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Potential Study of Solar Thermal Cooling in Sub-Mediterranean Climate

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Abstract: Air conditioning is becoming increasingly important in the energy supply of buildings worldwide. There has been a dramatic increase in energy requirements for cooling buildings in the Middle East and North Africa (MENA) region. This is before taking the effects of climate change into account, which will also entail a sharp increase in cooling requirements. This paper presents the potential of using a solar thermal absorption cooling system in Sub-Mediterranean Climate. Four sites in Jordan are now equipped with water-lithium bromide (H_2O-LiBr) absorption chillers with a total nominal capacity of 530 kW. The focus of the paper was on the pilot system at the German Jordanian University (GJU) campus with a cooling capacity of 160 kW. The system was designed and integrated in order to support two existing conventional compression chillers with a nominal cooling capacity of 700 kW. The system was economically evaluated based on the observed cooling capacity results with a Coefficient of Performance (COP) equals 0.32, and compared with the values observed for a COP of 0.79 which is claimed by the manufacturer. Several techniques were implemented to evaluate the overall economic viability in-depth such as present worth value, internal rate of return, payback period, and levelized cost of electricity. The aforementioned economic studies showed that the absorption cooling system is deemed not feasible for the observed COP of 0.32 over a lifespan of 25 years. The net present value was equal to −137,684 JD and a payback period of 44 years which exceeds the expected lifespan of the project. Even for an optimal operation of COP = 0.79, the discounted payback period was equal to 23 years and the Levelized Cost of Electricity (LCOE) was equal to 0.65 JD/kWh. The survey shows that there are several weaknesses for applying solar thermal cooling in developing countries such as the high cost of these systems and, more significantly, the lack of experience for such systems.

Keywords: thermally driven refrigeration; absorption chillers; solar collectors; solar air conditioning; feasibility study; present worth value; payback period

1. Introduction

The increasing desire for air conditioning is mainly due to the demanding modern codes and standards on ventilation and indoor air quality [1,2], according to modern glass buildings in hot dry areas without considering of the climate and character of the country [3].

In countries with a generally high need for air conditioning, considerable load peaks (summer peaks) occur in the public power grid, especially on hot summer days [4]. Complete blackouts in network supply have already occurred [4]. The energy supply companies must respond to the growing need for air conditioning and cooling by expanding investment-intensive peak load power plants.

A relief strategy for the power grids is observed in the substitution of the conventional electrically driven compression refrigeration system with thermally driven processes. In particular, the solar drive heat is an attractive technology solution due to the coincidence between cooling requirements and solar radiation. The extensive simultaneousness (seasonal and over the day) between solar supply and occurring cooling load in buildings suggests the use of solar energy to provide the required drive heat. The highest cooling loads occur at those hours when high radiation power is available (e.g., office building), which could be attributed to either the user profile or the cooling loads which are strongly linked to the radiation on the building envelope. [5,6].

The solar thermal air conditioning processes do not use environmentally harmful refrigerants [7]. Traditional refrigeration and air conditioning systems mainly use refrigerants that have a high potential for global warming [8]. Developments in the direction of natural refrigerants (propane, CO_2) offer alternatives, but these are not yet very widespread in current refrigeration or air conditioning systems. Therefore, by switching to thermal cooling processes, harmful substances are reduced.

The systems of »solar thermal cooling« primarily use solar energy as a thermal drive source for cooling. In well-designed and working systems for solar thermal cooling, primary energy savings can be achieved compared to conventional systems. This corresponds to a reduction in CO_2 emissions in accordance with the annual Heating, Ventilation and Air Conditioning (HVAC) electricity energy savings [9]. The use of electrical auxiliary energy is mainly consumed by driving pumps and fans of the solar thermal cooling system.

There are a variety of ways to convert solar energy into useful cooling or conditioned air (cooling and dehumidification). The combination of photovoltaics with compression cooling also offers these advantages. If only looking at the cooling side, photovoltaics in combination with compression cooling could be competitive in the future. However, the great ecological advantage of solar thermal cooling systems does not lie in the cooling side, but in the multiple uses of the solar systems for water heating and heating support, which could achieve the majority of the CO_2 savings [10].

Many studies have been accomplished related to thermal driven solar cooling and air conditioning. Solar thermal cooling can be mainly classified as open and closed cycles. In open cycles, operated at atmospheric pressure, the latent load (dehumidification) is handled using solid or liquid desiccants. The water vapour in the air is considered as a sorbate while the solid or liquid desiccant is considered as adsorbent or absorbent, respectively. Open processes consist of a combination of sorption dehumidification and evaporative cooling, whereby a wide variety of interconnections are possible and different sorbents are used. The most common method uses sorption rotors for dehumidification. Up to now, the rotor materials used have only been either silica gel or lithium chloride, which is incorporated into a cellulose matrix. Several studies were performed for desiccant evaporative cooling systems (DEC) applying liquid desiccants such as [11,12] and applying desiccant wheels such as in [13,14].

Closed processes are represented by adsorption and absorption chillers. Adsorption refrigeration systems use a solid to adsorb the refrigerant. Devices on the market use mainly silica gel as the adsorbent and water as the refrigerant [15]. The COP values of the systems are in the range of 0.65 and heat from approximately 60 °C can be used to provide cooling at correspondingly low re-cooling temperatures, [16]. The COP of adsorption chiller of 0.65 is obtainable only for high desorption temperatures, high cooled water temperatures, and low cooling temperatures. For the heating temperatures as low as 60 °C, it is drastically lower (down to 0.17–0.34) [17]. These systems have some special features due to the periodic adsorption and desorption of the sorbents. As a rule, two adsorbers are operated alternately, so that one adsorber is always available for the provision of cold. This periodic operation leads to fluctuating temperatures at all temperature levels, a constraint that must be taken into account when planning the system [18].

The main absorption chiller systems are the water-lithium bromide (H_2O-LiBr) and the ammonia water (NH_3-H_2O) systems. The H_2O-LiBr systems are generally used for air conditioning in buildings. The NH_3-H_2O systems are used for refrigeration applications with usable temperatures below the freezing point of water. For H_2O-LiBr, single-stage absorption chillers typically achieve a COP at the nominal operating point of around 0.7–0.8 and require drive temperatures above 75 °C [19]. Double-stage absorption chillers have another generator–condenser pair to the components of a single-stage absorption chiller, and a higher utilization of the heat supply can be achieved. Such systems are mainly offered in the area of large cooling capacities and achieve COP values from 1.1 to 1.2. The drive temperatures required are typically above 140 °C [20].

The greatest market potential for solar thermal cooling lies in the international market, in countries with a high solar radiation supply and therefore also a higher need for building and commercial cooling. Large sales markets are located in China, the USA, Japan, and Southeast Asia [15].

Thermally operated chillers are currently available on the market for the output range from 5 kW cooling to the megawatt range, as well as suppliers for DEC systems with an air volume flow of 4000 m^3/h and above. However, only around 1350 solar cooling systems were installed worldwide by the end of 2015 [21]. Figure 1 shows the market development between 2004–2015 for small to large-scale cooling and air conditioning systems [21].

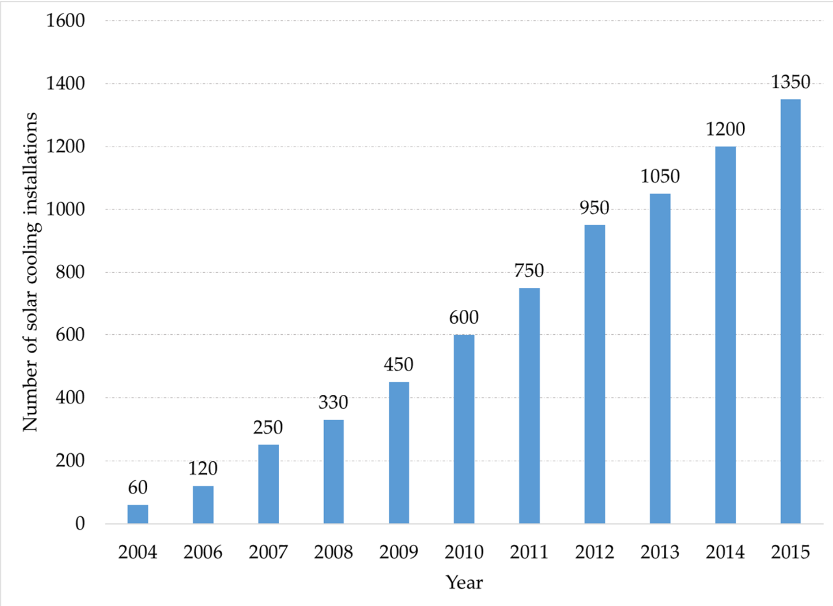

Figure 1. Number of solar cooling installations between 2004 and 2015. Reproduced with permission from [21], Copyright AIP Publishing, 2016.

The aim of this paper is to investigate and assess four H_2O-LiBr absorption chiller pilot plants located in different sites in Jordan. These pilot plants were funded by the German Corporation for International Cooperation GmbH (GIZ) on behalf of Federal Ministry for the Environment, Nature Conservation, Buildings and Nuclear safety of the Federal Republic of Germany. The current status of the installed systems is to be discussed. The absorption chillers have a total nominal cooling capacity of 530 kW (150 RT). The focus of the research was on the pilot system at the German Jordanian University campus. The system has a capacity of 160 kW for cooling and a 50 kW for heating. The system was designed and integrated in order to support the existing conventional compression system with a cooling capacity of 700 kW. Furthermore, an economic study was also carried out for the absorption system taking the environment effect of the reduction of CO_2 emissions into account.

2. Sites Description

Four absorption chillers were installed in four sites in Jordan. The sites represent different climate conditions that varied from a Mediterranean climate in Irbid (North-West) to a continental climate in Madaba (inner regions), to an arid climate in Petra (south). Figure 2 shows the four sites on a map of Jordan together with the annual radiation on horizontal surfaces [22].

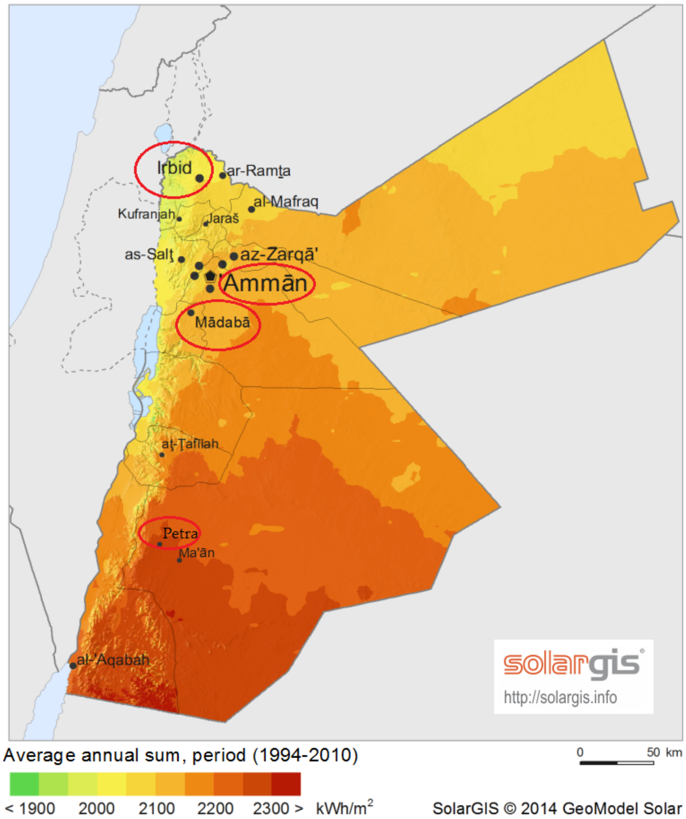

Figure 2. Map of Jordan with the four installed absorption chillers, encircled by red circles, accompanied with the annual radiation on horizontal surfaces. Reproduced with permission from [22], Copyright AIP Publishing, 2016.

2.1. Climate Conditions in Jordan

Jordan is located 80 km to the east of the Mediterranean Sea between latitudes 29°11′–32°42′ N and longitudes 34°54′–38°15′ E, with an area of 89,329 km^2 [23]. The climate of Jordan is predominantly of the Mediterranean type. It is marked by sharp seasonal variations in both temperature and precipitation. Summers are hot and dry while winters are cool and wet. Summer starts around the middle of May and winter starts around the middle of November, with two short transitional periods in between.

The temperature in Jordan varies by location and seasons. The temperature in the hilly regions experience cold weather with temperatures below 0 °C. The summer temperature can reach temperatures above 30 °C (as monthly average temperatures).

2.2. Climate Conditions of the Selected Sites

2.2.1. Irbid: Irbid Chamber of Commerce

The solar cooling unit has been installed at Irbid Chamber of Commerce since 2016. Irbid is located in the North of Jordan. Irbid is characterized by a semi-arid climate with high annual solar irradiation above 2000 kW/h, as shown in Figure 2. Heating is required during winter months in which the ambient temperatures drop significantly.

2.2.2. Amman: Royal Culture Centre

Located at Jordan's capital, Amman, which has an annual solar irradiation of above 2100 kW/h, the absorption system has been in operation since 2016 and it has 8 to 16 operating hours a day, the cooling demands are highest in the evening hours where most events take place. Thus, the system is equipped with hot water storage to allow cooling and heating of non-solar hours.

2.2.3. Madaba: German Jordanian University

This absorption chiller has been in operation since 2015 and is located at the German Jordanian University close to the ancient city of Madaba. Madaba has hot and dry summers with abundant sunshine, more than 300 days per year. The cooling demand is for 6 to 10 h per day and is highest at noon time with ambient temperatures that can reach 40 °C. This system is the focus of this study.

2.2.4. Petra: Petra Guest House

The absorption chiller is located at the gates of the UNESCO world heritage site of Petra and it has been in operation since February 2015 at the Petra Guest House. Petra has a hot and dry climate with an annual solar radiation above 2300 kW/h with ambient temperature up to 45 °C. the system operates daily for 24 h (24/7). The system is equipped with a thermal energy storage of 12 m^3 as driving heat after sunset is connected with a stand-by conventional compression for hours with peak load. An overview of the installed absorption chillers is listed in Table 1 [24].

Table 1. An overview of the installed absorption chillers.

	Irbid Chamber of Commerce	Royal Culture Centre	German Jordanian University	Petra Guest House
Location	Irbid	Amman	Madaba	Petra
Nominal cooling capacity, kW	50	160	160	160
Gross solar collector area, m^2	140	449	480	388
Operating hours per day	6–12	8–16	6–10	24
Chilled water supply temperature, °C	8–10	8–10	6–8	9–11

3. GJU System Description

3.1. Description of the Installation Site

The existing solar heating and cooling system was installed on the rooftop of building C in the campus of the German Jordanian University (GJU) in Jordan. GJU is a public university with around 5000 students, located near Madaba, Jordan. The absorption system under consideration is used to support the already-existing conventional compression system for Building C. The cooling capacity of Building C is equal to 700 kW and the share of H_2O-LiBr was planned to be around 11% of the total cooling capacity, i.e., 160 kW. Building C consists of four levels and a basement with a total floor area of about 7500 m^2. The ground and the third floors consist mainly of laboratories and offices. The first and the second floors consist mainly of education rooms in addition to the academic staff offices.

3.2. Meteorological Data

The Photovoltaic Geographical Information System (PVGIS) tool was used to generate Typical Meteorological Year (TMY) data of solar radiation, temperature, and other meteorological data [25]. The data was provided by the typical meteorological year (TMY2) format containing hourly global and beam radiation data in addition to ambient temperature and sunshine duration values. The considered period for the data that was exported was from 1991–2010. Figures 3 and 4 show the metrological data (daily ambient temperature and daily average global and diffuse radiation in June 2015) in the site over a period of a year.

The air temperature data for year 2015 in Madaba is presented in Figure 3. Madaba has an inland climate with large air temperature fluctuations across the seasons. In typical summer months (May–September), the highest air temperature normally occurs in June and between 12:00 and 14:00 where the air dry bulb temperature could reach 40 °C. The solar radiation normally reaches its peak value of around 1030 W/m^2 between 9:00 and 15:00, as shown in Figure 4.

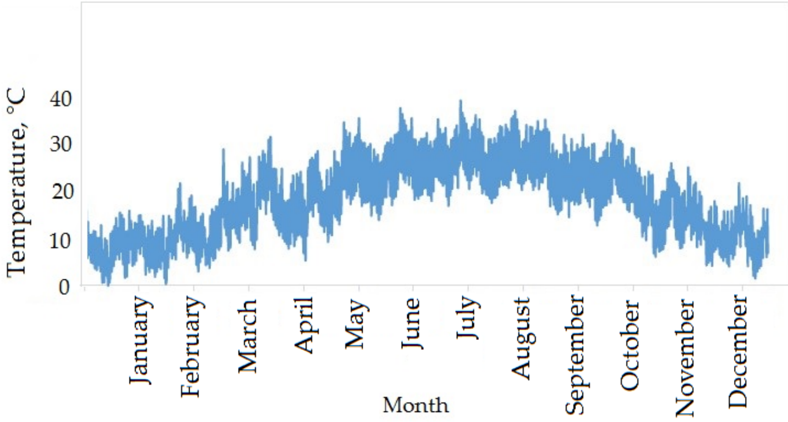

Figure 3. Daily ambient temperature at German Jordanian University (GJU) campus.

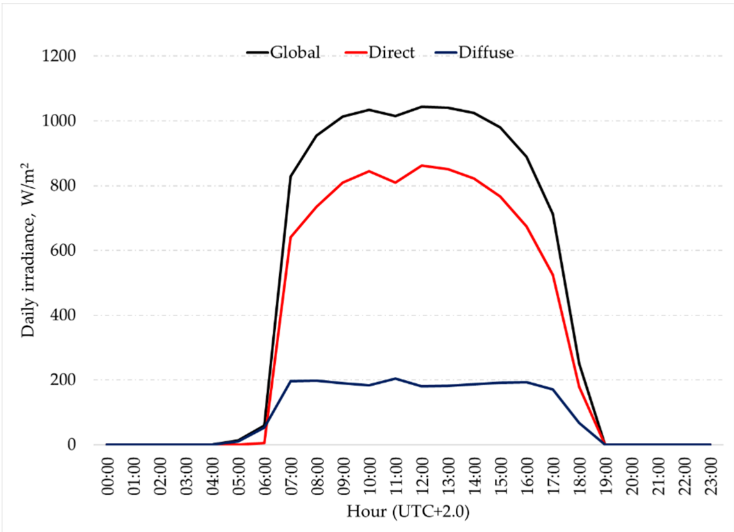

Figure 4. Daily average irradiance for June 2015 in the installation site at the GJU campus.

3.3. System Description

The solar heating and cooling system was installed on the rooftop of building C at the GJU campus. The solar heating system consists of 30 solar collector arrays each with five modules connected in series. Each module (model CPC1518) has 18 evacuated tube collectors with compound parabolic collector (CPC) geometry. The aperture total surface area of the solar field was 450 m^2 and the collectors were oriented to face the south with a tilt angle of 45°. Figure 5 shows the solar collector field installed on the rooftop of Building C at the GJU campus.

The solar field is supplying the absorption chiller with water at 85 °C, this amounts to 44 MWh seasonal thermal energy for the absorption chiller of 250 MWh produced by the collectors. Four heat storage tanks each with a volume of 3.5 m^3 were integrated to the solar heating system. One of the storage tanks is used for domestic hot water in building C and the other three hot water storage tanks were connected to the absorption chiller's generator. The solar hydraulic system is equipped with hot water pumps for each storage tank, two gas boilers (380 kW total capacity), and a dry cooler to remove excess heat.

The conventional cooling system consists of two air cooled multistage compression chillers, 700 kW each (one duty/one stand-by), and one of them can also work as a heat pump which operates only if the heating load reaches beyond the capacity of the solar field and the two boilers in cold winter days when there is no or minimum solar energy gain. The evaporator of the air-cooled multistage compression chillers provides chilled water in summer at a given set value for the chilled water outlet temperature, this temperature is set at 9 °C. The used refrigerant is R134a and is cooled down in an air-cooled condenser.

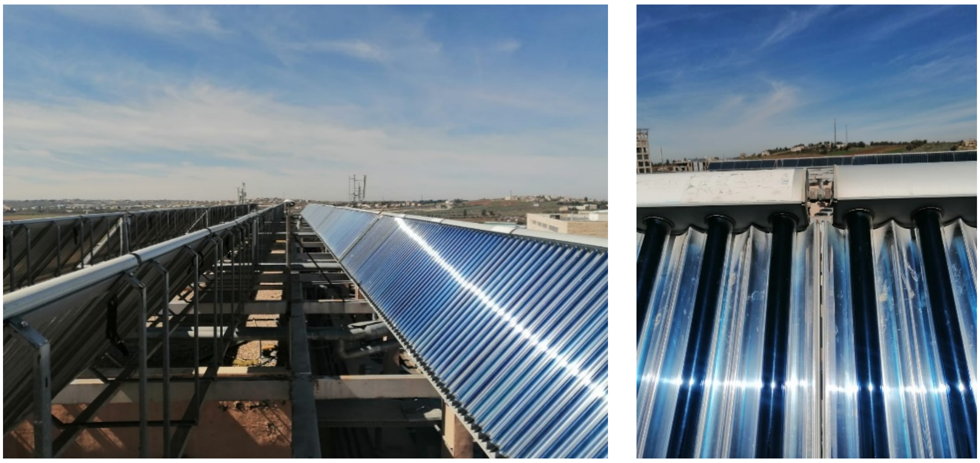

Figure 5. Solar collector field installed on the rooftop of Building C at GJU.

A 160 kW single-stage H_2O-LiBr absorption chiller developed by the Technical University of Berlin was used to assist the conventional cooling system. The system was designed in a way that it does not interfere negatively with the existing compression system and operates in a way that it can be started and stopped independently from the old system. It was designed to cool a part of the airstream exiting the building down to 16 °C contingent on the solar energy gain. Hot water from the solar field enters the generator with a volume flow rate of 3.3 L/s. The heat sink for the condenser and the absorber is cooled with a water-stream leaving a 300-kW dry cooler with a volume flow rate of 12 L/s and temperature range between 30 to 40 °C. The evaporator provides chilled water with a volume flow rate varies between 3.5 to 8 L/s and temperature between 8 and 10 °C, depending on the generation water temperature. The major components of the absorption refrigeration system are two large containers, the low-pressure tank, and the high-pressure tank. The unit contains the four copper tube heat exchangers: evaporator, absorber, generator, and condenser. The external circuits for the chilled, cooling, and heating water were connected to the four copper tube heat exchangers.

The internal sensors of the system consist of temperature and pressure sensors. The pressure in the vapor space of the three containers and the pressure in the absorber and the evaporator bottoms are measured. The temperature is measured at nine positions; this includes the reservoirs for the desorber, absorber, and evaporator, the condenser refrigerant sump of the evaporator circuit as well as all the inlets and outlets of the solution heat exchanger. The flow rate for the different circuits: solar collector field, generator, condenser, evaporator, and the compression chillers were measured via five ultrasonic flow meters. The ultrasonic heat flow meter (Ultraflow 54 DN 150–250) for the installation into the main chilled-water network and for the remaining circuits the ultrasonic heat flow meter devices T550 ULTRACOLD (UH50) and T550 ULTRAHEAT (UH50) were used.

The measurement of the global solar irradiance on a horizontal surface is carried out by means of a pyranometer. The measurement of the ambient air is carried out by means of the sensor unit type ARFT/A-I/S. In addition, the measurement of the electrical energy consumption (in kWh) of the components necessary for the solar cooling application was taken. The measurement of the electrical energy of components is completed by means of the watt-hour meter type iEM3150. Figure 6 shows the 160 kW H_2O-LiBr absorption chiller at GJU Building's C roof.

Figure 6. Water-lithium bromide (H_2O-LiBr) 160 kW absorption chiller on GJU rooftop.

4. Economic Feasibility

This economic study is intended to evaluate the overall economic viability in-depth. The key financial indicators used for the evaluation include Present Worth (PW), Payback Period, and Internal Rate of Return (IRR).

The *PW* method is the equivalent worth of all cash flows relative to some base or beginning point in time dubbed the present. That is, all cash revenues (incomes, saved energy, reduced CO_2 emissions) and expenses (auxiliary power consumption, maintenance) are discounted to the present point in time at an interest rate [26]. A positive PW for the absorption cooling system will mean that the project is feasible and a profit over the minimum amount required will be achieved. To find the *PW* as a function of interest rate (i%) of the cash inflows and outflows, the future amounts need to be discounted to the present by applying Equation (1) [27]. To discount future amounts to the present by using the interest rate over the appropriate study period, we used the following:

$$PW(i\%) = \left[\left(\sum_{k=0}^{N} F_k(1+i)^{-k}\right) + \left(A\left[\frac{(1+i)^k - 1}{i(1+i)^k}\right]\right)\right] \quad (1)$$

where (i%) is the effective interest rate; (k) is the index for each compounding period $0 \leq k \leq N$; (F_k) is future cash flow at the end of period (k); (A) is the end-of-period cash flows in a uniform series continuing for a specified number of periods, starting at the end of the first period and continuing through the last period; and (N) is the number of compounding periods in the study period. In this study, N was set to 25 years which represents the life expectancy of the system and the interest rate which was set to i = 6%.

Annual expenses include the maintenance costs and the operating energy and water costs. For maintenance costs, standards like the Association of German Engineers (VDI) 2067 use 2% of the investment costs. Chiller manufacturers calculate maintenance costs by 1% of the investment costs. For large thermal chillers, companies offer constant cost maintenance: the costs vary between 0.5% for large machines (up to 700 kW) up to 3% for lower-power machines [28].

The payback period is the time required to recover the total investments by profit gaining. The payback period can be calculated by setting PW to 0. The simple payback period, θ, ignores the time value of money and all cash flows that occur after θ ($\theta \leq N$) and calculates the number of years required for cash inflows (Revenues R) to just equal cash outflows (Expenses, E). For this study, where initial investment occurs at time 0, the simple payback period is given in Equation (2) [27]:

$$\sum_{k=1}^{\theta}(R_k - E_k) - I \geq 0 \tag{2}$$

In addition, the discounted payback period, θ' ($\theta' \leq N$), is calculated so that the time value of money is considered, as given in Equation (3) [27]:

$$\sum_{k=1}^{\theta'}(R_k - E_k)(P/F, i\%,\ k) - I \geq 0 \tag{3}$$

4.1. Absorption Chiller Monitoring Results

The absorption chiller was monitored on several sunny summer days between May and July 2015. The cooling capacity and the thermal COP as a function of generation temperature (T_g) are shown in Figure 7 [29]. As shown in Figure 7, the cooling capacity varies and the maximum value reached about 30 kW with a mean daily generator temperature reaching values not higher than 80 °C. The thermal coefficient of performance is defined as the ratio of the cooling achieved in the evaporator of the absorption chiller to the driving heat applied to the generator. The COP of the absorption chiller varied significantly depending on the operating conditions. Low COP values were observed, varying between 0.09 to 0.54 compared to 0.79 as claimed by the manufacturer regarding of the operating conditions. The absorber and condenser mean daily temperature is between 24 °C and 38 °C with maximum ambient air temperatures reaching 41 °C. The mean daily evaporator temperature is between 8 °C and 15 °C.

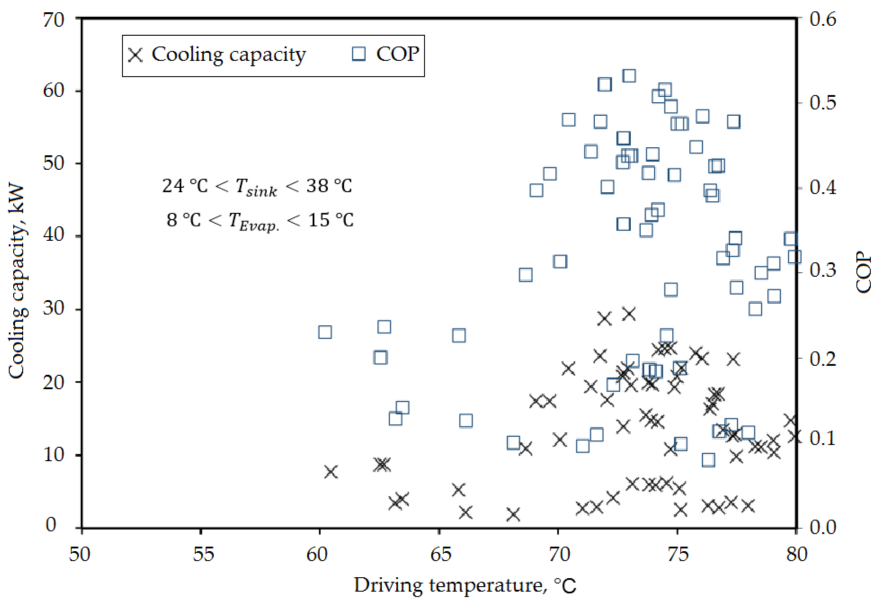

Figure 7. Cooling capacity and thermal Coefficient of Performance (COP) of the absorption chiller in GJU as a function of driving temperature, modified from [29].

The main result to investigate is the observed cooling capacity of just 18.7%, at maximum of the nominal cooling capacity value (160 kW). in addition, an average thermal COP of less than 0.3 can be observed. An explanation was listed by [29], who attributed this to the operation of the absorption chiller on non-demanding days (the University is closed on Fridays), the frequent operation of the solar dry cooler, and some control and instrument issues.

4.2. Cost and Tariffs

In order to determine the economic feasibility of the absorption chiller system, an estimation of the various components of the system was performed. A spreadsheet was tailored specifically to the absorption chiller system to perform the economic mathematical analysis. Various parameters were taken into account through the economic calculations. The system cost is defined through the cost of the absorption chiller according to the cooling capacity per watt, and the cost of the auxiliary component in the local market. Figure 8 shows the component share of the total cost.

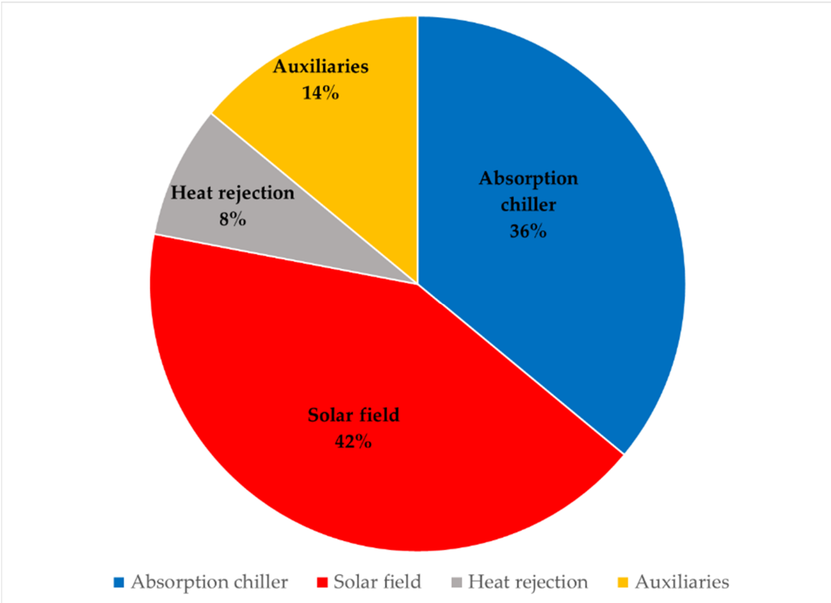

Figure 8. Share of absorption system components in the total cost.

As shown, the solar field has the highest cost of the solar cooling system with a share of 42%. The solar field at GJU was overdesigned regarding the supply of hot water to the generation of the weak H_2O-LiBr solution, since the solar collector is also used for heating domestic hot water for Building C. In addition, the solar field was overdesigned to ensure that the chiller was working with a COP of 0.79 regardless of the outlet conditions. The installation and the operational cost are considerably lower as a result of low local wages in Jordan compared to developing countries.

Table 2 shows the cost of the system components. The total cost of the system was 243,000 JD (Jordanian Dinar). The absorption chiller has a cost of 546.8 JD/kW and a total of 87,480 JD. The solar field total cost was equal to 102,060 with the highest cost share of the system. The heat rejection in the condenser and the absorber has a cost share of 19,440 JD and the auxiliaries have a cost of 34,020 JD.

Table 2. Total cost and cost of each of the individual components for the absorption cooling system.

Component	Cost in JD
Absorption chiller	87,480
Solar field	102,060
Heat rejection	19,440
Auxiliaries	34,020
Total	243,000

4.3. Economic Feasibility

The economic feasibility analysis of solar thermal cooling systems, which require high initial investments, plays a very important role in the assessment of the viability of the project.

For assessing the financial feasibility of the system some financial metrics were used in this study; namely the Net Present Value (NPV) and payback period. Net Present Value (NPV) is defined as the difference between the present value of cash inflows and the present value of cash outflows. NPV is used to analyse the profitability of a projected investment. The acceptance criterion for NPV is quite straightforward; when the NPV is greater than zero, the project will be accepted, otherwise, the project has to be rejected.

In this study, the system life expectancy is defined through the system components lifespan and maintenance. the feasibility calculations were performed for two scenarios with lifespan over 25 years. The lifespan was chosen according to the evacuated tube's expected life of 25 years, with some literature even expecting a lifespan of 20 years. The energy saving over 25 years was defined through forecasting the amount of electrical energy that would be saved from the solar cooling system of its operation based on the local distribution companies in Jordan. Operating and maintenance cost (O and M) percentage is defined through the changed costs for operating and maintaining the system based on the lifetime of the system. In addition, the annual inflation in O and M cost is defined through the percentage of inflation in the operation and maintenance costs per annum. The operating cost is mainly used to run the auxiliary components of the system; dry coolers, heating, cooling, and chilled water pumps. Figure 9 shows the share of the auxiliary power consumption components of the absorption system.

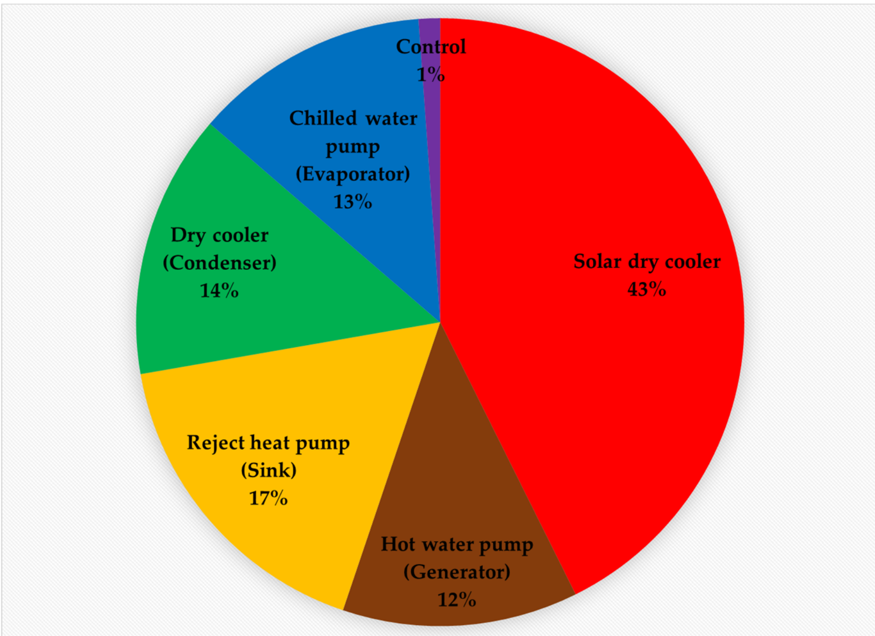

Figure 9. Percentage share of the auxiliary power consumption components of the absorption system.

The solar dry cooler (maximum power consumption 7.49 kW) was used to serve a uniform temperature from the hot water circuit. The solar dry cooler is turned on when the hot water temperature from the solar field exceeds 95 °C and turned off when the hot water temperature falls below 85 °C. The relative low set points for activating the solar dry cooler also contribute to a higher electrical consumption of the solar dry cooler. The reject-heat pump with an auxiliary power consumption of 3 kW is connected with heat sinks for the absorber and condenser. The dry cooler of the condenser has an auxiliary power consumption of 2.47 kW and the chilled water pump has a power consumption of 2.2 kW. Furthermore, 1% of the auxiliary power consumption was used to run the control boxes for operating the system actuators to a specified and adjustable sequence of operation depending on the operating mode.

The results of the Discount Cash Flow financial analysis are illustrated through Figures 10–12. In this study, the interest rate is assumed to be 6%, which is a suitable interest rate in a local commercial bank in Jordan. Therefore, a discount rate of 6% is used in the Discount Cash Flow analysis to determine the present value of future cash flows.

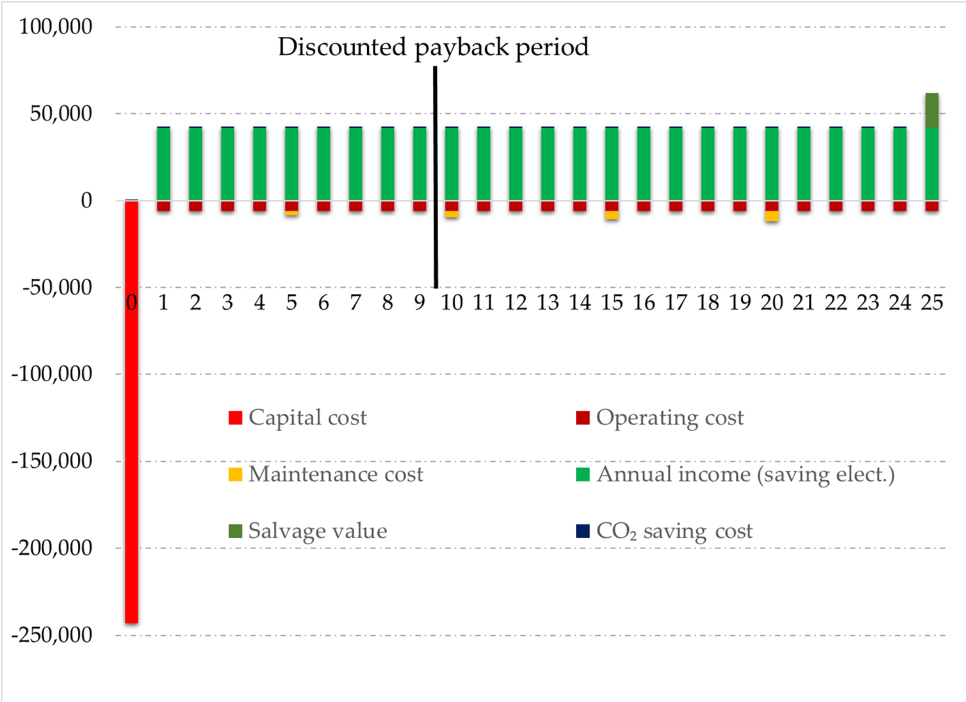

Figure 10. Absorption cooling system cash flow diagram with a COP of the absorption chiller of 0.79.

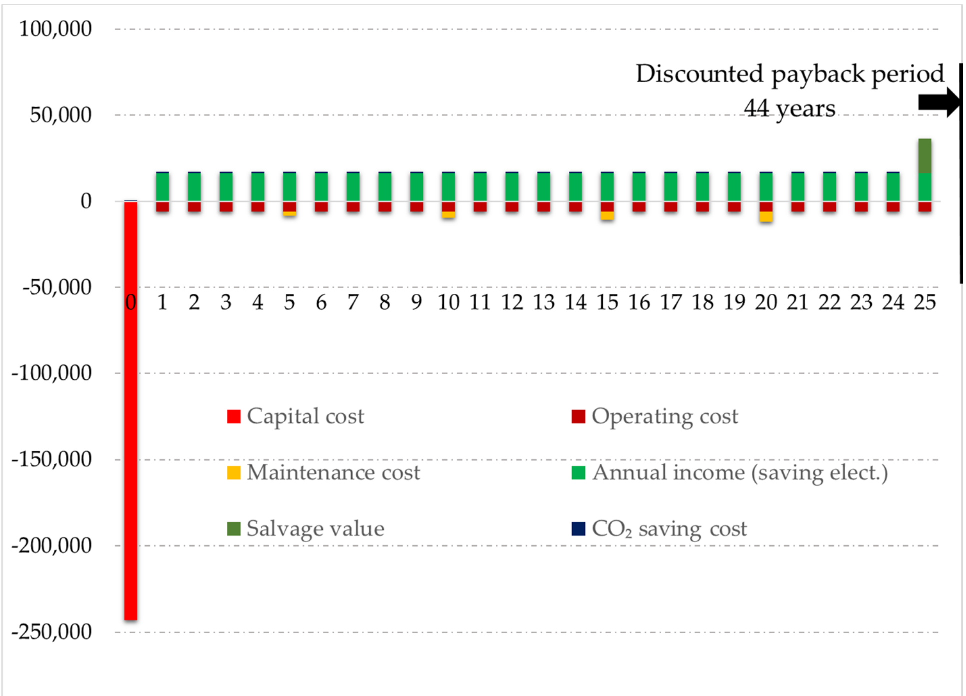

Figure 11. Absorption cooling system cash flow diagram with an average observed COP of the absorption chiller of 0.32.

As shown in Figure 10, the absorption cooling system is deemed as feasible for a COP of 0.79 as claimed by the manufacturer over a lifespan of 25 years. The net present worth is equal to +185,070 JD and the payback period is equal to 10 years. However, the feasibility study of the absorption cooling system under real measurements over four summer months (May 2015–August 2015) with an average COP of 0.32 shows that the system is not feasible, as shown in Figure 11. For the observed cooling capacity, the net present value was equal to −137,684 JD with a payback period of 44 years which exceeds the expected lifespan of the project.

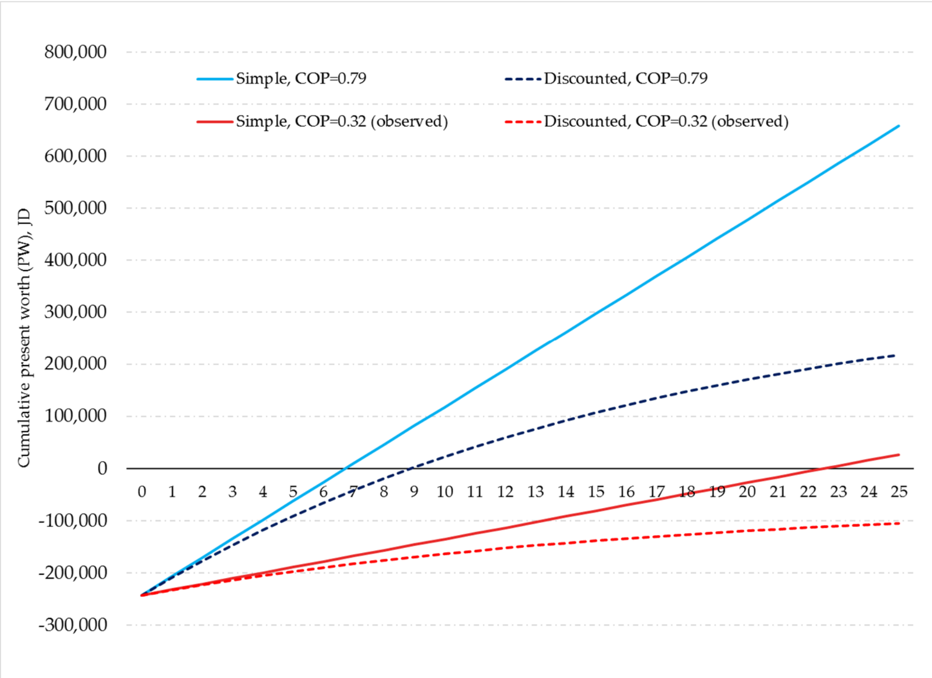

Figure 12. Simple (solid lines) and discounted (dashed lines) payback periods for the claimed COP = 0.79 (blue lines) and the observed COP = 0.32.

Table 3 summarizes the results in the analysis in terms of the financial metrics chosen for the evaluation of the feasibility of the system.

Table 3. Summary of the economic analysis of the solar absorption for the claimed and the observed results.

Parameter	Values for a COP = 0.79	Values for a COP = 0.32 (Observed)
Capital cost, JD	243,000	
Maintenance cost, JD	1% of CC, each 5 years with an increment of 0.5%	
Annual operating cost (Auxiliary components), JD	5737	5737
Annual save (electricity), JD	41,772	16,524
Annual saving (CO_2 reduction), JD	742	300
Net present value, JD	185,070	−137,684
Payback period, years	10	44
Rate of return	14.31%	0.82%
Levelized Cost of Electricity (LCOE), JD/kWh	0.65	1.65

The simple (solid lines) and discounted (dashed lines) payback periods for the claimed COP = 0.79 (blue lines) and the observed COP = 0.32 (red lines) are shown graphically in Figure 12.

One of the main drawbacks of the applying the payback period method is that it does not take into account several key factors including the time value of money, thus the discounted payback period is considered in this study. As shown in Figure 12, the discount payback period increased from 7 to 23 years and from 9 to 44 years for the simple and discounted payback techniques, respectively.

Moreover, the absorption cooling system is considered as infeasible economically with a payback period exceeding the system span life for the real observed cooling capacity.

In addition, a part of the cost analysis of the absorption chiller system was performed according to the levelized cost of electricity (LCOE). The LCOE is calculated by dividing the net present value of the total cost of absorption chiller system and operating the power generating asset by the total electricity saved over its lifetime. The LCOE values of the system are equal to 0.65 JD/kWh and 1.65 JD/kWh when the system operates at claimed COP of 0.79 and observed COP of 0.32, respectively. When taking into account the electricity tariff of 0.27 JD/kWh, it is obvious that the absorption chiller system is not feasible economically.

4.4. CO_2 Emissions Reduction

For the calculation of the total CO_2 emission reduction, it is important to know the emission factors. The emission factor used in this study was derived based on the numbers provided for Mediterranean cities that carried out their sustainable energy action plan with the only exception of the electricity emission factor, which is a characteristic of the country [30]. It was not possible to acquire the electricity emission factor for Jordan directly from the Ministry of Energy and Mineral Resources or any of the utilities servicing the country. Therefore, the utilization of available statistical energy data from the Ministry of Energy and Mineral Resources [31] was considered the best approach. Using the Energy data of 2015 and the energy production from different sources including renewable energy, as shown in Table 4, the Electricity Emission Factor (EEF) was calculated.

Table 4. Electrical energy production shares from different sources including renewable energy resources in Jordan [31].

Source	GWh	CO_2 Factor kg/kWh	Emission (Tons)
Natural gas	9211	0.4	3,684,400
Heavy fuel oil	6644	0.7	4,650,800
Diesel	2974	0.6	1,784,400
Renewable	184	0	0
Total	19,013	-	10,119,600

The main source of electricity generation in Jordan is the natural gas which has an emission factor of 0.4 kg/kWh, followed by heavy fuel oil with an emission factor of 0.7 kg/kWh. The average Electricity Emission Factor in Jordan for the year 2015 is calculated by using Equation (4), and it was equal to $EEF = 0.54\ kgCO_2/kWh$

$$EEF = \frac{CO_2\ Emission\ (kg)}{Electrical\ energy\ generated\ (kWh)} = \frac{10,120 \times 10^6 kg\ CO_2}{19,013 \times 10^6 kWh} \tag{4}$$

The electrical energy (kWh) saved by operating the absorption chiller was compared against operating the conventional vapor compression chiller with a COP of 2.5 which corresponds to 19,980 kWh in electricity savings. Thus, for the operating with COP of 0.32, the reduced CO_2 emissions is equal to 10,789 kg, as shown in Equation (5).

$$Reduced\ CO_2\ emission = EEF \times Saving\ in\ electrical\ energy = 0.54 \frac{kg\ CO_2}{kWh} \times 19,980\ kWh \tag{5}$$

Also, the reduction in CO_2 emissions is equal to 26,500 if the system reaches the claimed COP of 0.79. The annual savings for the reduction of CO_2 emissions with an assumption of 28 $\frac{JD}{ton\ of\ CO_2}$ was equal to 300 JD and 742 JD for COPs of 0.32 and 0.79, respectively.

5. Conclusions

Using solar power for the cooling and heating of buildings is a milestone in the search for environment-friendly technologies in the energy sector. Four solar absorption cooling systems with a nominal cooling capacity of 530 kW were installed in four sites in Jordan. The focus of the research was on the pilot system at the German Jordanian University campus. The system has a capacity of 160 kW for cooling and a 50 kW for heating. With the installed systems, Jordan is the first developing country to use solar thermal energy to cool buildings. The aim of these systems was not only to reduce cooling power consumption, but also to serve as a reference for researchers and experts in absorption chillers, as it is the first of its kind to be implemented in Jordan, the region, and among developing countries. An economic feasibility study was carried out for the absorption system taking the environment effect of the reduction of CO_2 emissions into account. This study was based on an evaluation of the solar thermal cooling system within four months of operation between May and July 2015.

The system was economically evaluated based on the observed cooling capacity results with a COP of 0.32, and compared with the claimed COP of 0.79 regardless of the operating conditions. Several techniques were implemented to evaluate the overall economic viability in-depth such as present worth value, internal rate of return, payback period, and levelized cost of electricity. The aforementioned economic studies showed that the absorption cooling system is deemed as not feasible for the observed COP of 0.32 over a lifespan of 25 years. The net present value was equal to −137,684 JD and there was a payback period of 44 years, which exceeds the expected lifespan of the project. Even for an optimal operation of COP = 0.79, the discounted payback period was equal to 23 years and the LCOE was equal to 0.65 JD/kWh.

The survey shows that there are several weaknesses for applying solar thermal cooling in developing countries, such as the high cost of these systems and, more significantly, the lack of experience for such systems. The solar thermal cooling systems currently installed in Jordan were either planned, built, and monitored by companies that specialize in solar thermal cooling, or were scientifically supported by a research institution and they were being evaluated via monitoring at the beginning of their operation.

From this perspective, the solar thermal cooling systems currently installed are not the technologically-possible optimum. There is significant potential for reducing costs and/or increasing performance through technological improvements mainly at the system level for overall system optimization. The introduction of a more advanced control through the absorption chiller components will increase operational efficiency, improve the cooling capacity, and contribute to the reduction of CO_2 emissions. The main component in solar thermal cooling systems is the chiller and the most relevant controlled parameter is the hot water inlet temperature and mass flow. Optimization between high water temperature to the generator should be achieved, to increase the cooling capacity of the absorber, while preventing possible pump damage in the case of crystallization. The improvement of this advanced technology requires higher level of process control and professional expertise.

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