Measurement Results and Operating Experience of Large-Scale Solar Air Conditioning Plants

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Abstract

The demand for air-conditioning has increased in the past years and is expected to rise even further. As an alternative to conventional air-conditioning systems, solar cooling may be used to reduce electricity peak loads and at the same time delivering environmentally-friendly cooling. This paper aims to analyze the monitoring data of four of the currently largest solar air-conditioning systems in order to show the potential of solar cooling systems and outline trends. This is done by calculating key performance indicators considering the boundary conditions, financials as well as solar and chiller performance of each system.

All solar systems performed as planned during the 7-month long calculation period, yielding more than 5.1 GWh total solar energy yield, with an average solar conversion factor of 34.6% and electric efficiency ratios of up to 26. The results also show increased performance of the solar collectors of the recently build (2017) solar system compared to the older ones commissioned in 2011 and 2014, with up to 46% higher solar conversion factors. Additionally, specific system costs decreased by approximately 70%. Even though the paper only could analyze four different solar systems with different boundary conditions, the sheer magnitude of performance and construction-cost improvements clearly supports the hypothesis that both costs and performance improved.

Keywords: solar cooling, large-scale solar thermal system, measurement results,

1. Introduction

In the past years the demand for air-conditioning and electric energy consumption has increased and is expected to rise even further (OECD/IEA 2018). Especially in hot tropical or subtropical countries increasing population and urbanization is expected to accelerate cooling demand (OECD/IEA 2018, Waite et al. 2017).

Conventionally, cooling is done with vapor compression refrigeration machines which are driven by electrical energy. However, to reduce the resulting high electricity peak loads and at the same time provide environmentally friendly cooling, solar thermal air-conditioning proved to be a good alternative. The combination of a solar system and a heat powered absorption chiller is especially beneficial as cooling demand perfectly aligns with available solar irradiation. Even though the technology is market-ready (SHC Task 48 2015), system designers are often faced with a lack of awareness and confidence for solar thermal cooling (Olsacher and Schnitzer 2016).

Therefore, this paper aims to show the potential of solar thermal air conditioning systems and tries to outline system-price and performance trends by analyzing the monitoring data of four of the currently largest solar thermal cooling systems worldwide. All of them were designed, installed and are operated by the company SOLID, which is a pioneer in this field of knowledge. The range of selected solar plants covers different climate conditions and systems with long monitoring periods as well as newly installed state-of-the-art systems. Furthermore, extensive monitoring equipment is installed at the different systems used for collecting and analyzing the monitoring data.

2. Selected Solar Systems

In this section a short overview of each selected solar system is given. From here on the systems are symbolized by their abbreviations: UWC, DMHS, MANAGUA and IKEA.

2.1 United World Collage (UWC)

At the United World Collage, Singapore, 3872m² of flat plate collectors were commissioned by SOLID in August 2011. The solar heat is used mainly for cooling the building, which encompass about 60000m² of air-conditioned space, but also to satisfy 100% of the domestic hot water demand. With a total of 2200 MWh/year of heat produced by the solar collectors supplying a 1475kW lithium bromide single effect absorption chiller, this solar plant was the largest solar cooling system worldwide until 2014 (Schubert et al. 2011, Olsacher and Schnitzer 2016). The collectors are positioned on the roof of the building facing different directions (see Fig.1 left). This way, the usage of available space and thus the solar fraction was optimized as collector orientation is less important due to Singapore’s location near the equator. Furthermore, two storage tanks with 30m³ each, together with a smaller 7m³ hot water tank were installed to store the solar heat (see Fig.1 right). The larger storage tanks are positioned next to each other in series and are used for both supplying the chiller with heat and feeding into the smaller domestic hot water tank if needed.

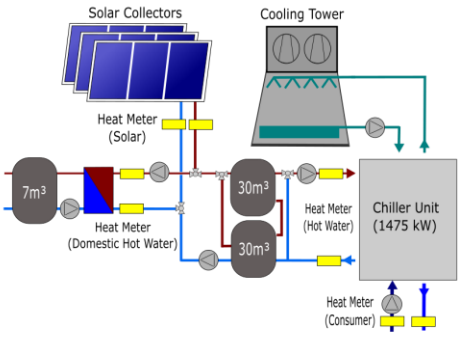

Fig. 1: Design view of the UWC campus with collector arrays in blue (left) and simplified hydraulic schema of UWC (right).

The school building with approximately 5000 enrolled students is located in the west of Singapore, near the Payar Lebar Air Base and the Bedok Reservoir. Situated in the tropical rainforest climate, there are no typical seasons as winter or summer, but constant high humidity, hot temperature and frequent and heavy rainfall. Average temperatures are in the range of 20°C to 34°C which lead to high cooling demands. However, high relative humidity of 80% throughout the year and the heavy rainfalls are a challenge for heat rejection at the cooling tower and for delivering heat at rainy days.

2.2 Desert Mountain High School (DMHS)

Fig. 2: Panorama view of DMHS.

In February 2014, SOLID commissioned a solar cooling system at the Desert Mountain High School in Scottsdale, Arizona (see Fig.2). With a gross collector area of 4935m² and a 1750kW lithium bromide absorption chiller, the solar system is currently the most powerful solar cooling system worldwide (Weiss and Spörk-Dür 2018) and has therefore also been previously studied by various authors (Schubert et al. 2011, 2014) (Buchinger et al. 2012) (Olsacher and Schnitzer 2016).

The school for over 2600 pupils has 55000m² of air-conditioned space, which is cooled with a solar driven lithium bromide single effect absorption chiller in combination with three conventional vapor compression chillers. The double-glazed flat plate solar collectors are positioned on different roofs of the building and are mainly tilted at 20 degrees, while some were installed with a 14 degrees tilt. For buffering the solar load, a 34.5m³ storage tank is used to connect the solar and chiller circuit (see Fig.3). As there are no accommodations for students, the solar heat is solely used for air conditioning during school operation.

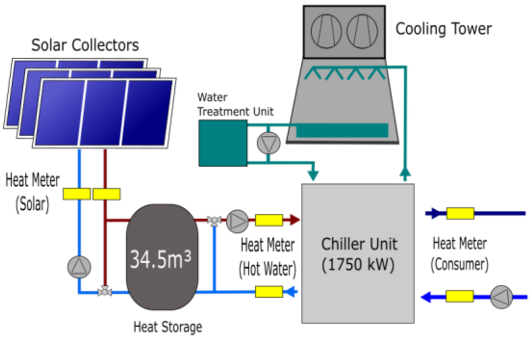

Fig. 3: Simplified hydraulic schema of DMHS.

DMHS is located in the arid desert climate and thus faces high ambient temperature, dry air and low precipitation. Ambient temperature ranges from over 45°C in July to low temperatures just above the freezing point in cold winter nights in January. Nevertheless, no anti-freeze protection has been used for the collector circuit as small amounts of water from the storage tank can be pumped through the collectors at these rare events to prevent freezing (Schubert et al. 2014). However, even in the winter high temperature maxima can occur during the day, resulting in cooling demand for approximately 12 months. In combination with the dry air, the climate is beneficial for the operation of the chiller and the cooling tower.

2.3 Hospital Managua (MANAGUA)

Fig. 4: Panorama view of 4450 m² collector area installed at Managua Hospital, Nicaragua.

The third of the selected solar systems was commissioned by SOLID in December 2017 at the Hospital *Militar Escuela Dr "Alejandro Dávila Bolaños"* in Managua, Nicaragua, with a collector area of 4450m² of high performance collectors (see Fig.4). Same as at UWC, the solar heat is not only used for cooling the building, but also for domestic heat for the laundry and the hospital. Therefore, a 75m³ storage tank is used to store the solar yield and to provide heat for the 1023kW lithium bromide single effect absorption chiller, the 2m² laundry tank and the 3.75m³ domestic hot water tank (see Fig.5).

MANAGUA has a tropical wet and dry climate, with a dry season between November and April and lots of rainfall between May and October. Nevertheless, ambient temperature is constantly high throughout the year with averages above 26°C. Relative humidity ranges between approximately 60% during the dry seasons to 80% during the rainy season.

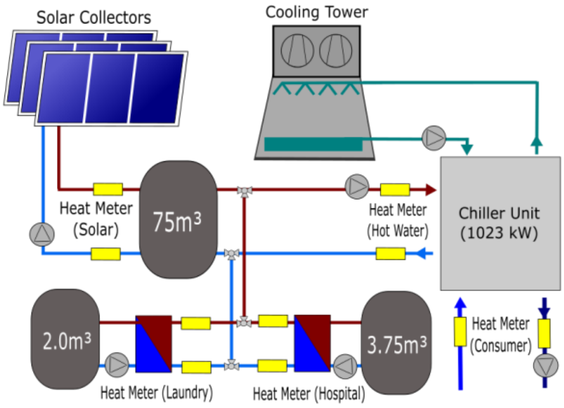

Fig. 5: Simplified hydraulic schema of MANAGUA.

2.4 Ikea Alexandria (IKEA)

Fig. 6: Panorama view of 2472m² collector area installed at IKEA.

Recently in December 2017, SOLID commissioned a solar cooling system with a collector area of 2472m² and an 880kW lithium bromide single effect absorption chiller at the Swedish furniture giant IKEA in Alexandria, Singapore (see Fig.6). Together with three conventional compression chillers, the solar powered chiller unit is used to cool the facility. The solar system with its 15m³ buffer storage reduces power consumption significantly and also helps to reduce expensive electricity costs. Due to Singapore's location near the equator, the solar collectors have been positioned at the top of the building facing southwest and northeast in turns to optimize annual solar yield and to minimize shading effects.

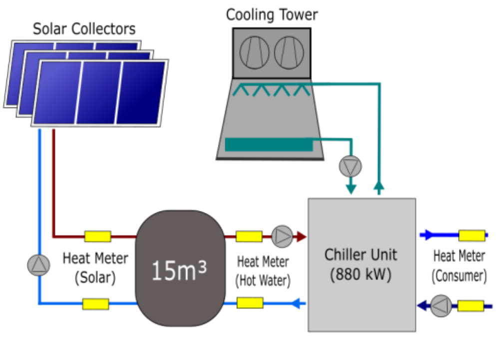

Fig. 7: Simplified hydraulic schema of IKEA.

Located in the same city as UWC, the solar system at IKEA faces the same tropical climate conditions as previously described. In contrast to UWC however, the cooling demand is not based on school operation, but almost constant throughout the year - determined by the opening hours and especially the number of visitors of the warehouse. Similar to DMHS, the solar heat is solely used for chilled water production (see Fig.7).

3. Method

Various key performance indicators can be calculated to analyze solar thermal cooling systems. To get a better overview, all considered key indicators are categorized into four different main categories, each describing a key section of a solar thermal air-conditioning plant: *Boundary Conditions*, *Solar Circuit*, *Chiller Circuit* and *Financials* (see Fig.8).

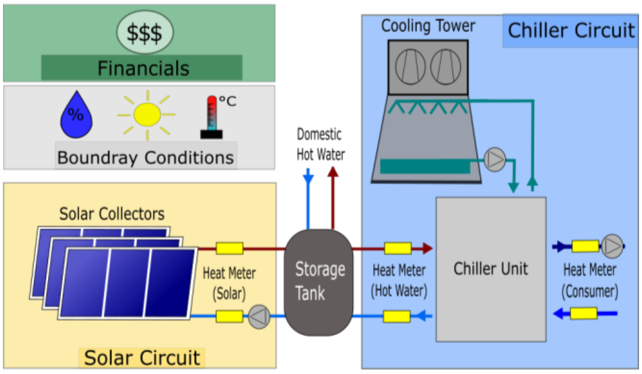

Fig. 8: Symbolic visualization of the key performance indicator categories: *Boundary Conditions*, *Solar Circuit*, *Chiller Circuit* and *Financials.*

To carry out this analyzation the monitoring data of each plant has been used, which is recorded in a one-minute interval and stored and pre-processed in SOLID's METHODIQA Database (Ohnewein et al 2016). For further analysis and visualization, the programming language Python has been used. The types of measurement devices used for collecting the monitoring data are shown in Tab.1. The calculation period is from 01.01.2018 to 31.07.2018, data from IKEA and MANAGUA is available since February and March 2018, respectively.

Tab. 1: Types of measurement devices installed at the selected solar systems.

Plant	Measurement Device	Brand	Description/Type
UWC	Radiation Sensor	MESA	MS-020VM
UWC	Temperature Sensors	TGH	PT1000 (1/3 DIN Class B, Silicone Cable)
UWC	Heat Meter	KAMSTRUP	ULTRAFLOW 54 + MULTICAL 602
UWC	Electric Power Meter	SCHRACK	Digital Industry Meter DIZ Generation G
DMHS	Radiation Sensor	MESA	MS-020VM
DMHS	Temperature Sensors	TGH	PT1000 (1/3 DIN Class B, Silicone Cable)
DMHS	Heat Meter	KAMSTRUP	ULTRAFLOW 54 + MULTICAL 602
DMHS	Electric Power Meter	SCHRACK	Digital Industry Meter DIZ Generation G
MANAGUA	Radiation Sensor	MESA	MS-020VM
MANAGUA	Temperature Sensors	TGH	PT1000 (1/3 DIN Class B, Silicone Cable)
MANAGUA	Heat Meter	KAMSTRUP	ULTRAFLOW 54 + MULTICAL 602
MANAGUA	Electric Power Meter	SCHRACK	NA 96
IKEA	Radiation Sensor	MESA	MS-020 VM (tilt: 0°)
IKEA	Temperature Sensors	TGH	PT1000 (1/3 DIN Class B, Silicone Cable)
IKEA	Heat Meter	KAMSTRUP	ULTRAFLOW 54+ MULTICAL 602
IKEA	Electric Power Meter	SCHRACK	Digital Industry Meter DIZ Generation G

3.1 Boundary Conditions

The environmental boundary conditions such as ambient temperature, humidity, radiation and energy demand of the consumers are important to bear in mind when analyzing other key indicators, as they are strongly influencing the performance of a solar system. Radiation is the main energy source of a solar thermal plant and thus is critical for comparing solar- or chilled-water energy yield. Ambient temperature also plays a vital role concerning heat losses and cooling demand. Humidity on the other hand strongly influences the heat rejection at the cooling tower. Therefore, average daily irradiation $\langle H \rangle$ and average ambient temperature $\langle T_a \rangle$ are calculated for each month, to show the potentials and challenges of solar cooling in these regions. As no measurement devices for humidity are installed at the systems, average relative humidity values are extracted from (Weatherbase) for each location.

3.2 Solar Circuit

The performance of the solar collectors and the produced solar heat are key to any solar thermal cooling system. To get comparable values, the specific solar yield $\tilde{Q}_s$ can be calculated by norming the solar energy yield Q_s by the gross collector area A_{col} of the considered system:

$$\tilde{Q}_s = \frac{Q_s}{A_{col}} \qquad \text{(eq. 1)}$$

For calculating the efficiency of the solar collectors, the solar conversion factor can be used, which characterizes the ratio of solar specific yield $\tilde{Q}_s$ to solar radiation H:

$$\eta_{col} = \frac{\tilde{Q}_s}{H} \qquad \text{(eq. 2)}$$

For both of these indicators daily averages are calculated. As indicated by Fig.8, produced solar heat Q_s is defined as heat supplied to the first (main) storage tank to consider different system designs regardless of whether domestic hot water is produced or not and whether the hot water tank is used as buffer or as storage device.

3.3 Cooling Circuit

To analyze the performance of a solar driven chiller unit, daily values for the electric- and thermal energy efficiency ratio (EER_{el} and EER_{th}) can be calculated:

$$EER_{th} = \frac{Q_c}{Q_{sup}} \qquad \text{(eq. 3)}$$

$$EER_{el} = \frac{Q_c}{Q_{el}} \qquad \text{(eq. 4)}$$

Here, Q_{sup} is the energy provided by the solar circuit that is supplied to the chiller unit, Q_c is the cooling energy that is transferred to the consumer and Q_{el} is the total electric energy used at the solar system for operating various pumps and the cooling tower. These indicators are often used for characterizing the performance of a chiller and are sometimes also called daily coefficient of performance (COP), or daily seasonal performance factor (SPF).

However, SOLIDs solar systems are never optimized in terms of chiller efficiency but in terms of providing useful energy. Therefore, the solar powered chiller will be in operation even if there are not full-load conditions as long as the electrical efficiency outnumbers the vapor compression chillers installed at these systems. Hence, this reduces the daily energy efficiency ratio, even though the system performs well during the day.

As the cooling tower at IKEA was preinstalled and is not only used by the solar thermal system, no electric meter to measure its electricity demand was installed. Therefore, its electric consumption corresponding to the solar absorption chiller is estimated by 80% of the remaining electric energy consumption, which is a benchmark derived as upper bound from data of the other selected solar systems.

3.4 Financials

Unfortunately, financial data is hard to compare due to various influencing factors such as different environmental conditions, the amount and quality of preinstalled equipment, customs, the availability of area and other specific construction-site dependencies. However, SOLID can provide rough benchmarks for the construction-costs of solar systems similar in terms of supply but not equal to the real solar systems, not taking into account any beneficial nor unfavorable influencing factors. Their values are based on SOLIDs vast experience for designing and installing various solar systems. For better comparison, these estimated total system-costs are normed by the gross collector area A_{col} and weighed by the solar conversion factor:

$$specific\ costs = \frac{costs}{A_{col} \cdot \eta_S} \qquad \text{(eq. 4)}$$

4. Monitoring Results

4.1 Boundary Conditions

At DMHS a seasonal pattern can be seen both for the average ambient temperature and the solar irradiation (see Fig.9 and Fig.10). With its maxima in May and minimum in January the irradiation at DMHS is very high compared to the other solar systems, with an average of 6.7 kWh/m²/day during the calculation period. Especially in the summer months, average daily solar irradiation reaches 8.0 kWh/m²/day. Ambient temperature shows high fluctuations – visualized by the black whiskers in Fig.10 - with measurements ranging from 5°C in the winter to 46°C in the summer. However, even during cold months high temperatures of over 25°C were not uncommon, yielding cooling demand also during winter-season. Compared to other solar systems, average relative humidity is very low with about 40% throughout the year (see Fig.11).

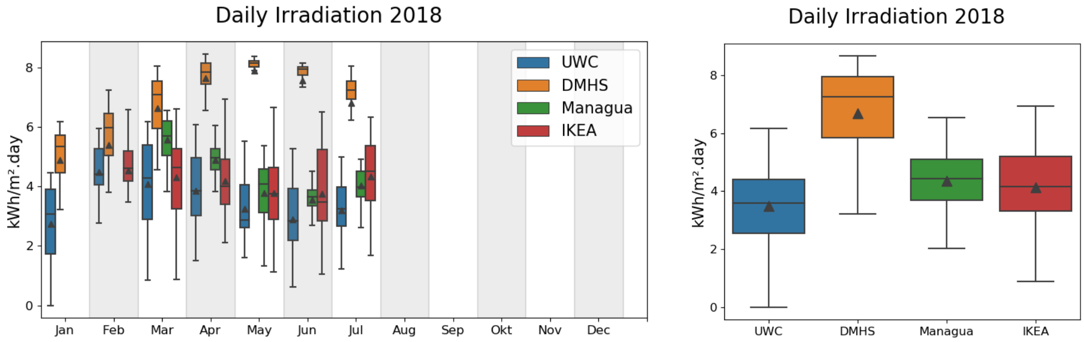

Fig. 9: Daily average irradiation at each system in 2018. Black lines mark the median, the border of the colored boxes mark the quartile and the whiskers mark the range of the measured data. Averages are displayed as black triangles.

In contrast to DMHS, there are no clear seasonal patterns visible for UWC and IKEA, located in Singapore's tropical rainforest climate. Both face high ambient temperatures of about 30°C and high relative humidity with an average value of about 80%. Due to its heavy rains occurring randomly throughout the year, daily irradiation values show high fluctuations from one day to the next. This leads to an average daily irradiation of 3.8 kWh/m²/day during the calculation period. Interestingly, there are differences between solar irradiation at IKEA and UWC, even though they are in the same city. This can be explained by the different orientation of the radiation sensors, but is also caused by different neighborhood settings (fog, clouds, reflection of buildings) as UWC is located near a lake while IKEA is surrounded by skyscraper buildings. Similarly, ambient temperature is slightly higher at IKEA than UWC for the same reason (see Fig.10).

MANAGUA shows similar results to UWC and IKEA: Average irradiation is at 4.4 kWh/m²/day during the calculation period, average temperatures are ranging from 25°C to 35°C and average relative humidity ranges between 40% and 90%. Due to its rainy season in May to October, relative humidity is rising and irradiation is a little bit lower during these months.

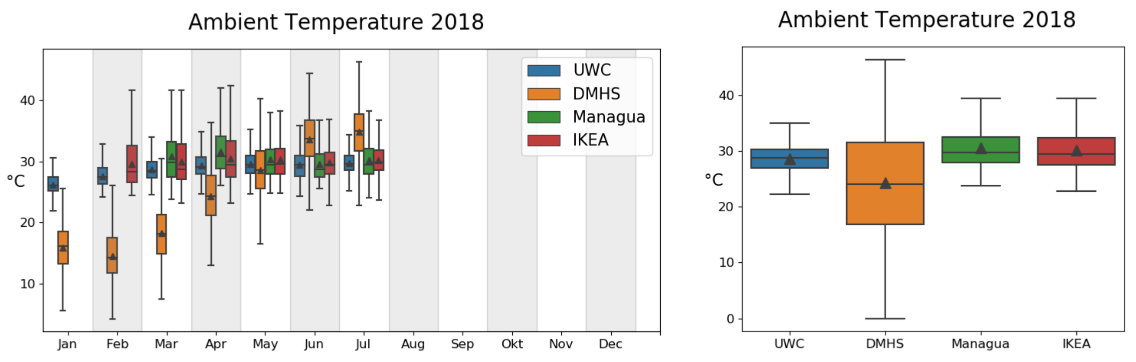

Fig. 10: Ambient temperatures at each system in 2018. Black lines mark the median, the border of the colored boxes mark the quartile and the whiskers mark the range of the measured data. Average values are displayed by black triangles.

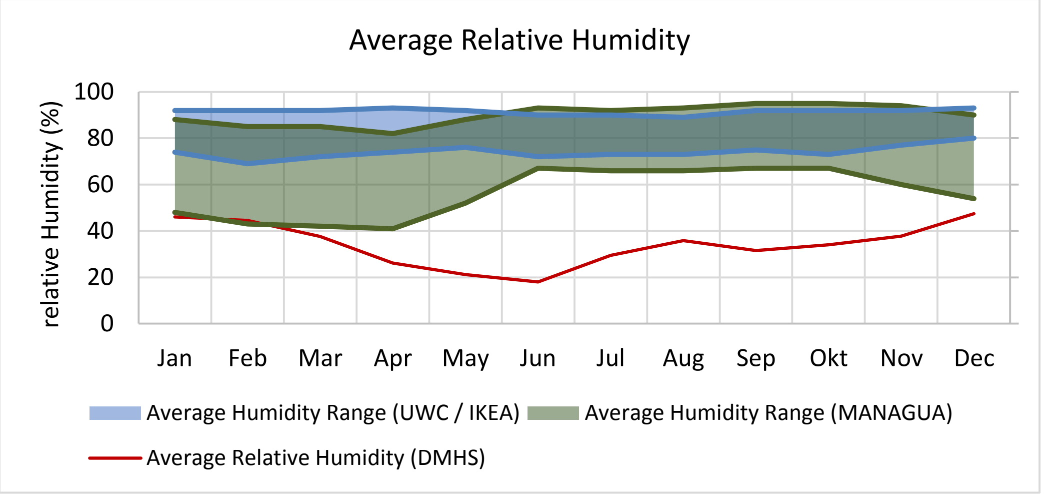

Fig. 11: Average relative humidity for each plant. Source: www.weatherbase.com.

4.2 Solar Circuit

All solar thermal systems performed very well during the calculation period from January to August 2018, with a total of 5.1 GWh of solar energy yield produced by the four solar systems. Fig.12 shows the average specific solar yield (left) and the solar conversion factor (right) of each plant, calculated by eq.1 and eq.2.

It can be seen that DMHS shows the highest average specific solar yield with 2.23 kWh/m²/day followed by MANAGUA with 1.80 kWh/m²/day and IKEA with 1.62 kWh/m²/day. However, this is due to DMHS's favorable climate conditions with its high solar irradiation. In contrast, when looking at the solar conversion factor η_s, it can be seen that MANAGUA and IKEA perform much better than DMHS. Another observation is that the solar conversion factor correlates with the time of commission of the solar systems. Compared to UWC (commissioned 2011) with an average solar conversion factor of 0.28, the performance of IKEA (commissioned 2017, $\langle\eta_s\rangle = 0.38$) and MANAGUA (commissioned 2017, $\langle\eta_s\rangle = 0.40$) improved by 36% and 46%, respectively. Compared to DMHS (commissioned in 2014, $\langle\eta_s\rangle = 0.32$) the improvement is still 17% to 25%.

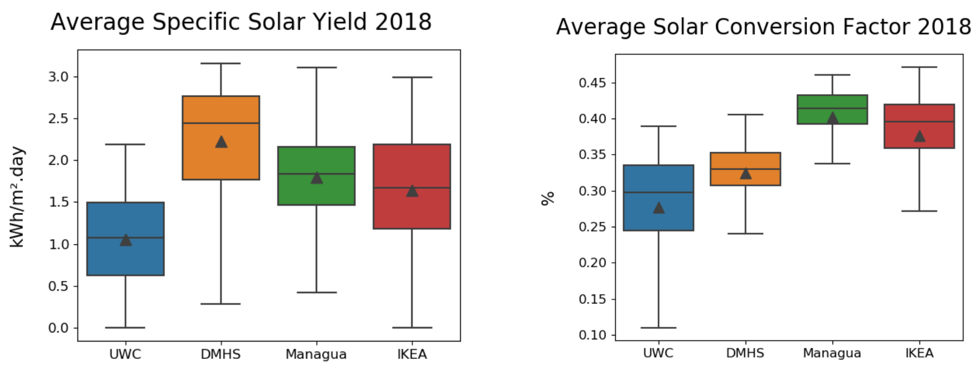

Fig. 12: Average specific solar yield (left) and average solar conversion factor (right) of each solar system in 2018. Median are displayed by a solid black line, quartiles are marked by colored boxes and the range of the measured data is displayed by the black whiskers. Averages are marked by black solid triangles.

4.3 Chiller Circuit

For analyzing the chiller circuit, the thermal and electrical energy efficiency ratio (EER_{th} and EER_{el}) have been calculated with Equation 3 and 4.

The results in Fig.13 show that the average EER_{th} is about 60% to 75% at all of the selected solar systems. Although located in the same climate region, IKEA thermal efficiency ratio is approximately 2%/day higher compared to UWC, indicating some performance improvements.

However, the highest values for EER_{th} can be observed at DMHS with daily averages ranging up to 80%, especially in the summer season. During the winter however, days with low cooling demand lead to lower thermal efficiencies, which in terms lead to the large value range visualized by the whiskers in Fig.13.

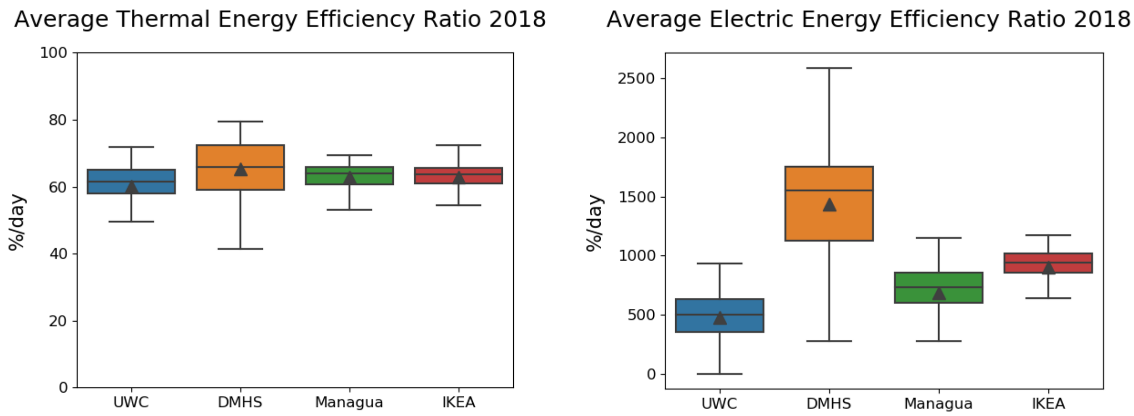

Fig. 13: Thermal (left) and Electrical Energy Efficiency Ratio (right) of each plant in 2018. Average values are displayed by black triangles, the median is displayed as horizontal line, the quartiles are marked by the coloured boxes and the range of the calculated data is marked by the black whiskers.

In comparison to the thermal efficiency ratio, there are more differences between the various systems when looking at the EER_{el}. DMHS clearly stands out with average daily thermal efficiency ratios of 15.6 compared to UWC ($EER_{el} = 4.8$), MANAGUA ($EER_{el} = 6.9$) and IKEA ($EER_{el} = 8.9$). Similar to the thermal efficiency, DMHS also shows the biggest range for average electric efficiency ratios. As described previously, this is caused by the low cooling demand in the winter season. However, during summer when the chiller operates in steady state, daily EER_{el} of 25 were reached. These high electric efficiency values might be the effect of the dry desert climate at DMHS, where average relative humidity is at low 40%, which contributes to the cooling tower efficiency.

Both UWC and MANAGUA show lower efficiency values compared to DMHS and IKEA. However, electrical meter installed at these plants only measure overall energy consumption – not only the consumption of chilled water related components. Therefore, and due to their system design, also electrical consumption contributing to the domestic hot water are included in the electric energy efficiency ratios. This way, their values can only be taken as lower boundaries of their actual performance. In addition, as mentioned in section 3, the solar cooling systems are optimized for maximizing cooling energy and not for optimizing efficiency and thus chiller are in operation as long as its performance is better than the vapor compression chillers installed at the system.

4.4 Financials

Estimated costs for solar systems with similar scope of supply and performance compared to the actual systems are shown in Fig.14. As described in section 3, these values are derived by standard-costs approximations not including any beneficial or unfavorable boundary factors (see eq.4). The results show major cost savings of the recently build systems with approximately 0.23 Mio.$/$\eta_s$m² in comparison to the older ones (0.62 and 0.75 Mio.$/$\eta_s$m²). Most of the improvements have been realized by decreasing component costs, but also by reducing the costs for design and commission, as SOLID has standardized various design and construction steps and increasing knowledge about solar cooling let to better dimensioning.

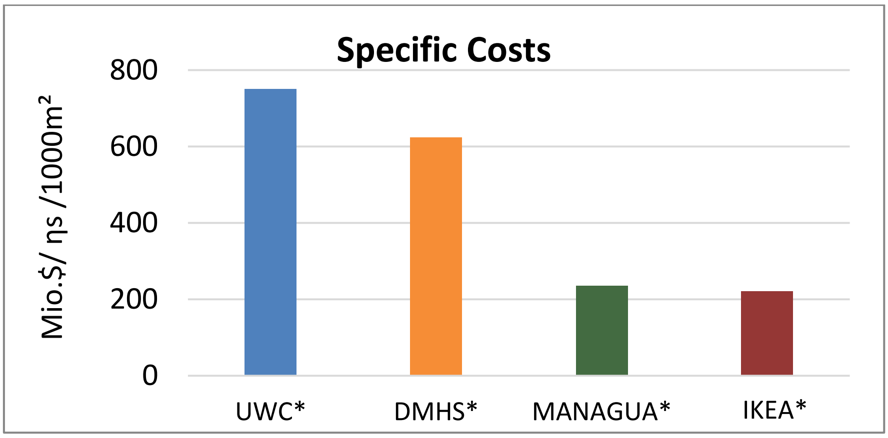

Fig. 14: (*) Estimated values for the specific costs of solar systems similar but not equal to the real commissioned solar systems.

5. Discussion

Various key performance factors of the selected solar systems have been calculated and analyzed. The results show the great potential of solar cooling at the considered regions, as high solar irradiation is available and high ambient temperatures lead to high cooling demand. With an average daily solar irradiation of 6.7kWh/m²/day, ambient temperatures up to 45°C and dry air, DMHS shows most favorable climate conditions for solar cooling. On the other hand, irradiation at IKEA, UWC and MANAGUA is lower, but cooling demand is higher due to constant high temperatures throughout the year.

All solar systems performed well during the 7-month long monitoring period, yielding more than 5.1 GWh total solar energy yield, with an average solar conversion factor of 34.6% and electric efficiency ratios of up to 26. Furthermore, thermal efficiency ratios of about 60% to 70% were reached for the absorption chillers. Comparison to previous analysis of UWC and DMHS from 2011 to 2014 show similar results, indicating that these systems still perform as expected. The high solar conversion factors enable even smaller solar systems to produce enough solar yield for supplying powerful absorption cooling machines. Together with the high electrical efficiency ratios of the system (> 4.8) and long technical lifespan this proves the potential of solar cooling as alternative to the conventional vapor compression technology.

Finally, both construction costs and performance of the solar systems seem to have improved. For example, the solar conversion factor of the recently build (2017) solar systems are up to 47% higher compared to the older ones commissioned in 2011 and 2014 and specific cost decreased by approximately 70% (Fig.14). Even though the paper could only analyze four different solar systems with different boundary conditions, the shear magnitude of performance- and construction-cost improvements clearly support these hypotheses. Additionally, the comparison of UWC and IKEA – both located in the same city – also show the same trend.

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