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Evaluation of Coupling PV and Air Conditioning vs. Solar Cooling Systems—Case Study from Jordan

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Abstract: When they were first conceived, solar cooling systems were designed to be cost-effective and environmentally safe alternatives for the majority of the developing nations that are characterised by their hot climates in contrast with the traditional air conditioning systems powered by electricity that is produced from fossil fuel resources. Nevertheless, developments in photovoltaic (PV) and air-conditioning technologies have impacted on the prospects of solar cooling systems. This study examined two different options: a coupled PV and air conditioner system and a solar cooling system (absorption chillers where thermal energy is provided by solar collectors) for a specific developing country located in the Eastern Mediterranean region whose climate is hot and dry (Jordan). The cooling system comprised a pair of cooled multistage compression, both of which were 700 kW, while the PV system's size was 2.1 MWp, the utility grid connection was a 0.4 kV 50 Hz net meter (2 m) and it was anticipated that 3300 MWh/year would be generated. The solar cooling system operated at a maximum coefficient of performance (COP) of 0.79 and had an actual recorded COP of 0.32 on the site; when the electricity tariff of $0.1/kWh was considered, the respective levelised cost of energy (LCOE) values were $0.9/kWh and $2.35/kWh respectively. The findings indicate that the initial costs for the solar thermal cooling system and the PV system were approximately $3.150M and $3M, respectively. The current value of future cash payments when discounts of 6% per year were applied to the payments for the combination of PV and air conditioning was about $9,745,000, whereas the solar thermal cooling system will not reach the breakeven point at negative $1,730,000. It is clear the absorption chiller did not display economic feasibility, whereas the value for the coupled PV and air-conditioning systems was under $0.05/kWh. In addition to the extensive maintenance needs, the reduced COP and the practicality and feasibility of the solar thermal cooling systems mean these kinds of technologies are under significant pressure to remain competitive when faced with the development of new air conditioning and PV technologies.

Keywords: coupled PV and air conditioner; solar cooling system; cooling of building; emerging markets

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1. Introduction

There is growing concern around the world about the consumption of fossil fuels. Studies have revealed that fossil fuel resources still constitute around 85% of the overall energy consumed, and buildings' energy consumption makes up around 20.1% of the overall delivered energy that is consumed globally [1]. To achieve a reduction in the proportion of fossil fuels consumed in this sector, the focus is increasingly turning to solar cooling.

The estimates provided by the International Energy Agency (IEA) have been gradually increasing for many years, although they are yet to predict that photovoltaic (PV) technology will actually be deployed in each of their forecasts [2]. The IEA predicts that by 2050, PV technology will produce 4.7 terawatts according to its high renewable energy scenario, where in excess of 50% will be implemented in India and China, thus rendering solar power the leading source of energy in the world. Bloomberg expects there to be growth in the number of solar installations around the world in 2019, which will add 125–141 GW, leading to an overall capacity of 637–653 GW by year end [2].

The idea of solar cooling emerged on the basis of the presumption that solar energy could satisfactorily meet the cooling needs of buildings in hot summer periods, when both the solar radiation and ambient temperature reach their highest levels during the year. The coupling of solar power with cooling could make a significant contribution to lowering the elevated power demands of electricity grids and addressing the problem of climate change caused by global warming. In its current form, solar cooling predominantly comprises solar PV mechanical compression cooling and powered vapor compression cooling [3,4] using solar absorption [5–7] and solar desiccant cooling [8]. From these different options, the power for solar electric compression cooling systems is provided by PV technology, where such systems can either be connected to utility grids or stand alone. As PV systems can also be utilised for powering heat pumps to heat spaces within buildings, the integrated system can more appropriately be defined as being a photovoltaic air conditioner (PVAC). The other options utilise solar thermal energy and generally comprise a variety of different thermal collectors, including flat-plate collectors and evacuated tube collectors [9]. In PVACs, the energy can be supplied to the air conditioner by either the PV system or the power grid. Surplus PV power can be fed back into the grid in order to allow the PV system to continue working under the maximum peak power tracking (MPPT) function [10]. With regard to applications, PVACs connected to the grid are consistently perceived as being a component of the energy systems in buildings. Related studies concentrate on control strategies that are capable of smoothing the PV generation [11], increasing the cost-effectiveness [12] and enhancing the thermal comfort within buildings [13]. Stand-alone PVACs always include a system for storing energy that could be intended to either store electrical energy [14] or thermal energy [15]. Charging of the energy storage system occurs when the PV technology generates excess energy, whereas it is in a discharged condition when the solar radiation levels are reduced. The capabilities of cold storage batteries to save energy for stand-alone photovoltaic air conditioner systems were compared, which indicated that the energy-saving ability of the cold storage option was worse than the battery option because the coefficient of performance (COP) was comparatively low for air conditioners with cold storage. Nevertheless, stand-alone PVACs with batteries are not currently feasible in economic terms [16].

Both the generation of solar energy and the cooling demands of buildings are highly sensitive to local weather conditions. Associated studies are focused on the evaluation of different kinds of solar cooling approaches in different regions. For example, a study was conducted on the five above-mentioned kinds of solar cooling in a Hong Kong office building [17]. The researchers used the TRaNsient SYStem (TRNSYS) simulation platform in order to compare critical indicators, including the solar portion, primary energy consumption COP and solar thermal gain. It was determined that the systems of solar cooling that showed the highest potential to conserve energy in sub-tropical zones like Hong Kong were solar absorption refrigeration and solar electric vapour compression [18].

Nonetheless, the feed-in tariff of surplus photovoltaic electricity, which has the potential to increase the benefit of solar electric cooling, did not receive significant attention in the research. An analogous study was performed that involved the investigation of the solar thermal and photovoltaic alternatives for an office structure according to the climates of two regions in Europe [19]. Extensive technical and economic research of solar cooling was conducted, including 25 feasible amalgamations of cooling technologies and solar energy collection. It was shown by the analysis that the solar fraction and storage capacity were critical when designing systems of solar cooling. Furthermore, if the relationship between the cooling demand and the availability of solar resources is not considered, this can cause the solar cooling potential to be overestimated [20].

The growing demand for air conditioning is largely the result of stricter contemporary codes and standards governing how buildings should be ventilated and the quality of the air inside the buildings [21,22], as well as the construction of modern glass structures in hot dry countries with no consideration for the country's climate and character [23].

In places where the demand for air conditioning is generally elevated, significant load peaks (in the summer) impact the public utility grid, particularly on hot days during the summer. Total network supply outages have already been recorded [24]. The companies that are responsible for supplying energy must devise strategies for satisfying the expanding demand for air conditioning and cooling by improving their investment in power plants to deal with the peak load.

One approach that can relieve utility grids involves traditional refrigeration systems powered by electricity being replaced with processes driven by thermal energy. Specifically, solar-driven heat is an appealing technology option as a result of the simultaneous occurrence of cooling needs and solar radiation. Because the solar supply and increased cooling in buildings largely occur simultaneously (both seasonally and during the day), this indicates that solar energy could be utilised for supplying the demanded drive heat. Cooling loads peak at times when the levels of radiation power are high (e.g., in office structures), which may be caused by either the profile of the user or the cooling loads that have a strong correlation with the radiation on the external envelope of the structure [25,26].

Refrigerants that could damage the environment are not used in solar thermal air conditioning systems [27]. Conventional air conditioning and refrigeration systems predominantly utilise refrigerants that pose a significant risk in terms of global warming [28]. Advancements regarding the potential use of natural refrigerants (propane, CO_2) provide different options; however, their use remains relatively limited in existing air conditioning and refrigeration systems. Hence, changing to thermal cooling processes can reduce the volume of the damaging materials used.

The thermal drive source used for cooling in solar thermal cooling systems is predominantly solar energy. In effectively designed and functioning solar thermal cooling systems, it is possible to gain primary energy savings in comparison with traditional systems. This equates to a lowering in the level of CO_2 emissions that is in line with the yearly electrical energy savings made in relation to heating, ventilation and air conditioning (HVAC) [28]. The consumption of auxiliary electricity in solar thermal cooling systems is largely for driving the system's fans and pumps.

Solar energy can be converted into beneficial cooling or conditioned air (cooling and dehumidification) using various approaches. Combining photovoltaics and compression cooling additionally provides such benefits. Purely from the perspective of cooling, the amalgamation of photovoltaics and compression cooling could offer increased competition going forward. Nevertheless, the primary environmental benefit of solar cooling systems is not related to cooling, but rather the fact that such systems can be used for multiple purposes, including heating water and supporting heating, which could provide most of the CO_2 savings [29].

Numerous researchers have conducted studies on air conditioning and solar cooling driven by thermal energy. Solar thermal cooling can largely be categorised in terms of either closed or open cycles. In the former, which functions at atmospheric pressure, handling of the latent load is performed with liquid or solid desiccants. The sorbate is the water vapour from the environment, while the liquid or solid desiccant are the absorbent or adsorbent, respectively. Open processes comprise both evaporative cooling and sorption dehumidification, in which various interconnections can occur and a variety of sorbents are employed. The most frequently used techniques employ sorption rotors for dehumidifying. The rotor materials employed thus far have been limited to lithium chloride or silica gel, which are integrated into a cellulose medium. Various researchers have conducted studies in which liquid desiccants were applied to desiccant evaporative cooling systems, including [30,31], while others have applied desiccant wheels, including [32,33].

Closed processes involve absorption and adsorption chillers. In adsorption systems of refrigeration, the refrigerant is adsorbed using a solid. Commercially available devices predominantly utilise water and silica gel as the refrigerant and adsorbent, respectively [34]. The system's COP values are around 0.65 and heat from around 60 °C can be utilised to deliver cooling at reduced re-cooling temperatures [35,36]. It is only possible to obtain a COP of 0.65 for an adsorption chiller when the desorption temperatures and cooled water temperatures are high but the cooling temperature is low. This value can be significantly lower when the heating temperature drops to 60 °C (ranging between 0.17–0.34) [36]. Such systems incorporate a particular functionality as a result of the regular desorption and adsorption of the sorbents. In general, two adsorbers function in an alternating manner, meaning that one of the adsorbers is always ready to provide cooling. This intermittent functionality causes the temperatures to fluctuate across a range of temperatures, which is a limitation that must be considered in the system design process [37].

The most common absorption chillers are the ammonia water (NH_3-H_2O) and water-lithium bromide (H_2O-LiBr) systems. The former is used for refrigeration systems with usable temperatures under the point at which water freezes, while the latter is predominantly utilised in buildings' air conditioning systems. In the context of H_2O-LiBr, the COP achieved by single-stage absorption chillers is generally around the nominal operating point of 0.7–0.8 and operative temperatures in excess of 75 °C are required [38]. In comparison to single-stage absorption chillers, dual-stage absorption chillers have an additional pair (generator and condenser), which means that the utilisation of the heat supply is increased. These types of systems are predominantly utilised for larger cooling capabilities and the COP values achieved range from 1.1–1.2. They generally require operative temperatures in excess of 140 °C [39].

Commercially available chillers powered by thermal energy offer cooling outputs ranging from 5 kW to megawatts, in addition to suppliers for drying and cooling without refrigeration systems with air volume flows starting from 4000 m^3/h. Nevertheless, according to statistics from the end of 2015, only approximately 1350 cooling systems had been installed globally [40].

According to past studies, it can be stated that from the different types of solar cooling, photovoltaic vapour compression cooling shows increased promise for application in buildings from the economic and energy conservation perspectives. It is generally recognised that they offer cooling systems with an increased efficiency that can be conveniently integrated into standard buildings. Additionally, solar electric vapour compression heating functions in a same manner as solar electric vapour compression cooling and has been investigated for applications in winter months in the aforementioned studies. Therefore, by combining PV electric heating and cooling in a PVAC, this could provide a more beneficial option for buildings that require both cooling and heating.

It is essential for future sustainable developments that the occupants incorporate some adaptive techniques to save energy, such as opening the windows, using low-energy fans, using external shading to prevent the summer sun from heating the cooled areas and wearing suitable clothes instead of totally relying on the air conditioning. Many studies indicate that using these measures could save up to 50% of the cooling energy [41–43].

Similar to the majority of other countries, it is anticipated that the need for air conditioning in Jordan will double by 2030 compared to 2015 levels [44]. This increased demand is caused by various factors: an overall rise in the standard of living, economic development transformation in architectural design, the increased utilisation of glazing in constructions and the gradually rising temperatures caused by global warming. Consequently, there will be a drastic increase in emissions, which will make a further contribution to climate change.

2. Materials and Methods

Sustainable cooling technologies that are powered by renewable sources of energy and environmentally friendly cooling liquids are becoming increasingly popular. Refrigeration and air conditioning that is driven by solar energy is specifically advantageous for countries with increased ambient temperatures and solar radiation rates. Compared with fossil fuels, solar radiation is both sustainable and renewable and is available when the demand for cooling is at its highest. Sorption technologies are generally employed by solar thermal systems within a hermetic or open thermodynamic cycle. Moreover, it is possible to convert the surplus electricity produced by PV modules into cooling via the use of vapour compression cycles. The primary obstacle preventing the use of solar thermal systems within developing countries is the absence of available systems and the necessary parts. To penetrate markets in countries like Jordan, it is necessary for solar cooling systems to satisfy various criteria, including that they should be robust, affordable and available.

This study investigated two kinds of cooling systems powered by photovoltaic and solar thermal cooling systems, respectively, where both were situated on the German Jordanian University (GJU) campus located in Amman, Jordan.

2.1. Solar Radiation within Jordan and the Cooling Demand

The potential for successfully applying solar cooling technologies within the country of Jordan is particularly high. As a result of its geographic position, as well as the average number of 650 cooling degree days, solar radiation is provided for most of the year. Furthermore, the peak demand for cooling coincides with elevated solar radiation in the country. Even a small fraction of indirect radiation produces solar radiation that exceeds 2 MWh/m^2 per year, which exceeds the average recorded in the Middle East and North Africa (MENA) region [45].

As a country in which the average ambient temperatures are exceptionally high, it is anticipated that the demand for cooling and refrigeration technologies will double by 2030 compared to 2015 levels. The systems that are currently used generally do not have good energy efficiency, experience more leaks, and release substances that damage the climate and ozone into the atmosphere. As a result of its elevated levels of solar radiation, it is expected that Jordan will be able to benefit from solar thermal cooling systems that depend on renewable energy and do not directly produce emissions since they use natural refrigerants. The charts shown below reveal the daytime and night-time temperatures (monthly averages).

There will be increased demand for air conditioning going forward. In addition to economic expansion and rising standards of living, elevated temperatures and heat waves could also be contributory factors. Even today, one out of every two commercial buildings utilises a chiller system. It is expected that commercial chillers will have a lifetime of around 20 years. Therefore, approximately 5% of all installed chillers must be replaced on an annual basis.

The expanding demand for compression chillers in Jordan provides an opportunity to discontinue the utilisation of older chiller systems and move to more sustainable and ecological options. The installation of alternative air conditioning systems with increased energy efficiency will facilitate the achievement of a considerable reduction in emissions, which will enable the country to comply with the climate agreements it has ratified. Based on the assumption that that solar cooling systems will have a market penetration rate of 25%, it is predicted that a 3.74 Mt CO_2-e/year reduction in emissions can be accomplished [46].

2.2. Site Description

German Jordanian University is a public university situated in Amman, close to Madaba, Jordan, with a latitude of 31.77° and a longitude of 35.802°. The climate of Amman is characterised as being inland with significant variations in air temperature experienced in different seasons. In the standard summer months from May to September, the maximum temperatures generally happen in July and August between the hours of 13:00 and 15:00, during which, the air temperature can be as high as 40 °C. The solar radiation typically peaks at approximately 1000 W/m^2 on optimally inclined planes in Amman at noon, as illustrated in Figure 1.

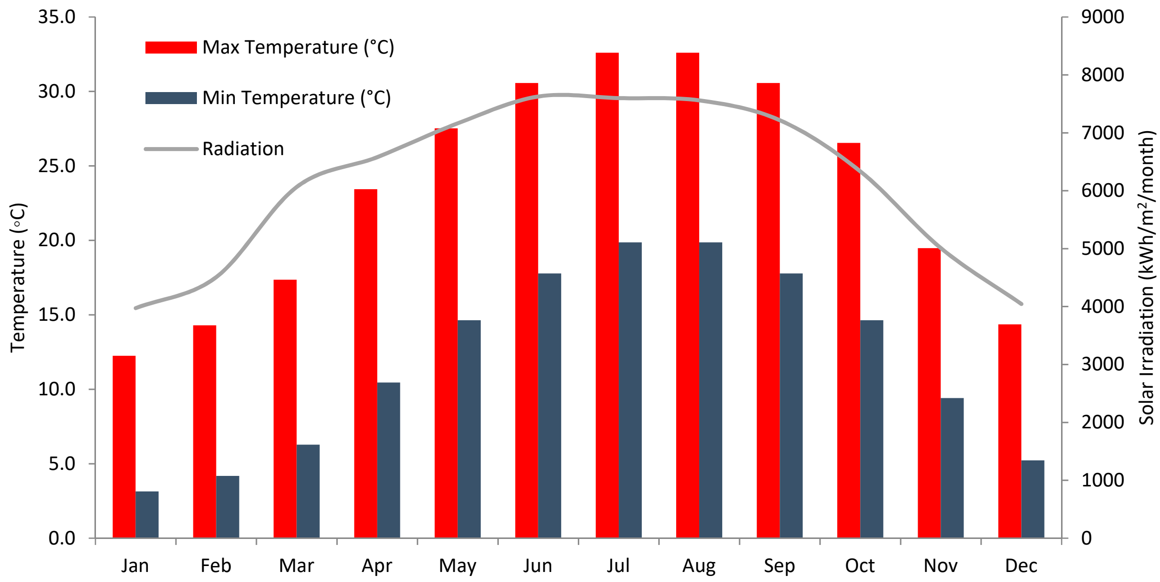


Figure 1. Maximum and minimum temperatures (°C) and solar irradiation (kWh/m^2/month) recorded at the site.

The extant system of solar cooling and heating is positioned on the roof of Building C located on the GJU campus in Amman, Jordan, in which approximately 5000 students are enrolled. The absorption system that was examined for this study will complement the already installed traditional compression system in Building C. Building C's cooling capacity equates to 0.7 MW and the proportion of H_2O-LiBr was intended to be approximately 10% of the overall cooling capacity. Building C comprises four storeys, as well as a basement, where the overall floor area is around 7500 m^2. The ground and third floors are primarily used as offices and laboratories, whereas the other floors include classrooms and offices for academic personnel.

2.3. Photovoltaic System Description

There are 6697 solar modules and 79 solar inverters on the campus of GJU in Amman, which are spread across different facilities within the campus that are designed as carports for 600 vehicles, as well as aisle canopies for pedestrians and students, in addition to plants on building rooftops and those of prefabricated structures, as illustrated in Figure 2. All the above-mentioned plans add to the formation of shaded zones for pedestrians and vehicles, while also enhancing the aesthetic quality of the campus. A supervisory control and data acquisition system (SCADA) was also included in the project, which incorporates the latest technology used to control and monitor all system elements and productivity, as well as to immediately deal with issues or failures that may happen when the system is operating. Additionally, an integrated wireless automatic Vantag weather station was incorporated into the project to monitor specific environmental and meteorological factors, such as solar radiation, temperature and precipitation ratios, which has rendered it the focus of scientific research and a variety of different projects by connecting its outputs with the plant's outputs and productivity.

The PV system's size was 2.1 MWp, while the utility grid connection was a 0.4 kV 50 Hz net meter (2 m) and it was anticipated that 3300 MWh/year will be generated, which is enough to satisfy the electricity needs of the whole campus. Jinko Solar supplied the silicon polycrystalline Wp utilised, which had a module efficiency of >16% in normal testing conditions. Multistring inverters from ABB for the grid inverter technology PV mounting structure were constructed from aluminium and galvanised steel supplied by Schletter (type of installation: predominantly installed in car parks along with a number of rooftops).

Figure 2. Photovoltaic (PV) technology layout over the German Jordanian University (GJU) campus.

2.4. Air Conditioning Systems

The energy efficiency of newly developed air conditioning units has increased significantly. They utilise variable speed motors for the purpose of maximising the airflow efficiency by operating at different speeds to correspond with the output and also include an automatic fan delay switch such that any residual cool air can be pushed into the building to be reused. Thermal expansion valves limit the refrigerant flow when required in order for the consumption of energy to be minimised.

Air conditioners come in five different types, each with a different purpose: basic central AC, ductless (mini-split air conditioners), portable unit, window unit and portable and window unit (hybrid). The least costly air conditioning option is a portable or window AC unit to cool an individual room. Mini-split air conditioners offer cost-effectiveness when only a few rooms or offices must be cooled. A more costly alternative is the central air conditioning unit, which is more suitable for large buildings with multiple rooms.

Natural, i.e., non-synthetic, refrigerants that can be used as refrigerants in air conditioning systems include various natural hydrocarbons, carbon dioxide, ammonia, and water. They are replacements for artificial refrigerants (chlorofluorocarbon (CFC), hydrofluorocarbon (HFC) and hydrochlorofluorocarbon (HCFC)) [47].

Both the seasonal coefficient of performance (SCOP) value for heating and the seasonal energy efficiency ratio (SEER) value for cooling are reflective of the actual amount of energy consumed by a heat pump. Both temperature variations and periods of standby are considered in the longer term to provide a clear and reliable picture of the average energy efficiency that can be achieved across a whole heating or cooling season. The energy efficiency rating (SEER) is an indicator of the volume of BTUs that are removed each hour for every watt of power used, whereby an increased rating denotes that the energy efficiency is higher and the SEER values of central air conditioners range between 13 and 24.

2.5. Coupled PV and Air Conditioning

Most common PV efficiencies are around 15 to 20%, while some high-quality PV panels can go above 22% efficiency. The efficiency of PV technology has increased and the cost has dropped in the past few years due to large scale installations and the learning curve. The c-Si PV module has around a 75% share of the PV technology market. PV systems' prices are expected to decrease by 60% in the coming decade [48].

In this research, two electricity sources were used to power the air conditioners: the main source was photovoltaic, while the utility grid acted as a backup for periods without sunlight, where the system automatically switched between sources, ensuring that the power supply was not disrupted. They could be utilised in air conditioning mode in addition to heating or dehumidification modes. Both the photovoltaic panels and 220 V grid power supply were directly connected to an external unit, as shown in Figure 3. It included a dual MPPT tracker to optimise the usage of available solar energy and to reduce the extent to which the electricity grid was used.

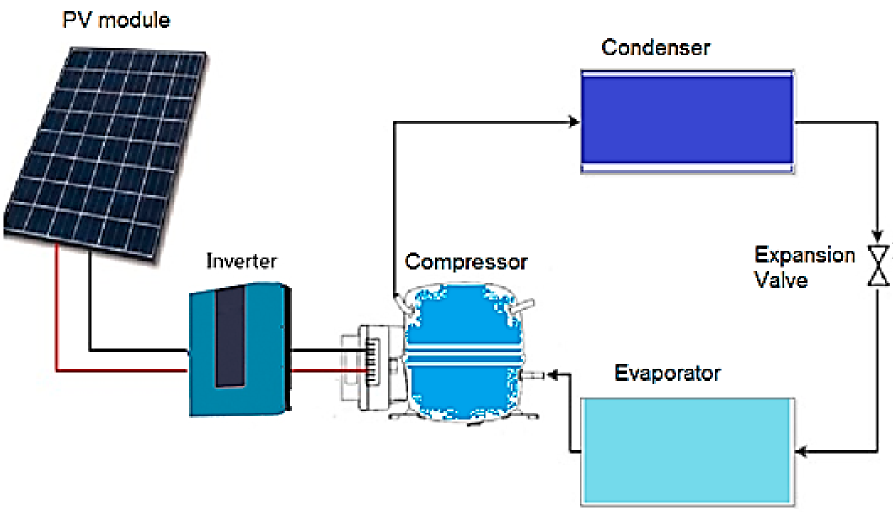


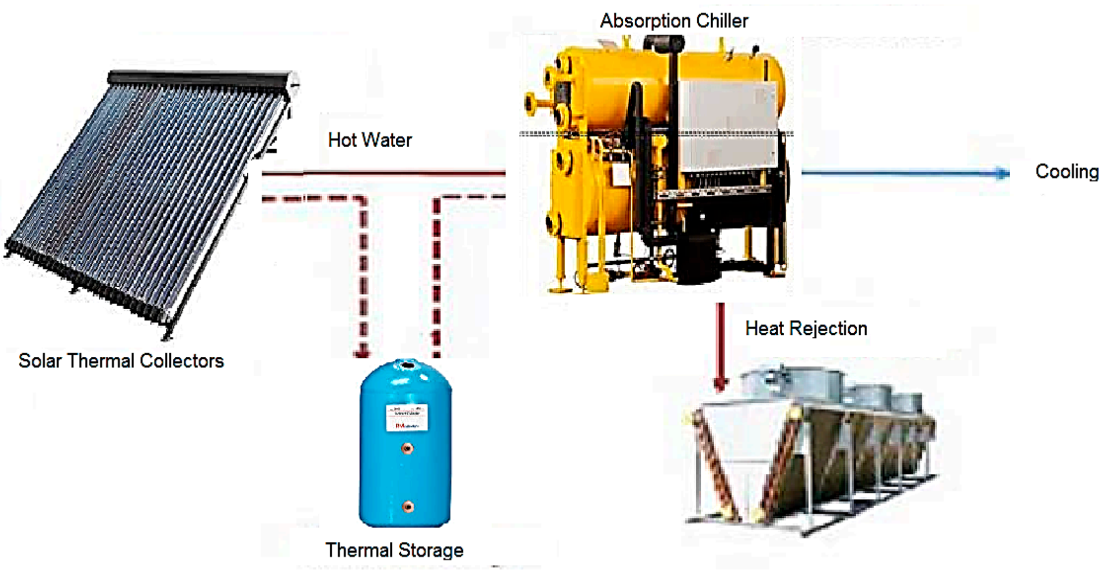
Figure 3. Coupled PV and air conditioning main components.

The seasonal refrigeration efficiency (SEER), which denotes the air-conditioner's cooling output over the electricity costs, can be as high as 24 BTU/W. When the sun is shining, hybrid air conditioners function completely on the photovoltaic source, and if energy class A+++, can offer 3500 W (12,000 BTU) or 5000 W (18,000 BTU) of air conditioning and heating.

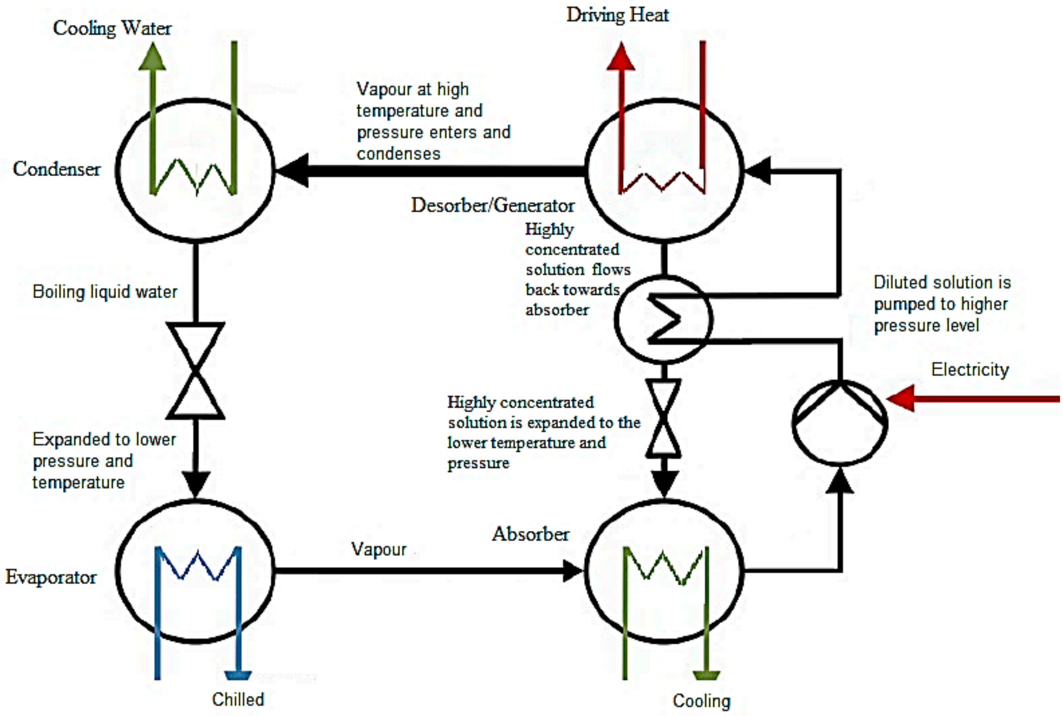
2.6. Solar Thermal Cooling System

Driving absorption chillers in which the thermal energy is supplied by solar collectors and the absorption chillers provided the cooling for the purpose of supporting the compression chillers autonomously. An available option was that thermal energy could be stored to minimise the variation and extend the source of cooling after the sun has set. When functioning in the form of a heat pump, absorption chillers can also provide heat in winter.

The installation of the solar cooling and heating system was situated on Building C's rooftop on the campus of GJU. The solar heating system comprised thirty arrays of solar collectors that were each formed from a series of five connected modules. Every module possessed eighteen tube collectors (evacuated) containing multiple parabolic collectors. The total surface area of the solar field's aperture was 450 m^2, while the collectors were positioned in a southerly facing direction, with an angle of 45° between the horizontal plane and the solar plane. The solar collector field located on the rooftop of Building C is shown in Figure 4 [49].



(a)



(b)

Figure 4. (**a**) Solar thermal cooling system main components and (**b**) absorption chiller cycle.

Water was supplied at a temperature of 85 °C to the absorption chiller, which was equal to 44,000 kWh of thermal energy for the absorption chiller out of the 250,000 kWh generated by the collectors. The solar heating system included a total of four storage tanks (heat), where each had a capacity of 3.5 m^3. One of the aforementioned tanks was utilised for Building C's domestic hot water. In the solar hydraulic system, there was a hot water pump for each of the storage tanks, a pair of gas boilers (total capacity of 380 kW) and a dry cooler for the removal of surplus heat [49].

The traditional cooling system comprised a pair of cooled multistage compression chillers, both of which were 700 kW (one operation/one standby), where one of the chillers could additionally function as a heat pump that only worked when the heating load overtook the capability of the absorbed solar availability on site, as well as the pair of boilers on cold days in the winter when the amount of solar gain was negligible or zero. The multistage compression chillers' evaporator supplied chilled water during summer at a predetermined temperature [49].

The system's internal sensors comprised pressure and temperature sensors. Measurements were taken for the pressure within the vapour space of the three containers and the bottom of the evaporator. Temperature measurements were taken at nine positions: the absorber, desorber and evaporator reservoirs; the evaporator circuit's condenser refrigerant sump; both the outlets and inlets of the solution heat exchanger. Five ultrasonic flow meters were utilised for the purpose of measuring the flow rates for the various circuits, namely, the condenser, solar collector, generator, compression chillers and evaporator. An ultrasonic heat flow meter (Ultraflow 54 DN 150–250) was employed in the primary chilled water network, whereas T550 ULTRACOLD/ULTRAHEAT (UH50) ultrasonic heat flow meter devices were used for the remaining circuits.

The process of determining the global solar irradiance on a horizontal surface was performed using a pyranometer. Ambient air measurements were obtained using an ARFT/A-I/S sensor. Additionally, the amount of electrical energy consumed by the components required in the solar cooling system was measured (in kWh) using a watt-hour meter type iEM3150 [49].

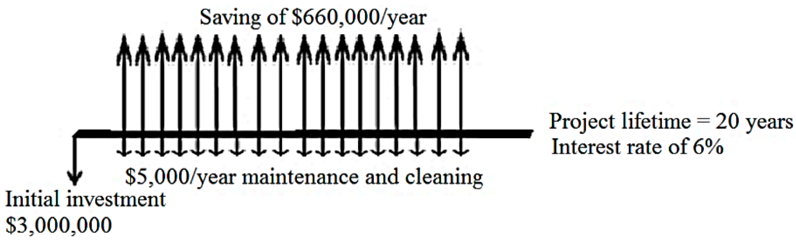
3. Results and Discussions

In this research, two kinds of cooling systems were investigated, in which the power was supplied by a photovoltaic system and a solar thermal cooling system, respectively, where both were situated on the grounds of German Jordanian University (GJU) in Amman, Jordan.

3.1. Coupled PV and Air Conditioning

The continual, significant decline in the cost of electricity produced by utility-scale PV extended into 2018, with a decline in the worldwide weighted-average levelised cost of energy (LCOE) of PV technology to $0.085/kWh, which represents a 13% decrease compared to projects implemented in 2017. Consequently, the decrease in the worldwide weighted-average LCOE of PV technology between 2010 and 2018 amounted to 77%. A further 94 GW of capacity was added in 2018, which amounted to 55% of the overall renewable power generation capacity expansion. In 2010, the worldwide weighted-average LCOE of the utility scale was $0.371/kWh, which had decreased to $0.085/kWh by 2018, a decline of 77% compared to 2010 and an annual decrease of 13%. The reductions in cost in 2018 were complemented by decreases in the price of crystalline silicon modules ranging from 26 to 32%. As of December 2018, the European module prices for high-efficiency modules varied between $216/kW and $400/kW. The LCOE of utility-scale PV technology had an estimated learning rate for the period between 2010 and 2020 that was greater than the International Renewable Energy Agency (IRENA) estimate of 35% reported in January 2019. Recent data indicates that the cost of electricity generated using PV technology could decrease to $0.048/kWh by 2020 [50].

The original cost of the PV system and air conditioning units was approximately £3M and has saved around $655K/year (minus the maintenance and cleaning ($5K)); the expected life for the PV system is around 20 years and the interest rate for this calculation was 6% per year with no salvage value for the system after 20 years. The present value profit minus the expenses will be approximately $7,455,450 across the lifetime of the project. The cooling capacity of a total floor area of around 7500 m^2 with 200 occupants will need to be approximately 118 tons (1,415,200 BTU or 415 kW), which can be achieved via the installation of a number of central air conditioners (6 units × 20 tones), which is less expensive than the existing price of $100k that is available on the market. As demonstrated by Figure 5 shown below, the PV system installed on the campus of GJU had an LCOE of under $0.05/kWh ($0.045/kWh), which was attributed to the wide accessibility of solar radiation on the campus, which is exposed to 300 days of sun on an annual basis.



$$\text{Present Worth} = A\left[\frac{(1+i)^N-1}{i(1+i)^N}\right] = \$7{,}455{,}450$$

Figure 5. Cash flow diagram including the present worth of the future money with an interest rate of 6% over a period of 20 years.

3.2. Solar Thermal Cooling System

The solar field on the campus had a complex design with regard to the provision of hot water to generate the weak solution of H_2O-LiBr because the solar collector was additionally utilised to heat water in Building C for domestic use.

The system's overall cost was $350k. The cost of the absorption chiller was $88k, whereas the solar field cost $145k, which accounted for the largest proportion of the system costs. The cost for the absorber and for condenser units was $28k, while the auxiliary unit was around $48k. A critical factor in assessing a solar thermal system's viability is the economic feasibility analysis due to the fact that initial investments can be high [49].

The life expectancy of the system was determined on the basis of the lifespan of the system components and the necessary maintenance. The feasibility analysis involved the calculation of two different scenarios with a lifespan greater than 25 years. The energy saved across the 25-year lifespan was calculated by estimating the amount of electrical energy that would be saved when running the system according to local Jordanian distribution companies. The operating and maintenance (O and M) cost percentage was determined on the basis of the varying costs incurred when operating and maintaining the system over its lifetime. Additionally, the yearly inflation in the O and M costs was determined as the inflation rate of the O and M costs on an annual basis. The operating cost was primarily generated by the functioning of the system's auxiliary components (the chilled water pumps, cooling, heating, and dry coolers) [49].

For the purposes of the present study, the assumption was made that the interest rate was 6%. According to the central bank guidelines, the absorption cooling system's feasibility for a lifetime of 25 years required a COP of 0.79. The net present worth equalled $256k, whereas the payback period equated to 10 years. Nevertheless, according to the results of the feasibility analysis of the absorption cooling system using actual measurements taken over a period of four months in the summer (May 2015–August 2015), the system's average COP was 0.32, thus indicating the lack of feasibility of the system, as the net present value equalled −$195k and the payback period was 45 years, which was more than the project's anticipated lifespan [49].

Furthermore, the absorption cooling system was perceived to lack economic feasibility due to the fact that the payback period was longer than the anticipated lifespan of the system according to the identified cooling capacity. Additionally, the cost of the absorption chiller system was conducted on the basis of the LCOE. In order to calculate the LCOE, the net present value was divided by the overall cost of operating the power generating unit and absorption chiller system and the total electrical energy savings across the system's lifespan. When the system is operating at a maximum COP of 0.79 (under standard test conditions) and the actual recorded COP of 0.32 on the site, the respective LCOE values were $0.9/kWh and $2.35/kWh. In this study, we assumed the electricity tariffs based on total demand (not peak demand) were fixed at $0.1/kWh; as such, it is clear that the absorption chiller does not have economic feasibility [49].

As the initial cost for installing the solar thermal cooling system on one building was $350k, the cost will rise to $3.150M if it is installed on 9 buildings throughout the campus, while the initial cost for the central air conditioning and PV system is $3M. When discounted by 6% per year, the present worth of future cash payments is approximately $9,745,000, whereas the solar thermal cooling system will not reach the breakeven point with a value of negative $1,730,000, as illustrated in Figure 6. The solar thermal cooling system's LCOE value was $2.35/kWh, whereas the value for the coupled PV and air conditioning systems was under $0.05/kWh.

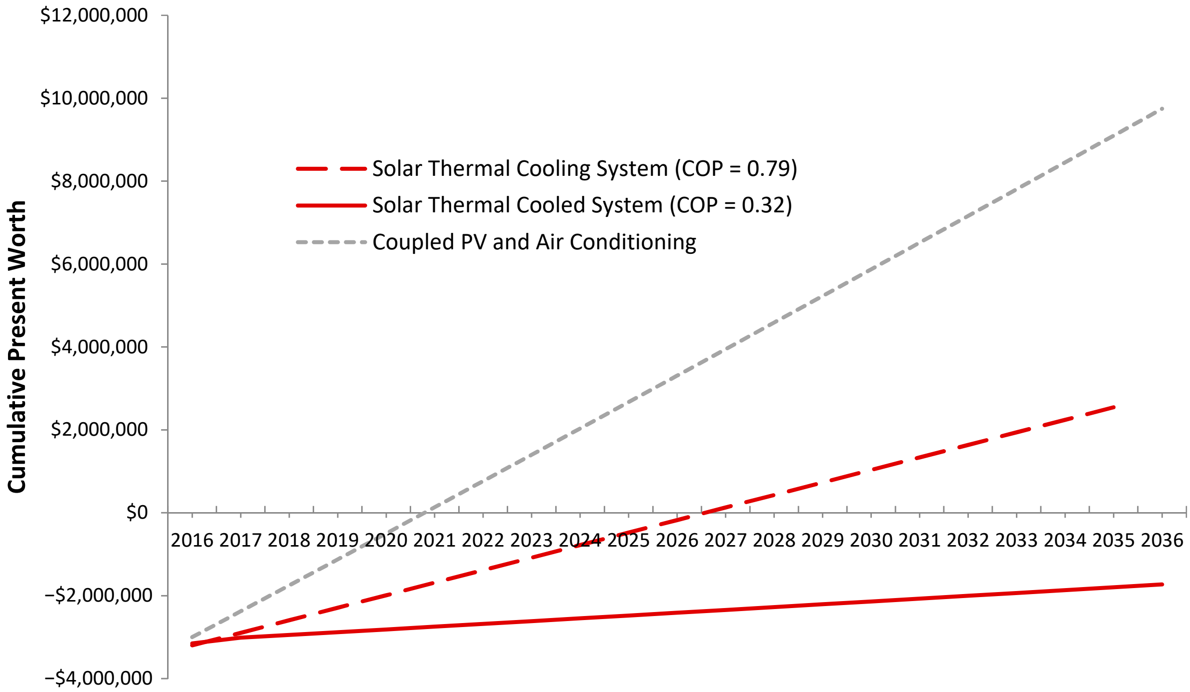


Figure 6. Payback period and the cumulative present worth across the lifespan for the two alternatives.

However, assuming the solar cooling system will run at it is maximum COP of 0.79, this will increase the feasibility of the project and the payback time of the project to around 10 years, which is still way below the coupled PV and air-conditioning systems. The internal rate of return (IRR) to estimate the profitability of different options is summarized in Table 1.

Table 1. Internal rate of return (IRR) for different cooling systems.

Cooling Option	IRR
Solar Thermal Cooling System (COP = 0.79)	5%
Solar Thermal Cooling System (COP = 0.32)	−4%
Coupled PV and Air Conditioning	19%

In addition to the extensive maintenance needs, the reduced COP, along with the practicality and feasibility of the solar thermal cooling systems, mean these kinds of technologies are under significant pressure to remain competitive when faced with the development of new air conditioning and PV technologies.

4. Conclusions

Solar heating power systems for the purpose of cooling buildings were purported to be a turning point in the quest to find environmentally friendly technologies in the energy field. Jordan is a pioneer among developing nations in terms of the utilisation of solar thermal energy for cooling buildings. In this study, a solar thermal system and air conditioning that was driven by PV technology were evaluated. From the outset, solar cooling systems were planned to be cost-effective and environmentally friendly alternatives for many developing nations situated in hot climates, which could replace the traditional air conditioning systems where the supplied power is electricity generated from fossil fuels. Nevertheless, the development of PV technology and air-conditioning technologies impacts the prospects of solar cooling systems. This study analysed two different options for cooling: PV technology coupled with air conditioning and a solar cooling system (absorption chillers where solar collectors provide the thermal energy) for a specific developing country located in the Eastern Mediterranean region that is characterised by a hot dry climate (Jordan).

These two kinds of cooling systems, in which the power was supplied by a photovoltaic and solar thermal cooling system, respectively, were situated on the campus of GJU situated in Amman, Jordan. The findings indicated that the solar thermal cooling system's initial cost was approximately $3.150M, whereas it was about $3M for the central air conditioning and PV system. When discounted by 6% per year, the present worth of future cash payments for the PV technology coupled with air conditioning was approximately $9,745,000, whereas the solar thermal cooling system will not reach the breakeven point at negative $1,730,000; additionally, the solar thermal cooling system's LCOE value is $2.35/kWh, whereas the value for the air conditioning system coupled with PV is under $0.05/kWh.

The implementation of solar thermal cooling systems within developing countries has certain shortcomings, including the increased costs, and more importantly, the fact that there is a lack of experience in using such systems in these countries. Added to the extensive maintenance needs, the reduced COP and the practicality and feasibility of the solar thermal cooling systems increase the pressure on such technologies to maintain competitiveness when faced with the developments in air conditioning and PV technologies.

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References

1. U.S. Energy Information Administration. International Energy Outlook 2016. 2016. Available online: https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf (accessed on 10 November 2020).
2. Metayer, M.; Breyer, C.; Fell, H.J. The projections for the future and quality in the past of the World Energy Outlook for solar PV and other renewable energy technologies. In Proceedings of the 31st European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 14–18 September 2015; Volume 5.
3. Li, Y.; Zhang, G.; Lv, G.Z.; Zhang, A.N.; Wang, R.Z. Performance study of a solar photovoltaic air conditioner in the hot summer and cold winter zone. *Sol. Energy* **2015**, *117*, 167–179. [CrossRef]
4. Zeyghami, M.; Goswami, D.Y.; Stefanakos, E. A review of solar thermo-mechanical refrigeration and cooling methods. *Renew. Sustain. Energy Rev.* **2015**, *51*, 1428–1445. [CrossRef]
5. Abdulateef, J.M.; Sopian, K.; Alghoul, M.A.; Sulaiman, M.Y. Review on solardriven ejector refrigeration technologies. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1338–1349. [CrossRef]
6. Zhai, X.Q.; Qu, M.; Li, Y.; Wang, R.Z. A review for research and new design options of solar absorption cooling systems. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4416–4423. [CrossRef]
7. Wang, R.Z.; Oliveira, R.G. Adsorption refrigeration—An efficient way to make good use of waste heat and solar energy. *Prog. Energy Combust. Sci.* **2006**, *32*, 424–458. [CrossRef]
8. Dai, Y.J.; Wang, R.Z.; Xu, Y.X. Study of a solar powered solid adsorption–desiccant cooling system used for grain storage. *Renew. Energy* **2002**, *25*, 417–430. [CrossRef]
9. Wang, R.Z.; Ge, T.S. *Advances in Solar Heating and Cooling*; Woodhead Publishing: Sawston, UK, 2016.
10. Kouro, S.; Leon, J.I.; Vinnikov, D.; Franquelo, L.G. Grid-connected photovoltaic systems: An overview of recent research and emerging PV converter technology. *IEEE Ind. Electron. Mag.* **2015**, *9*, 47–61. [CrossRef]

11. Mammoli, A.; Barsun, H.; Burnett, R.; Hawkins, J.; Simmins, J. Using highspeed demand response of building HVAC systems to smooth cloud-driven intermittency of distributed solar photovoltaic generation. In Proceedings of the IEEE PES Transmission and Distribution Conference and Exposition, Orlando, FL, USA, 7–10 May 2012; pp. 1–10.
12. Schibuola, L.; Scarpa, M.; Tambani, C. Demand response management by means of heat pumps controlled via real time pricing. *Energy Build.* **2015**, *90*, 15–28. [CrossRef]
13. Zhang, W.; Lian, J.; Chang, C.Y.; Kalsi, K. Aggregated modeling and control of air conditioning loads for demand response. *IEEE Trans. Power Syst.* **2013**, *28*, 4655–4664. [CrossRef]
14. Li, Y.; Zhao, B.Y.; Zhao, Z.G.; Taylor, R.A.; Wang, R.Z. Performance study of a gridconnected photovoltaic powered central air conditioner in the South China climate. *Renew. Energy.* **2017**, *126*, 1113–1125. [CrossRef]
15. Xu, Y.; Li, M.; Luo, X.; Ma, X.; Wang, Y.; Li, G.; Hassanien, R.H.E. Experimental investigation of solar photovoltaic operated ice thermal storage air-conditioning system. *Int. J. Refrig.* **2018**, *86*, 258–272. [CrossRef]
16. Wang, X.; Dennis, M. Influencing factors on the energy saving performance of battery storage and phase change cold storage in a PV cooling system. *Energy Build.* **2015**, *107*, 84–92. [CrossRef]
17. Fong, K.F.; Chow, T.T.; Lee, C.K.; Lin, Z.; Chan, L.S. Comparative study of different solar cooling systems for buildings in subtropical city. *Sol. Energy* **2010**, *84*, 227–244. [CrossRef]
18. Klein, A.; Beckman, A.; Mitchell, W.; Duffie, A.; Duffie, N.; Freeman, T. *TRNSYS 17—A Transient System Simulation Program*; Solar Energy Laboratory: Madison, WI, USA, 2011.
19. Hartmann, N.; Glueck, C.; Schmidt, F.P. Solar cooling for small office buildings: Comparison of solar thermal and photovoltaic options for two different European climates. *Renew. Energy* **2011**, *36*, 1329–1338. [CrossRef]
20. Mokhtar, M.; Ali, M.T.; Bräuniger, S.; Afshari, A.; Sgouridis, S.; Armstrong, P.; Chiesa, M. Systematic comprehensive techno-economic assessment of solar cooling technologies using location-specific climate data. *Appl. Energy* **2010**, *87*, 3766–3778. [CrossRef]
21. ASHRAE. *ASHRAE 62-2001, Ventilation for Acceptable Indoor Air Quality*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2001.
22. Öberg, V.; Goswami, D.Y. Experimental Study of the Heat and Mass Transfer in a Packed Bed Liquid Desiccant Air Dehumidifier. *J. Sol. Energy Eng.* **1998**, *120*, 289. [CrossRef]
23. Sayed, M.A.A.E.D.A.; Fikry, M.A. Impact of Glass Facades on Internal Environment of Buildings in Hot Arid Zone. *Alex. Eng. J.* **2019**, *58*, 1063–1075. [CrossRef]
24. Huang, L.; Zheng, R. Energy and Economic Performance of Solar Cooling Systems in the Hot-Summer and Cold-Winter Zone. *Buildings* **2018**, *8*, 37. [CrossRef]
25. Martínez, P.J.; Martínez, P.; Soto, V.M.; Bujedo, L.A.; Rodriguez, J. Design of a 35 KW Solar Cooling Demonstration Facility for a Hotel in Spain. *Appl. Sci.* **2020**, *10*, 496. [CrossRef]
26. Pesaran, A.A.; Neymark, J. *Potential of Solar Cooling Systems for Peak Demand Reduction*; National Renewable Energy Laboratory: Golden, CO, USA, 1995.
27. Kalkan, N.; Young, E.A.; Celiktas, A. Solar Thermal Air Conditioning Technology Reducing the Footprint of Solar Thermal Air Conditioning. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6352–6383. [CrossRef]
28. Calm, J.M. Emissions and Environmental Impacts from Air-Conditioning and Refrigeration Systems. *Int. J. Refrig.* **2002**, *25*, 293–305. [CrossRef]
29. Ma, Y.; Saha, S.; Miller, W.; Guan, L. Comparison of Different Solar-Assisted Air Conditioning Systems for Australian Office Buildings. *Energies* **2017**, *10*, 1463. [CrossRef]
30. Henning, H.-M.; Döll, J. Solar Systems for Heating and Cooling of Buildings. *Energy Procedia* **2012**, *30*, 633–653. [CrossRef]
31. Jaradat, M.; Al-Addous, M.; Albatayneh, A. Adaption of an Evaporative Desert Cooler into a Liquid Desiccant Air Conditioner: Experimental and Numerical Analysis. *Atmosphere* **2019**, *11*, 40. [CrossRef]
32. Rafique, M.; Rehman, S.; Alhems, L.; Ali Shakir, M. A Liquid Desiccant Enhanced Two Stage Evaporative Cooling System—Development and Performance Evaluation of a Test Rig. *Energies* **2017**, *11*, 72. [CrossRef]
33. Niemann, P.; Richter, F.; Speerforck, A.; Schmitz, G. Desiccant-Assisted Air Conditioning System Relying on Solar and Geothermal Energy during Summer and Winter. *Energies* **2019**, *12*, 3175. [CrossRef]
34. Narayanan, R.; Halawa, E.; Jain, S. Dehumidification Potential of a Solid Desiccant Based Evaporative Cooling System with an Enthalpy Exchanger Operating in Subtropical and Tropical Climates. *Energies* **2019**, *12*, 2704. [CrossRef]
35. Choudhury, B.; Saha, B.B.; Chatterjee, P.K.; Sarkar, J.P. An Overview of Developments in Adsorption Refrigeration Systems towards a Sustainable Way of Cooling. *Appl. Energy* **2013**, *104*, 554–567. [CrossRef]
36. Halon, T.; Pelinska-Olko, E.; Szyc, M.; Zajaczkowski, B. Predicting Performance of a District Heat Powered Adsorption Chiller by Means of an Artificial Neural Network. *Energies* **2019**, *12*, 3328. [CrossRef]
37. Dieng, A.O.; Wang, R.Z. Literature Review on Solar Adsorption Technologies for Ice-Making and Air-Conditioning Purposes and Recent Developments in Solar Technology. *Renew. Sustain. Energy Rev.* **2001**, *5*, 313–342. [CrossRef]
38. Shirazi, A.; Taylor, R.A.; Morrison, G.L.; White, S.D. Solar-Powered Absorption Chillers: A Comprehensive and Critical Review. *Energy Convers. Manag.* **2018**, *171*, 59–81. [CrossRef]
39. Ghafoor, A.; Munir, A. Worldwide Overview of Solar Thermal Cooling Technologies. *Renew. Sustain. Energy Rev.* **2015**, *43*, 763–774. [CrossRef]

40. Albatayneh, A.; Alterman, D.; Page, A.; Moghtaderi, B. The significance of the Adaptive thermal Comfort Limits on the Air-Conditioning Loads in a Temperate climate. *Sustainability* **2019**, *11*, 328. [CrossRef]
41. Albatayneh, A.; Alterman, D.; Page, A.; Moghtaderi, B. The impact of the thermal comfort models on the prediction of building energy consumption. *Sustainability* **2018**, *10*, 3609. [CrossRef]
42. Albatayneh, A.; Alterman, D.; Page, A.; Moghtaderi, B. Development of a new metric to characterise the buildings thermal performance in a temperate climate. *Energy Sustain. Dev.* **2019**, *51*, 1–12. [CrossRef]
43. Albatayneh, A.; Alterman, D.; Page, A.; Moghtaderi, B. Assessment of the thermal performance of complete buildings using adaptive thermal comfort. *Procedia Soc. Behav. Sci.* **2016**, *216*, 655–661. Available online: https://www.greencooling-initiative.org (accessed on 10 November 2018). [CrossRef]
44. Weiss, W.; Spörk-Dür, M. Solar Heat Worldwide. Global Market Development and Trends in 2017. Detailed Market Figures 2016. Available online: https://www.iea-shc.org/Data/Sites/1/media/events/webinars/2018-06-12/shc-market-and-industry-trends--wweiss.pdf (accessed on 5 March 2020).
45. Alrwashdeh, S.S.; Alsaraireh, F.M.; Saraireh, M.A. Solar radiation map of Jordan governorates. *Int. J. Eng. Technol.* **2018**, *7*, 1664–1667. [CrossRef]
46. Solar Cooling for Industry and Commerce (SCIC)—Study on the Solar Cooling Potential in Jordan. 2013 Deutsche Gesellschaft für International Zusammenarbeit (GIZ) GmbH. Available online: https://energypedia.info/images/3/33/Solar_Cooling_for_Industry_and_Commerce_%E2%80%93_Study_on_the_Solar_Cooling_Potential_in_Jordan.pdf (accessed on 22 November 2020).
47. ASHRAE. Position Document on Natural Refrigerants. Available online: https://www.epa.gov/sites/production/files/documents/ASHRAE_PD_Natural_Refrigerants_2011.pdf (accessed on 22 November 2020).
48. Cengiz, M.S.; Mamiş, M.S. Price–efficiency relationship for photovoltaic systems on a global basis. *Int. J. Photoenergy* **2015**. [CrossRef]
49. Jaradat, M.; Al-Addous, M.; Albatayneh, A.; Dalala, Z.; Barbana, N. Potential Study of Solar Thermal Cooling in Sub-Mediterranean Climate. *Appl. Sci.* **2020**, *10*, 2418. [CrossRef]
50. Anuta, H.; Ralon, P.; Taylor, M.; La Camera, F. Renewable Power Generation Costs in 2018. International Renewable Energy Agency, Abu Dhabi. 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf (accessed on 20 November 2020).