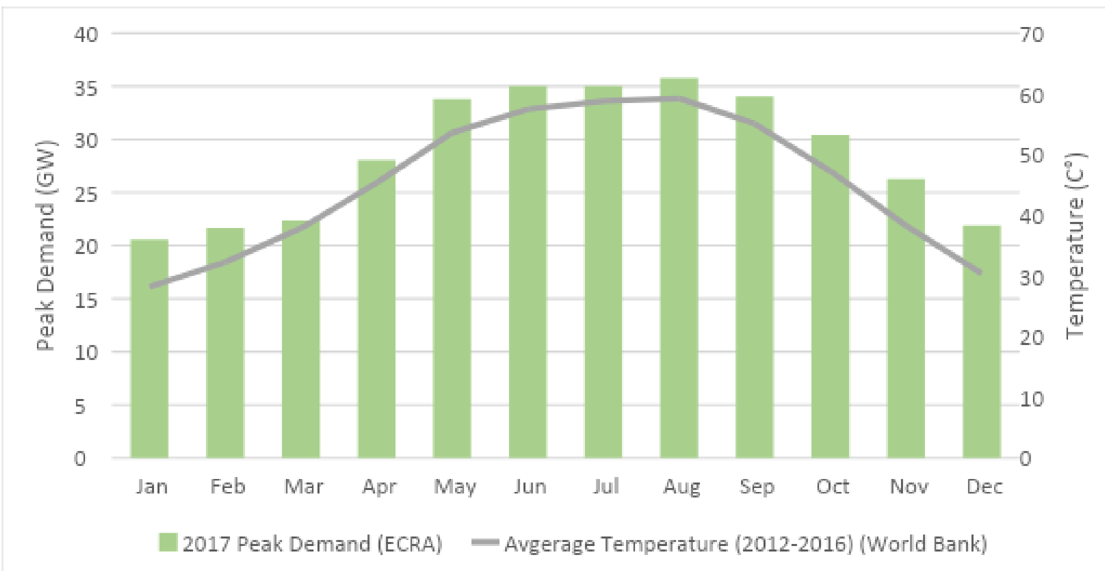

Figure 1. Monthly Saudi Arabia peak electricity demand associated with average ambient temperature

Among the various HVAC technologies used for space cooling, vapor-compression HVAC systems are widely used in both residential and commercial buildings in Saudi Arabia. These heavily contribute to total electricity consumption and generation capacity. Absorption chillers, which use a heat input delivered to a thermal generator as a replacement for the mechanical compressor in vapor-compression systems, can also be used [4][5]. This development in the refrigerating cycle allows renewable energy resources, e.g. solar thermal energy, to replace conventional energy resources, e.g. electricity or natural gas, as the energy resource to the generator. As a result, reductions in both electricity consumption and CO_2 emissions can be achieved. Thus, replacing conventional HVAC systems with renewable energy-driven systems can be economically and environmentally attractive at both the stakeholder and national level.

Solar-thermal energy is highly suitable for use in cooling systems since peak cooling demand coincides with peak solar radiation, avoiding the problems inherent in other solar-thermal or electrical systems, where the energy time-of-use and storage become problematic. In different solar-thermal and/or electrical systems, the peak demand does not match the peak energy yield either over the course of the day or even over the course of the year, making these systems technically challenging and economically less attractive. In Saudi Arabia, where the average daily normal irradiance (DNI) reaches 7.3 kWh/m^2 [6], utilizing the harmony between energy needs and energy availability incentivizes adopting solar energy for cooling applications to reduce electricity consumption and mitigate CO_2 emissions.

One crucial aspect of cooling processes is heat rejection. In typical absorption chiller systems, cooling towers are used to reject the heat collected from the conditioned space to the atmosphere. These cooling towers use the evaporation of water to remove heat from working fluid to reach the wet bulb temperature of the air. Due to the relatively low and semi-stable temperature of the shallow geothermal layers when compared to the temperature of the working fluid leaving the absorption chillers, replacing cooling towers with shallow ground loop can be technically applicable.

2. Literature Review

To the best of the authors' knowledge, there is no published study investigating the viability of coupling a solar-assisted absorption chiller with a ground loop in Saudi Arabia. Indeed, only a small number of studies have been conducted on the viability of replacing conventional cooling systems with solar driven ones in the Middle East and North Africa (MENA) region. In one such study, Al-Ugla et al. [7] conducted a techno-economic study to compare three air conditioning systems (conventional vapor compression, solar LiBr-H_2O absorption, and solar photovoltaic vapor-compression) using two economic indicators (payback period, and net present Value) in a commercial building in Khobar city, Eastern Region of Saudi Arabia. They found that a solar absorption system is more economically attractive than a solar PV-vapor compression system. Al-Alili et al [4] present a modeling of a solar-driven absorption cycle under Abu Dhabi weather conditions. Evacuated Tube Collectors (ETC) were used as a heat input for a relatively small ammonia-water absorption chiller. Their results show that an up to 53% reduction in electricity consumption can be achieved using a solar-driven absorption chiller instead of a vapor compression cycle. They also found that collector area is the key to minimizing the payback period. Moreover, the proposed system in their study succeeded in reducing CO_2 emissions by 12 metric tons/year. Al-Ugla et al. [8] investigated three alternative designs for a 24-hour operating solar-driven LiBr-Water absorption air conditioning system, heat storage, cold storage, and refrigerant storage. The system was modeled based on the weather data of Dhahran, Saudi Arabia. They found that even though a continuously operating absorption cooling system with heat storage has the highest Coefficient of Performance (COP) value, a system with refrigerant storage is more beneficial and suitable for continuous operation due to its smaller collector area, smaller storage capacity, and simplicity of design. Assilzadeh et al. [9] conducted simulation and optimization of a LiBr-H_2O solar absorption cooling system connected to ETC. They suggest that to achieve non-stop operation and improve a system's reliability, a hot water storage tank is essential. In their research, Balghouthi et al. [10] assess the feasibility of using a solar-powered absorption chiller under Tunisian climate conditions. In this study, an 11 kW-absorption chiller received heat from a 30 m^2 flat plate collector and 800 L thermal storage tank. They found that absorption solar air conditioning systems are suitable for Tunisian weather conditions despite their high initial cost. Rosiek, and Batlles [5] analyzed existing solar-assisted air conditioning systems installed in the Solar Energy Research Center (CIESOL) in Spain. This study shows how matching of active and passive solar techniques can result in making buildings more efficient. A 160 m^2 flat plate collector was able to deliver the vast majority of heating and cooling demand with minimal auxiliary heating contribution. This study also shows the importance of integrating a hot water storage tank into the system as it not only helps in the clod's alternation when the solar hot water is too low to cover the absorption machine demand but also helps in the starter moments in the morning when the solar radiation is low. An average COP of 0.6 was obtained in summer. L.A. Chidambaram et al [11] conducted an extensive review of approaches related to better integrating solar energy in cooling systems. They also conclude that thermal storage is critical for getting the greatest number of benefits from solar energy resources and controlling differences between the cooling/heating demand and solar radiation availability.

Elsafty & Al-Daini [12] conducted an economical comparison between single and double effect solar-driven absorption chillers and vapor compression air conditioning systems in the Middle East. Their analysis is based on two different economic measures, the present worth value and the equivalent annual cost, for the initial and operating costs of each system. The results of this study show that the total cost of the double-effect solar absorption system was 45% less than that of the single-effect system and 30% less than the vapor compression system using a present worth comparison. Thus, they recommend the double-effect solar air-conditioning system in cooling applications, especially in hot climate conditions. Shirazi et al. [13] employed a transient simulation in order to assess the feasibility of single, double, and triple effect absorption chillers in combination with a variety of solar thermal collectors. Their results reveal that a double-effect absorption cycle coupled with evacuated flat plate collectors present the best trade-off between the energy efficiency and costs for a wide climatic range.

Eicker et al [14] studied different options of heat rejection for a solar absorption system. Dynamic simulation models were used for a solar single effect absorption system. The studied heat rejection options were wet cooling towers, dry cooling towers, and geothermal loop. The geothermal heat rejection was found to save 30% of the electricity consumed by the best case, with wet cooling towers and frequency control of all components. Aldubyan and Chiasson [15] studied the impact of integrating a Photovoltaic-Thermal (PVT) array and Ground-Coupled Heat Pump (GCHP) to a single ground loop system in hot and cold climates. They conclude that the impact of heat added by the PVT on the GCHP can be ignored and the ground loop is able to meet the cooling and heating demand in both climates.

3. Methodology

This study examines the techno-economic viability of a novel solar-driven absorption chiller coupled to a geothermal loop system under the weather conditions of Riyadh, Saudi Arabia. The system is simulated using the Transient Energy System Simulation Program (TRNSYS) in hourly time-step over a 20-year period and was sized to meet a typical small-size commercial building's cooling demand with maximum cooling load of 3.5 tons. The solar thermal collector along with the thermal energy storage tank (TST) were designed to provide sufficient heat input for the absorption chiller while the geothermal loop was designed to act as a heat sink, replacing the cooling towers in conventional absorption chiller systems. Multiple runs were conducted to choose parameters that help the system satisfy the cooling demand in an economical way. Figure 2 provides the layout of the proposed system, which includes an ETC, TST, auxiliary heater, absorption chiller, and geothermal loop (heat sink). In addition, some controllers were also employed to control the water flow between the different components. In this section, each component will be described along with its identifying characteristics, all of which is summarized in Table 1.

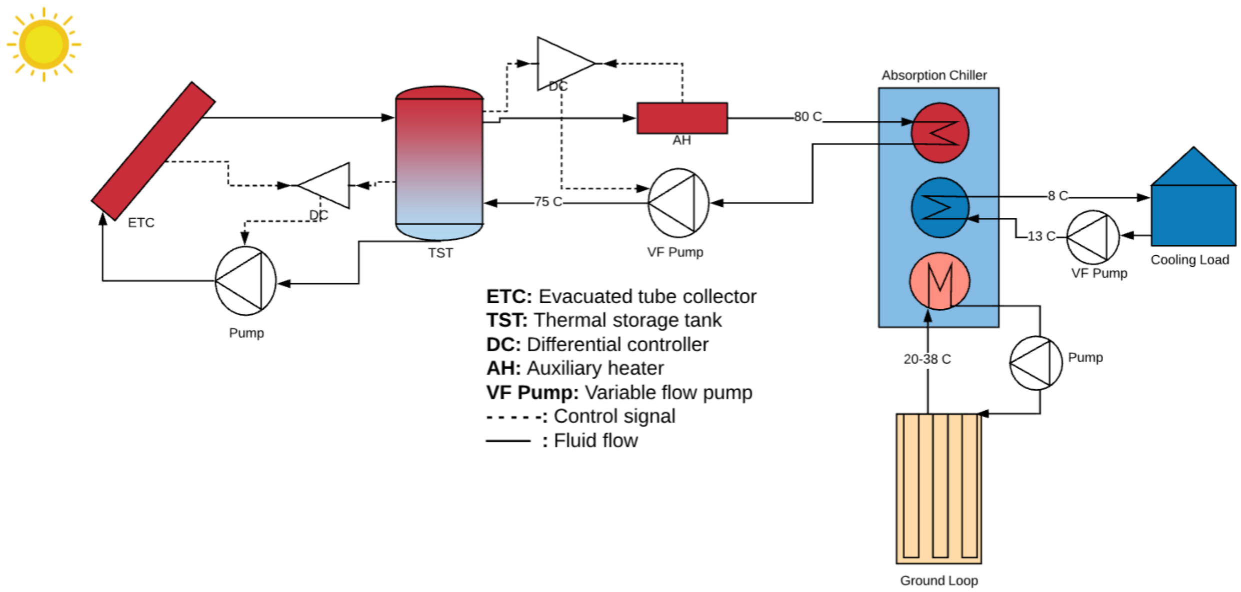

Figure 2. General Schematic of the Solar-Driven Absorption System

The ETC is used to simulate the solar energy absorbed and delivered to the system. It is believed to be the optimum option for delivering heat in the range of 60 – 200°C [16]. To continue providing a sufficient amount of heat to the absorption chiller during the night or low solar radiation times, a component of a vertical cylinder TST is modeled. This component helps improve the system's efficiency and increase its solar fraction. To overcome solar intermittency and ensure that sufficient heat is delivered to the chiller, an electrical auxiliary heater is modeled. It elevates the temperature of the flow stream when it falls below 80°C, which is the minimum input temperature required by the absorption chiller [17]. Because the underground temperature over the course of the year is semi-stable, a vertical ground-loop is simulated to replace cooling towers, which are widely used in conventional cooling systems. It absorbs the heat from the condenser and releases it into the ground.

Table 1: System Components' Data

Parameter	Value
Solar collector specifications	
No. of collectors	23

Aperture area (m^2/collector)	1.085
Efficiency (%)	60.1
Working fluid	Water
Specific heat (Joule/gram.ºC)	4.186
Thermal storage tank specifications	
Tank volume (m^3)	1
Tank height (m)	1
Heat exchanger type	Coiled Tube
Tube inner diameter (m)	0.01
Tube outer diameter (m)	0.015
Wall conductivity (kJ/hr-m-ºC)	900
Tube length (m)	65
Cross section area (m^2)	2
Coil diameter (m)	0.6
Coil pitch (m)	0.05
Absorption chiller specifications	
Cooling capacity (kW - Ton)	12 – 3.5
Generator inlet water temperature (ºC)	80
Generator outlet water temperature (ºC)	80
Generator water flow rate (kg/s)	2.8
Chilled water output temperature (ºC)	8
Chilled water input temperature (ºC)	13
Chilled water flow rate (kg/s)	6.776
Cooling water output temperature (ºC)	31
Cooling water input temperature (ºC)	36
Cooling water flow rate (kg/s)	14.7
Geothermal loop specifications	
Number of boreholes	23
Borehole depth (m)	50
Borehole spacing (m)	5.744
Storage volume (m^3)	81,674
Thermal conductivity of ground (W/m.ºC)	4.68
Tube type	U tube

A single-effect LiBr-H2O absorption chiller is the component by which we measure the system's Coefficient of Performance (COP), assessing the thermal performance of the solar and geothermal components in providing sufficient heat to the absorption chiller and absorbing heat from the conditioned space, respectively. Economically, payback period (PBP) and internal rate of return (IRR) are the economic indicators for assessing the systems' viability over a period of 20 years. Table 2 lists assumptions considered in the economic comparison of the conventional vapor compression and solar- driven chillers.

Table 2: Economic Assumptions

Parameter	Solar absorption chiller	Vapor compression chiller
Chiller life cycle (years)	20 [18]	12 [18]
COP	-	2.5
Maintenance cost [14]	0.1% of initial investment	4% of initial investment
Solar collector cost ($/m^2)	650 [19]	-
Energy storage ($/m^3)	1000 [21]	-
Chiller cost ($/Ton)	1820 [7]	1400 [7]
Heat rejection equipment cost	$25/m	$200/ton
Electricity cost	$0.08/kWh	$0.08/kWh
Annual CT fan energy cost	-	$395/ton

3. Results and Discussion

This section presents the technical, economic, and environmental performance of the proposed system. July 1st and January 4th were chosen to be representative days to illustrate the daily performances in summer and winter, respectively.

3.1 Technical Performance

A 25 m^2 ETC-array with 0.437 kg/s water flow rate was found to be able to supply a sufficient amount of heat to the system when the demand is at the highest. In summer, the maximum temperature of the output water from the collector is 130^{o}C while in winter it goes up to 140^{o}C, as shown in Figures 3 and 4. The relatively small cooling load in winter keeps the water temperature in the TST high. Consequently, the temperature of the water input to the ETC-array, when circulated, is high too. This makes the maximum temperature of the output water from the collector in winter higher than what it can reach in summer. The simulation shows that the efficiency of the solar collectors reaches 60% with neglected degradation throughout the 20-year simulation period. The ETC-array output temperature is able to keep water inside the TST at a sufficient temperature level which leads to an increase in the solar fraction of the system. The higher the outlet fluid temperature from the TST, the lower the auxiliary heater electrical consumption

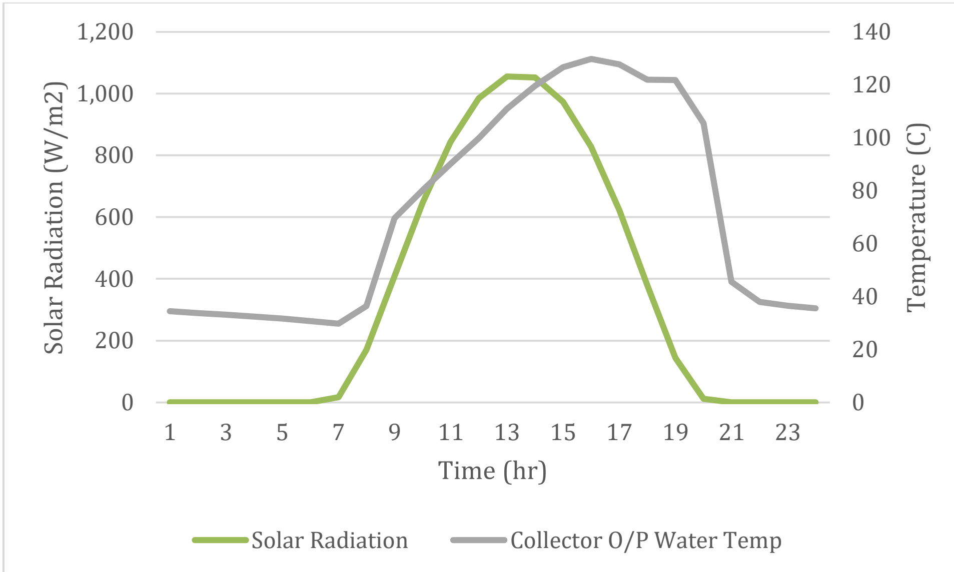

Figure 3: Solar Radiation Vs. Collector O/P Temp in summer

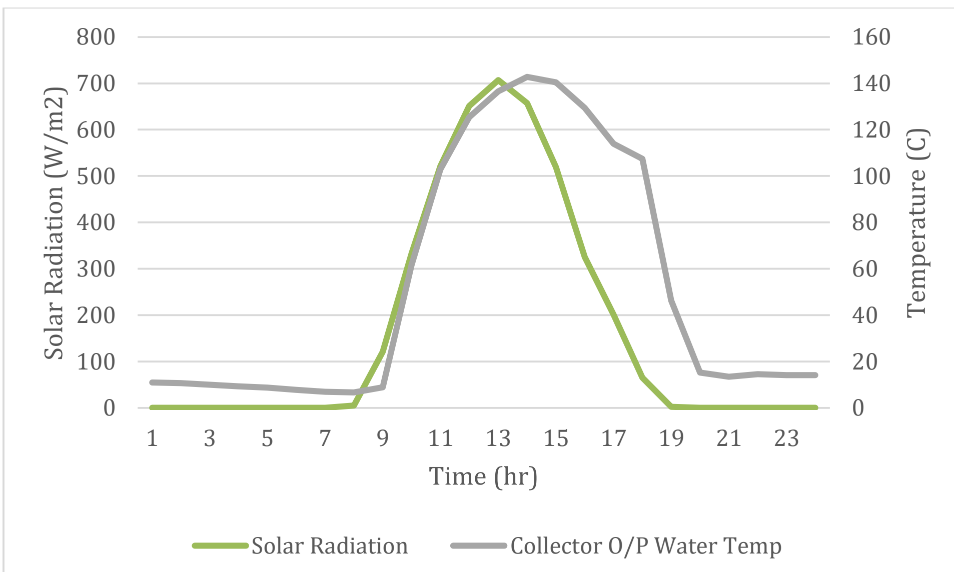

Figure 4: Solar Radiation Vs. Collector O/P Temp in winter

To ensure providing water at a minimum of 80°C to the absorption chiller, a 5 kW auxiliary electric heater was integrated between the TST and absorption chiller. This component adds a stream of heat (Qmax) to the water whenever there is cooing demand and the TST output water temperature (Tout) is less than 80°C (Tset).

Figures 5 and 6 show the auxiliary heater behavior on the two designated days (one in summer and one in winter). They reveal that whenever the TST output temperature fell below Tset, the auxiliary heater started providing heat. In summer, the results show that even though there was a high cooling demand all day, the TST was able to deliver the needed amount of heat during peak demand. The combination of the ETC and the TST helps the proposed system not to rely heavily on the auxiliary heater, especially in summer. This should have an impact on both amount of electricity consumed and peak electricity capacity in the region especially if such a clean technology was widely employed. In winter, figure 6 shows that the maximum output water temperature does not exceed 108^{o}C, which is lower than the temperature reached in summer. This might seem unrealistic because the maximum output water temperature from the solar collector in winter is higher than the temperature of the same flow in summer as shown in figures 3 and 4. However, TST produces a lower water temperature in winter because of the high heat loss from the TST, through the wall, due to the low ambient temperature. During the first year, the auxiliary heater consumed approximately 3,600 kWh, which is relatively low.

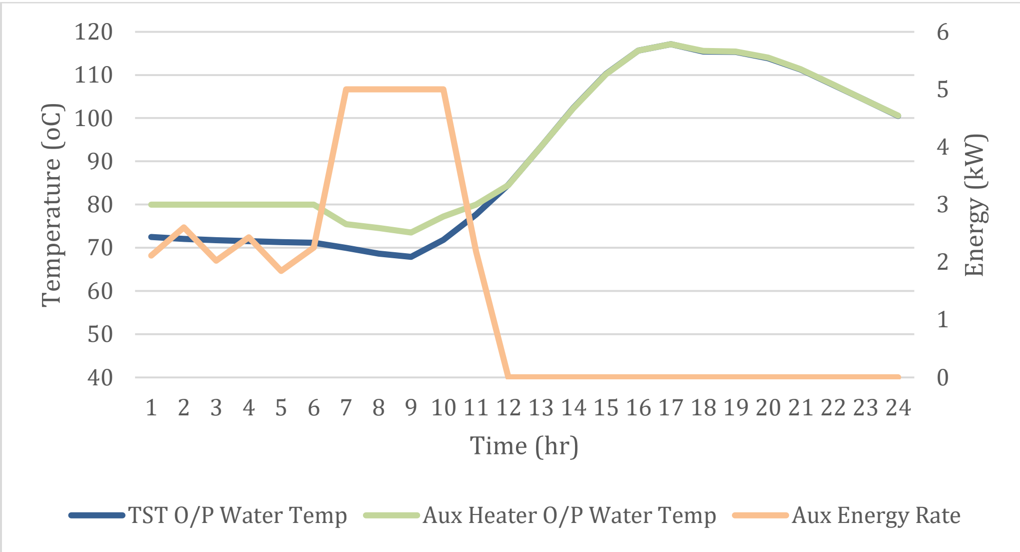

Figure 5. I/P Water Temp and Aux Energy Rate in summer

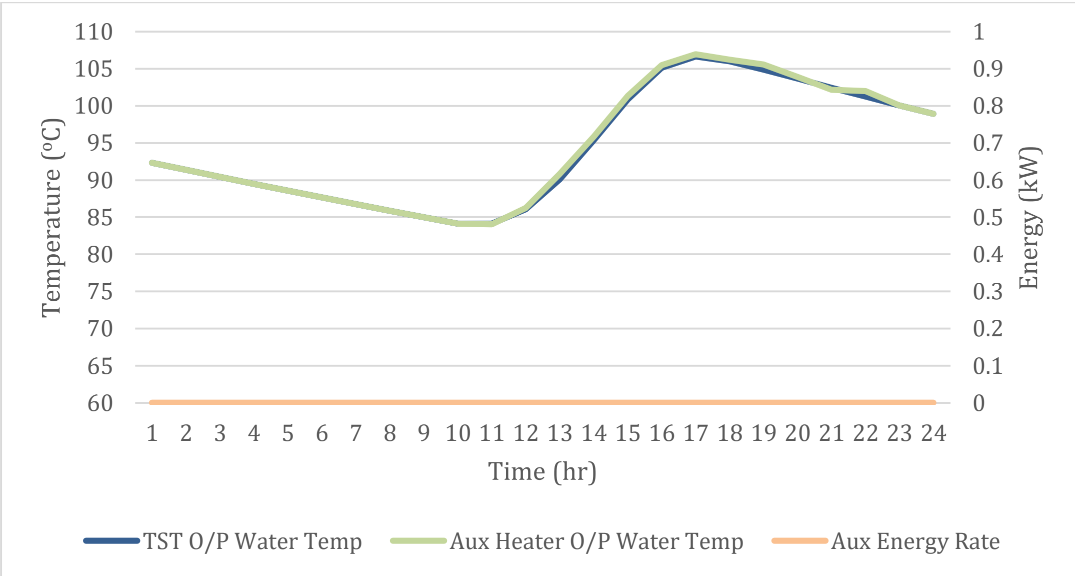

Figure 6. I/P Water Temp and Aux Energy Rate in winter

As mentioned in the previous section, the LiBr-H2O absorption chiller is a single-effect unit with a nominal cooling capacity of 12 kWc. Figure 7 shows the cooling load in comparison with the thermal energy supplied to the generator. The difference between these two loads forms the COP of the chiller, which on a typical summer day was around 0.75.

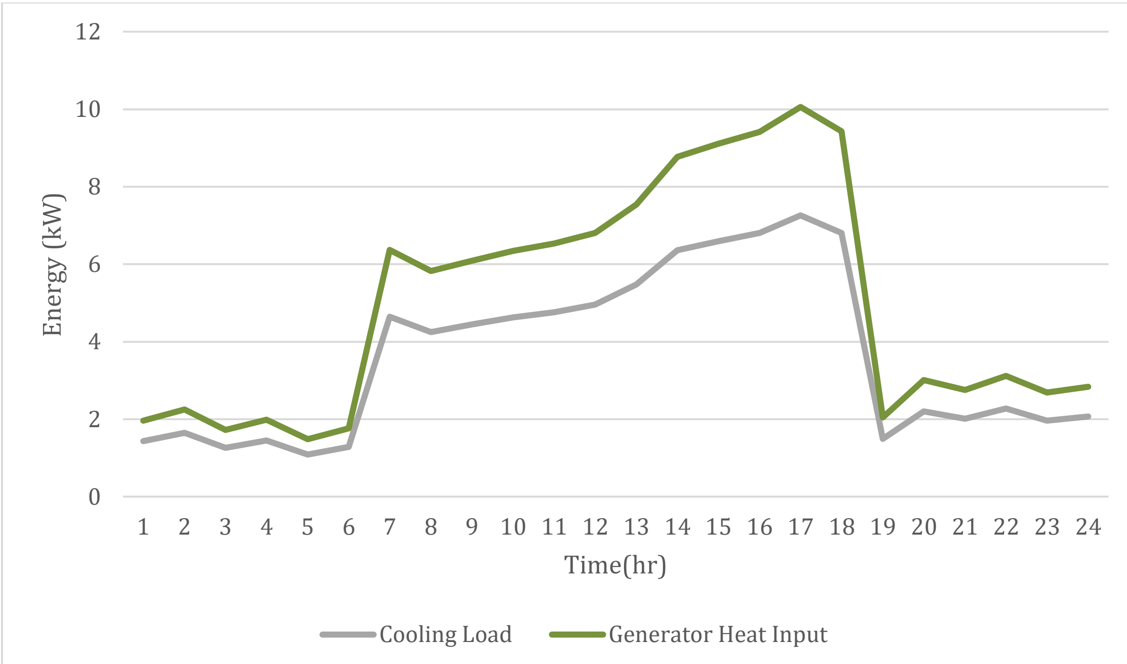

Figure 7: Cooling Load Vs. Thermal Energy Input to the System (Summer)

In terms of heat rejection, the simulated 23 vertical boreholes show the ability to absorb the heat collected from the cooled space by the absorption chiller over the 20 years. During the peak cooling demand in the 20th year, the temperature of the BTES output water temperature reached 39.3ºC and the average ground temperature reached 30ºC. Even though the underground is capable of absorbing the heat from the cooled space until the 20th year, its temperature, and hence the outlet fluid temperature, shows a gradual increase throughout the project's lifespan due to the continuous heat rejection. Thus, the system's performance is more likely not to be as efficient and viable as in the first 20 years.

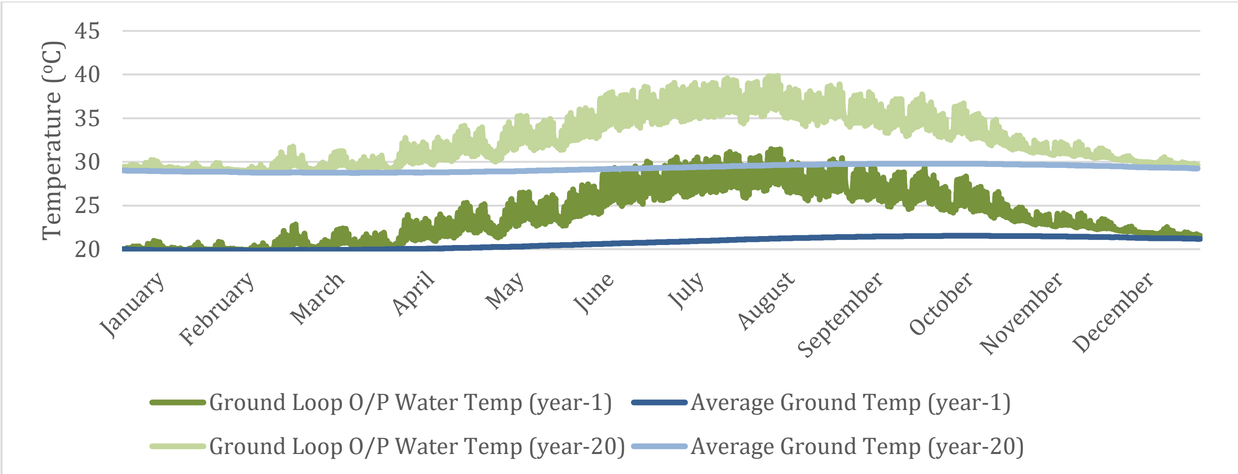

Figure 8: Ground Loop O/P water temperature and average ground temperature

3.2 Economic Performance

Even though solar cooling systems, in general, have a high initial cost, their operational cost can be competitive with conventional systems in many ways. In comparison, the initial cost of VC cooling systems is relatively low, yet their operational expenses are considerably high. As illustrated in Table 4, the initial cost of the solar driven absorption system coupled with BTES is 93% higher than the initial cost of the VC system. It should be noted that this extreme difference in capital costs is not common; in the literature, the cost variation is found to be no more than 70% [7]. It is clear from Table 4 that the initial cost of BTES, which comprises of 72% of the system's capital cost, is what contributes to the massive difference in the total costs of the two systems. Despite its high initial cost, the operational cost of the proposed system was found to be 46% lower. This lower operational cost is associated mostly with the savings, 12,300 kWh/year, in annual electricity consumption of the proposed system when compared to the annual electrical consumption of 3.5 ton VC chiller, 25,000 kWh/year. A 20-year cash flow for both systems (Figure 9) shows that the solar-driven system with BTES has a payback period of 23 years. However, when considering using a cooling tower as the heat rejection component in the solar driven absorption chiller instead of BTES, the initial cost would drop from $51,070.00 to $23,020.00 and the payback period would be reduced to 10.5 years with 8% IRR.

Table 4. Comparison of Initial & Operating Costs

Solar driven absorption chiller with BTES	**VC chiller**
Initial Cost	Initial Cost

Solar Collector	$14,950.00	VC Chiller	$4,900.00
Thermal Storage Tank	$1,000.00	Heat Rejection	$700.00
Absorption Chiller	$6,370.00		
Geothermal Ground Loop	$28,750.00		
Total	**$51,070.00**	**Total**	**$5,600.00**
1st Year Operating Cost		Ann. Operating Cost	
Ann. Energy (12,690 kWh/yr)	$1,015.00	Ann. Energy (25,000 kWh/yr)	$2,000.00
Maintenance	$51.00	Cooling Tower Fan Energy	$474.00
		Maintenance	$224.00
Total	**$1,066.00**	**Total**	**$2,698.00**

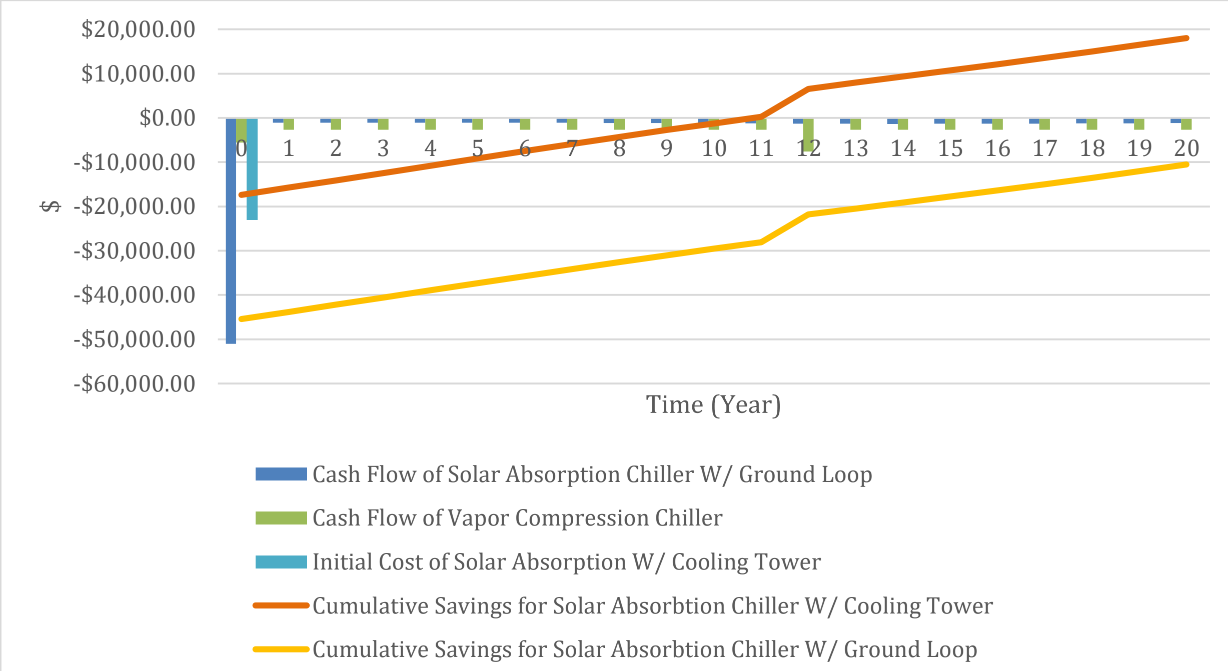

Figure 9: 20-year cash flow and cumulative for various systems.

3.2 Environmental Assessment

Saudi Arabia is ranked the 8th highest CO_2 emitter worldwide [22]. Adopting the technology presented in this study in commercial buildings could mitigate CO_2 emissions by allowing for reduction in the burning of crude oil, the main energy source for electricity generation in Saudi Arabia. Based on our analysis, the amount of CO_2 emissions that might be avoided by replacing conventional VC with a renewable driven absorption chiller for a similar cooling load could reach 9.2 metric tons [23].

Future research should consider working on how to make BTES more efficient and less expensive. One way to improve the efficiency of the ground loop would be to use the solar collector, ETCs, for nocturnal radiation cooling of the BTES. This would help in reducing the size of the ground loop by a considerable amount. Chiasson et al. [24] succeeded in reducing the borehole field size by 75% when using unglazed solar collectors operating at night and during winter.

4. Conclusion

This research project investigated the viability of using a solar-driven absorption chiller coupled to BTES instead of a conventional VC cooling system under the weather conditions of the capital city of Saudi Arabia, Riyadh. The system was designed to meet the typical cooling load of a medium-sized commercial building; it was simulated using TRNSYS. The proposed system consists of 3.5 Ton solar-driven absorption chiller, which receives its heat energy from a 23 m^2 evacuated tube solar collector. The chiller is coupled with 23 boreholes to reject heat extracted from the building. To overcome fluctuations in solar energy availability, a 1 m^3 thermal storage tank and 5 kW auxiliary heater were integrated into the system. The simulation results show that the designated system, as a replacement for a VC cooling system, is technically achievable under Saudi Arabian conditions but not economically applicable due to the extremely high initial cost of the ground loop system. The proposed system demonstrates a strong positive environmental impact reducing the annual electricity consumed by approximately 49%, which is equivalent to 5 metric tons of CO_2. However, the initial cost of the proposed system would fall by 55% if the ground loop, as a heat sink, was replaced with a cooling tower. This would also shorten the payback period from 23 years to 10.5 years. This study makes it clear that solar cooling technologies can be economically viable and environmentally beneficial, making them a good investment in regions with intense solar radiation.

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