Simulations of Solar Thermal Cooling System in the Oman climate: Case study for a Building at Innovation Park Muscat

Tom Cordes[1, 3], Sausan Al Riyami[2, 3*], Jörn Scheuren[1] and Rutger Schlatmann[1,3]

[1] HTW Berlin - University of Applied Sciences, Renewable Energy Systems, Berlin, Germany

[2] Institute of Advanced Technology Integration (IATI)/ The Research Council (TRC), Muscat, Oman

[3] Helmholtz-Centre Berlin, PVcomB, Berlin, Germany

Abstract

An increasing demand in space cooling and thus in electricity is not only a challenge for the public electricity supply in Oman, but also leads to an increase of CO2-emission, as the electricity production in Oman relies almost completely on fossil fuels. This work aims to investigate different options of a solar cooling system for a non-residential building at Innovation Park Muscat in Oman with the target autarky from the public electricity grid. Therefore, the two main principles of solar cooling, thermally driven with solar thermal systems and electrically driven with photovoltaics, are modelled in a dynamic simulation environment. The solar thermal system contains double covered flat plate collectors, a s hot water tank storage and an absorption chiller with aquifer cooling for heat rejection. The electrically driven systems consist out of a PV system with batteries and a compression chiller. The results of the simulations show the suitability of solar cooling and give the optimised dimensions for each system. A high correlation between the cooling load and the solar radiation makes the full coverage even at small storage sizes possible, where the PV driven system has an advantage in terms of required space.

Keywords: weather data, solar irradiation, cooling demand, solar thermal collectors

*corresponding author: sausan.alriyami@trc.gov.om

---

1. Introduction

The worldwide demand for space cooling, mostly covered through electrical energy, is increasing and is expected to double within the next 40 years [1]. This also applies for the countries in the Middle East like Oman, where 97 % of electricity is generated from the CO_2-emmiting conversion of fossil fuels [2]. Apart from the international climate objectives, which force a reduction of the use of fossil fuels, the electricity demand for space cooling causes peak loads in the electricity networks. This might become an issue in Oman, as almost half of the electric energy for residential living is used for cooling [3]. The need for climate friendly technologies makes solar cooling a promising technology for space cooling, as solar energy is available almost the same time when cooling is needed.

There are two main principles of solar cooling. The first implies the conversion of the solar energy into electricity, using photovoltaic cells (PV), to drive a vapour compression chiller. The other one uses heat, produced through solar thermal systems, to drive a sorption chiller. Both technologies have advantages and disadvantages, depending on the targets and system boundaries. However, in terms of autonomy from electricity grid, interaction with additional heat sources or sinks and lager variety of storage technologies, solar thermal cooling systems are offering the better options for this project. Hence, different options of solar thermal cooling will be investigated and compared to a PV driven system in this work.

With the goal of minimal grid interaction, the most suitable option will be realized as a demonstrator to provide space cooling for a building at the Innovation Park Muscat (IPM) in the Sultanate Oman. A consortium of the German Research Centre for Geosciences (GFZ), the Technical University Berlin (TUB), the Helmholtz Centre Berlin (HZB), the University of applied sciences Berlin (HTW-Berlin) and the Omani Institute for Advanced Technology

doi:10.18086/eurosun2018.04.08 Available at http://proceedings.ises.org

Integration (IATI) is cooperating closely and couple their expertise in the fields of geosciences, thermally driven chillers and solar energy. This project is supposed to not only create an example of environmentally friendly space cooling, but also to transfer the knowledge to Oman.

2. Methodology

Basis of this study is the annual weather profile and the cooling load of the building. A Typical Meteorological Year (TMY) by Meteonorm dataset of Seeb in Muscatis used as a weather file, after a detailed comparison with historical weather data provided by the Public Authority of Civil Aviation (PACA) in Oman. Some key values of the system are listed in Table 1.

Table 1: Climate data of the location

Max. ambient temperature	50 °C
Annual mean temperature	28.6 °C
Annual solar radiation	1990 kWh/m²/a
Mean annual sunshine hours	3,493 h/a

To gain the cooling load profile, the target building was modelled based on the architectural databy Dr. Saleh Al Saadi from college of Engineering at Sultan Qaboos University. The single-storey building hosts a restaurant, a gym and other facilities. Some key values are listed in Table 2.

Table 2: Key data of the target building 'Social Centre'

Space area	1500 m²
Max. cooling load	280 kW
Annual cooling demand	391 kWh/a

After selecting the components and system configuration of the solar thermal cooling system, the system is modelled in the simulation environment TRNSYS. In a parameter variation the collector slope, the specific collector mass flow, the storage size, the nominal cooling power of the absorption chiller and the collector area are optimized for the lowest investment costs and land consumption for different solar shares. For each option the auxiliary electrical energy was calculated and recorded in an electrical load profile. Based on this load profile, the sizing of a PV-Battery system, to cover the electrical demand, was carried out in a developed programme in Matlab. The results are compared to a purely electrically driven system. This system was modelled with the PV-Battery system in Matlab and optimised for the lowest investment costs.

3. Concepts and modeling

3.1 Electrically driven system

As a reference, an electrically driven system is developed. It consists of a PV-Battery system, a compression chiller and a dry cooling tower (dry cooler) with the option of a grid connection, as shown in Fig.1. This system with all its components is modelled in Matlab. The key parameters are stated in Table 3

Table 3: Parameters of PV Module used in the simulations

Cell type	Poly-si
η (STC)	15.2 %
Temperature coefficient	-0.43 %/K

The chiller and dry cooler comply with the highest market available energy efficiency. The generated electricity is calculated with respect to the module temperature, the incidence angle and losses at the inverter. The battery system with its periphery is modelled as a lithium-ion battery. Losses are respected for charging and discharging, controls and cooling.

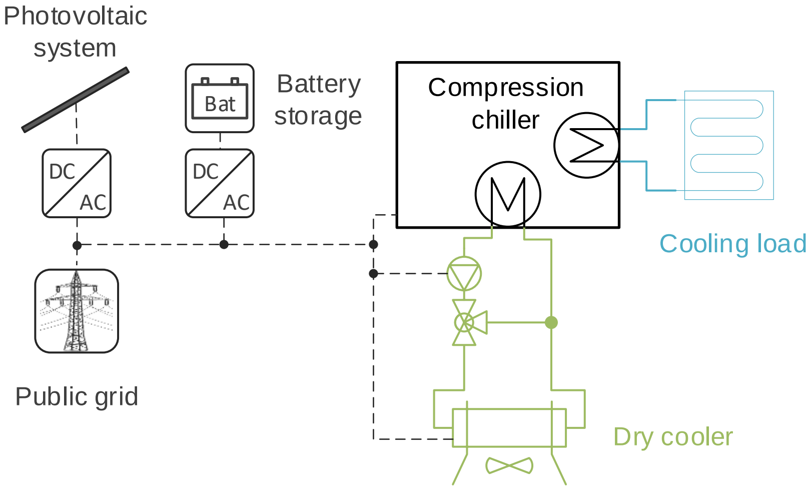

Figure 1: Design of the electrically driven system

3.2 Thermally driven system

Absorption chillers with the working pair Lithium-Bromide/Water are the most efficient absorption chillers at relatively low costs and they are environmental harmless. They require hot water temperatures between 70°C and 120°C and a heat rejection temperature below 40°C to provide chilled water at a temperature of 5.5°C. To produce heat at this temperature level, double covered flat plate collectors (see Table 4) are used in a combination with a pressurized insulated hot water tank storage (30 cm at $\lambda = 0.04$ W/m/K).

Table 4: Performance data of the solar thermal collector used in the simulations with reference to the aperture area

Collector type	Double covered flat plate
η_0	0.77
a_1 in W/m²/K	2.89
a_2 in W/m²/K²	0.006

A heat exchanger between the solar thermal collectors and the storages is not necessary, because the ambient temperature is always above 0°C. As the dry cooler is not able to maintain the cooling water temperature below 40°C all year and a water consuming wet cooling tower is excluded, an aquifer is used to reject the heat at high ambient temperatures. The auxiliary energy of pumps, absorption chiller and heat rejection are covered by a grid connected PV-Battery system. All the components, pumps and pipes are implemented in a simulation model in TRNSY according to the scheme in Fig. 2.

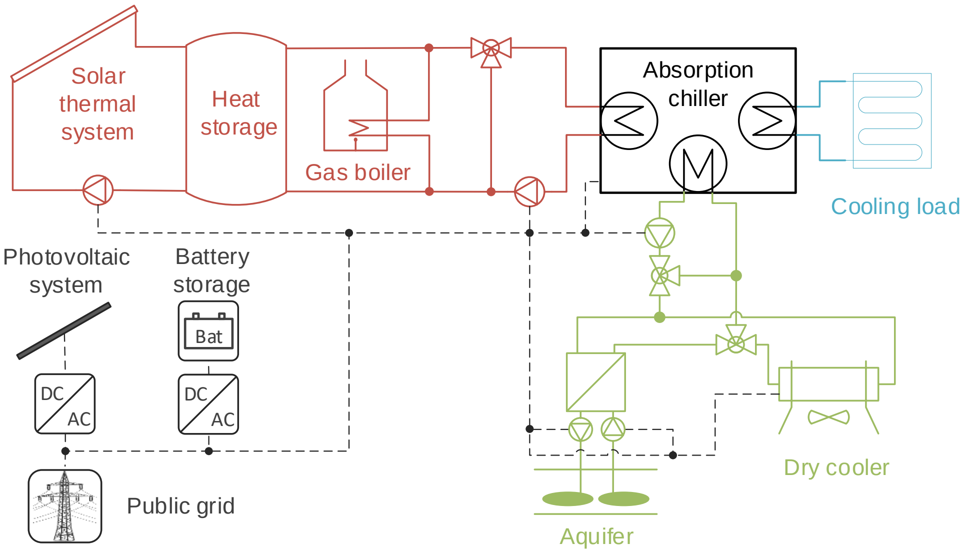

Figure 2: Design of the thermally driven system

4. Results

The results of the simulations show that the high sun radiation makes solar cooling a suitable way to provide space cooling for buildings in Oman. For both cases studied, the autarkic operation, without electricity grid connection or external gas supply, is possible, but will not present the optimal solution in all respects. In the following, the results of the best options in terms of sustainability, complexity, maintenance and investment costs are shown in more detail.

Electrically driven system

Figure 3 shows the degree of autarky as a function of the installed PV power. It can be seen that without any battery storage, the degree of autarky (DOA) levels of at a maximum of about 60%, irrespective of installed PV power. The electrically driven system contains an optional grid connection to the public electricity grid, which functions as back-up. Depending on the installed PV power and the battery capacity, the share between electricity used from PV and electricity used from the public grid varies. To reach grid independency (an autarky of 100 %) the battery storage has to have a size of at least 900 MWh. On the other hand, a larger storage than 1000 kWh can reduce the required PV capacity only slightly.

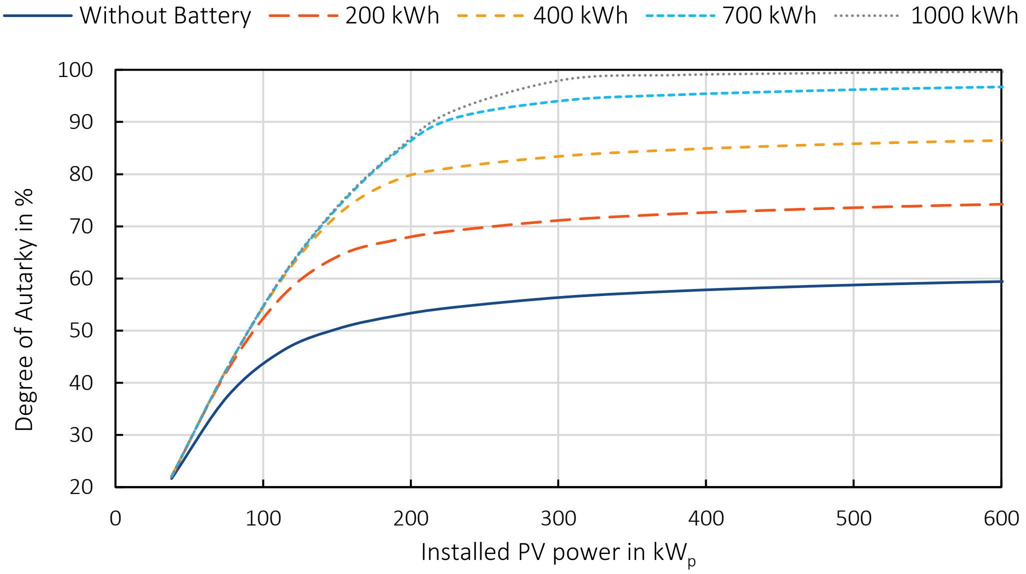

Figure 3: Share of PV-generated energy on the energy demand for space cooling over the installed PV power at different battery capacities

The option with the lowest investment costs to reach almost full autarky (99 %), is a 440 kW$_p$ PV-System with

1000 kWh battery storage. A reduction to 300 kW_p and 800 kWh can reduce the investment costs significantly, while the degree of autarky is still at 95 %. In this case a grid connection is needed and to support the electricity supply mostly in the early morning before sun rise when the battery storage is exhausted.

Thermally driven system

The analysis and evaluation of the established simulation model is performed for an annual simulation with the parameter settings shown in Table 5.

Table 5: Optimzed parameters for the the solar thermal system

Collector slope	20 °
Specific collector mass flow	20 kg/h/m²

Figure 3 shows the degree of autarky as a function of the installed solar thermal collector area, for different size of the thermal storage tank. It can be seen that even without very modest storage, the degree of autarky (DOA) levels can reach very much higher levels than are usually seen in more moderate climates. The thermal energy, needed to drive the absorption chiller, can be either provided by the solar thermal system or the optional back-up gas boiler. Both operate without significant interaction with the electricity grid. Thus it is not necessary to cover the whole demand of driving heat through the solar thermal system to meet the main goal of grid independency. The cheapest option to reach a full coverage (99 %), without using the gas boiler, requires a solar thermal system with a collector area of 2740 m² and a storage of 200 m³. As shown in Fig. 4, a reduction of the solar fraction to 95 % can reduce the required collector area by more than 25 %.

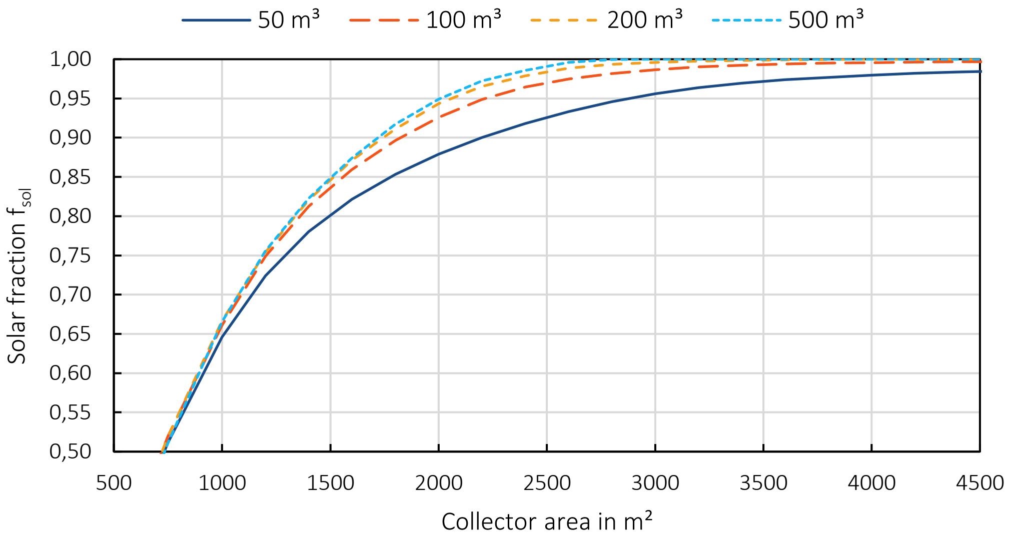

Figure 4: Share of solar thermal energy on the driving heat demand of the absorption chiller versus solar thermal collector area at different storage sizes

Due to the low seasonal differences in the profile of cooling load and solar radiation, the storage only has to cover the daily mismatches. This makes the full coverage of the cooling load with the solar thermal system even at relatively small storage sizes possible. A storage larger than 500 m³ has only a small effect on the required collector area, but increases the investment costs.

In addition to the thermal energy needed to drive the chiller, electrical energy is needed for pumps, fans and other electrical applications. The required driving heat amounts 1214 MWh_{th}/a and the electrical energy 115 MWh_{el}/a. Figure 5 shows the expected annual electricity consumption of the different devices in the cooling system.

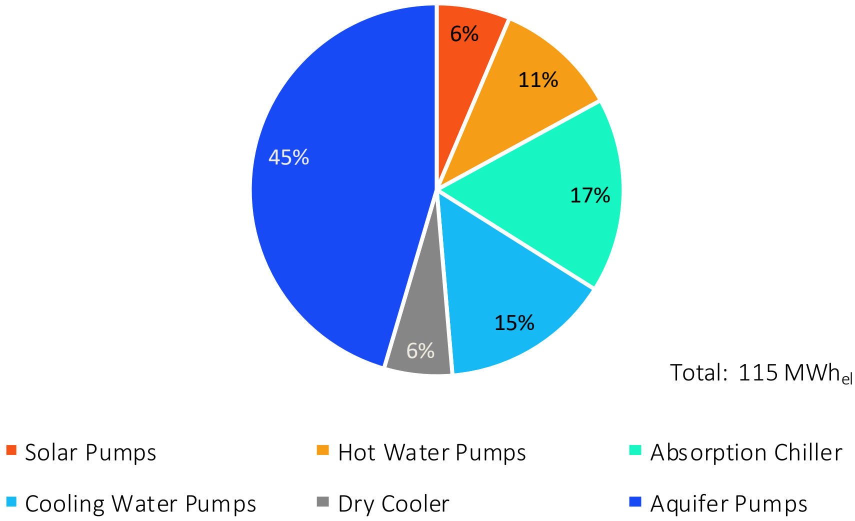

Figure 5: Percentage of electrical consumption for different devices on the annual electricity demand of the cooling system

A share of 45 % of the annual electricity consumption for the cooling system is expected to be consumed by the aquifer pumps, as shown in Fig. 5. This value mostly depends on the permeability of the rocks at the location and might reduce after the results of the drilling are available.

Figure 6 shows the resulting total land consumption required to cover the whole electricity demand of the cooling system at different shares of solar thermal energy on the driving heat at with the respective storage volume to obtain the lowest investment costs.

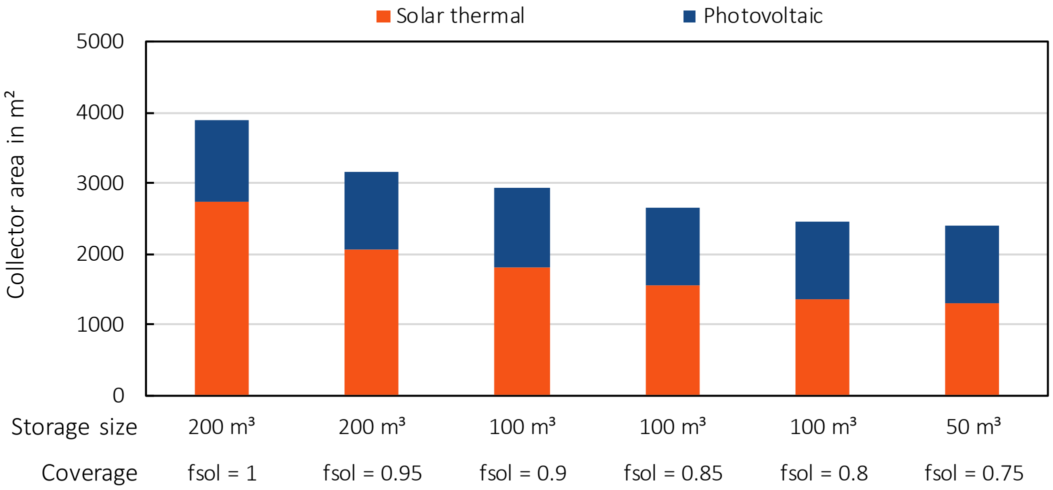

Figure 6: Comparison of land consumption for the thermally driven systems with the required PV area to cover the auxiliary electrical energy demand at different solar shares and storage sizes.

For a full coverage of the cooling system in terms of thermal and electrical energy, a total area of solar thermal collectors and PV modules of 3890 m² is required. Reducing the share of solar thermal energy reduces the required solar thermal collector area, while the PV area almost stays the same, because the percentage of electrical energy for the solar pump is relatively small.

Comparison

A comparison of the thermally driven system with the electrically driven system as a reference can be carried out for various aims like the costs, degree of autarky, the complexity, sustainability, primary energy consumption and CO_2 emission. In this project the main goal was to develop an electrically autarkic system with a high degree of sustainability and reliability at low land consumption. Fig. 7 shows the land consumption of thermally driven systems and electrically driven systems at different coverage rates. The thermally driven system uses a gas boiler to cover the remaining part of thermal energy in the options with a solar share below 1, while the electrically driven system uses the public electricity grid to cover the residual energy.

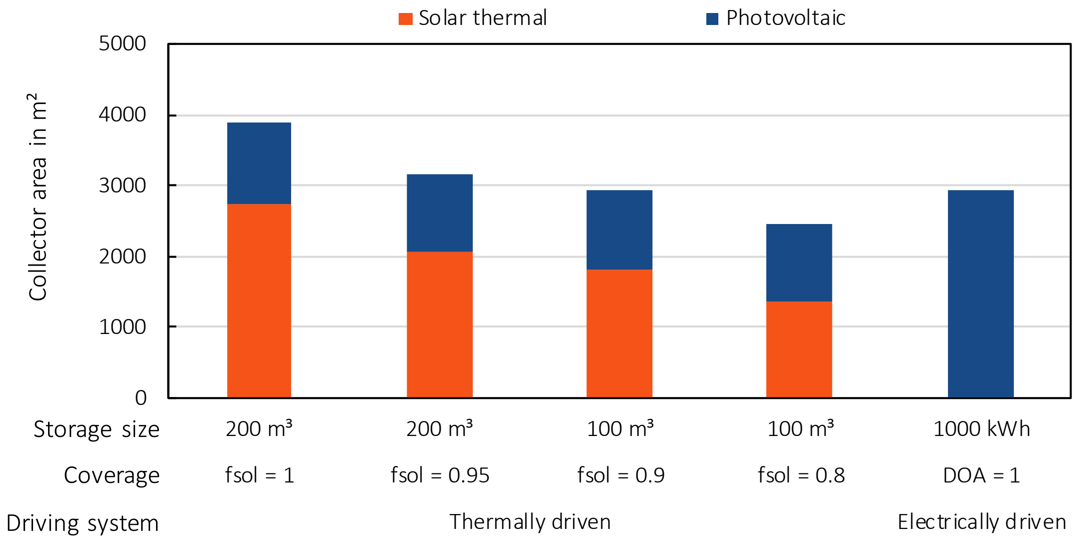

Figure 7: Comparison of land consumption of solar thermally driven systems and electrically driven systems at different coverage rates.

The energy autarkic thermally driven system, with a full coverage of thermal energy from solar thermal and electrical energy from PV, has a land consumption with the total area of 3890 m². The autarkic electrically driven system requires an area of PV modules of 2895 m². Using the gas-boiler as a backup and for peak-loads, reduces the required solar thermal collector area, while the goal of electrical grid autarky can be obtained. The total area for a thermally driven system is the same as the area needed for an autarkic electrically driven system when 10 % of the thermal energy is covered through the gas boiler.

Besides the land consumption, the complexity, reliability and costs have to be considered too. While the investment costs of both systems are in the same range, the lifetime and reliability of the components of the PV-Battery system in the desert-like region could be expected to be lower and thus lead to higher operating costs. On the other hand, the surplus electrical energy, produced by a PV-System can be used to cover a part of the electricity demand of the building. These aspects will be studied in more detail as a next step in the project.

5. Conclusion

A thermally driven and an electrically driven design of a solar cooling system could be developed and optimised for a non-residential building in Oman and the study has shown that both are suitable for space cooling. Due to the extreme climatic situation in Oman, it is worthwhile to note that with both options one can achieve full solar coverage at relatively modest storage sizes. Depending on the objectives, one or the other principle has advantages and disadvantages. To reach autarky from the electricity grid, the thermally driven system has the option to use a gas boiler and has hence the potential to reduce the solar thermal area and thus requires less space. When considering the auxiliary electrical energy of the thermally driven system too, the electrically driven systems requires less totals space if a 100 % renewable system is desired. The additional PV area to cover the electricity demand, which is mostly traces back to the heat rejection, amounts more than one third of the area needed for solar thermal collectors. This highlights the facts, that auxiliary energy demand cannot be neglected when comparing solar thermal cooling and PV assisted cooling and that the heat rejection is a big issue in countries with high ambient temperatures. The future work in this project will include a detailed economic study and the comparison with other technologies for heat rejection.

6. Acknowledgments

The authors are grateful to our colleagues from German Research Centre for Geosciences (GFZ), Technical University of Berlin, Innovation Park Muscat (IPM), and Public Authority for Civil Aviation (PACA) for their support and constructive discussions. All the detailed cooling load calculations building at Innovation Park Muscat (IPM) was performed by Dr. Saleh Al Saadi from Sultan Qaboos University (SQU). The Research leading to these results has received funding from Institute of Advanced Technology Integration (IATI) under The Research Council (TRC) of the Sultanate of Oman. TRC Research contract No. TRC/RCP/15/003.

7. References

[1] International Energy Agency report. 2012. Technology Roadmap: Solar Heating and Cooling. Fig. 17, p. 28. https://www.iea.org/publications/freepublications/publication/Solar_Heating_Cooling_Roadmap_2012_WEB.pdf ,June 2018.

[2]www.iea.org/statistics/?country=OMAN&year=2016&category=Electricity&indicator=ElecGenByFuel&mode=chart&categoryBrowse=false&dataTable=ELECTRICITYANDHEAT&showDataTable=false, June 2018.

[3] Sweetman, T., et.al, 2014. Residential energy use in Oman: a scoping study. Oman final report v8. http://discovery.ucl.ac.uk/1425280/ , January 2014.