Multi-objective Optimization of a Solar Air Collector for Desiccant Cooling Systems for a Warm and Humid Climate

Abstract

A Solid Desiccant Cooling (SDC) system requires low-temperature heat, which can be supplied using a Photovoltaic Thermal (PV/T) collector. However, the increase in PV/T outlet air temperature is limited by PV surface temperature. Therefore, an auxiliary heater is needed to meet the required regeneration temperature, but high auxiliary heater energy consumption renders the system impractical. The objective of this study is to optimize the design parameters of a Solar Assisted Desiccant Cooling System (SADCS). An integrated solar air collector (PV/T + Solar Air Heater, SAH) and SDC system has been designed to cool a retail store in a low-rise mixed-use building in a warm and humid climate. A multi-objective optimization study has been conducted to maximize the PV electricity production and minimize the SDC subsystem's auxiliary heater energy consumption, limiting the PV surface temperature. The results show that increasing the solar collector outlet air temperature directly impacts the auxiliary heater energy consumption, which reduces the operational energy cost.

Introduction

Building-sector is accountable for more than half of the world's total electricity consumption (*The Critical Role of Buildings*). Among different end-uses in the building sector, space cooling not only has the major share of building energy consumption, but it is also responsible for building-related CO_2 and GHG emissions worldwide (*Southeast Asia Energy Outlook 2019 – Analysis*; *The Critical Role of Buildings*; *The Future of Cooling – Analysis*). Currently, most of the building-related space cooling demand is fulfilled using conventional Vapor Compression Cooling Systems (VCS). Particularly, in regions with a hot and humid climate, the way VCS achieves dehumidification of highly humid air makes its operation more energy-intensive and renders the system inefficient (Fan et al., 2019; Jani et al., 2016). Alternatively, clean energy technology like solar thermal assisted Solid Desiccant Cooling (SDC) operates with the support of solar thermal energy. This system uses separate components to remove the moisture from the air and then cool the air to achieve thermal comfort conditions. This type of arrangement is economical and more efficient in handling air with high humidity (Jani et al., 2016). An SDC system consists of many components which can be assembled in several different configurations (Jani et al., 2016). In an SDC, the process air is dehumidified and cooled by moisture removal in a Desiccant Wheel (DW) and water evaporation in a Direct Evaporative Cooler (DEC). In the regeneration air cycle, the hot air coming from the solar collectors and Auxiliary Heater (AH) is passed over the desiccant material to replenish it for continuous operation. Generally, the DW can be regenerated by hot air in the range of 50-80^oC (Ge et al., 2014; Gommed & Grossman, 2007; Jani et al., 2016; H. Li et al., 2011), but it may require higher temperatures in extremely hot and humid conditions.

Solar thermal heat has been widely regarded as a great source of clean and abundant energy which is capable of supplying regeneration air at a high temperature during daytime (Fan et al., 2019; Jani et al., 2016). Among different types of solar collectors, air-based PV/T systems can produce electricity and thermal energy at the same time. Rounis et al. reviewed the performance of air-based PV/T and BIPV/T systems in both theoretical and experimental studies considering wind effects (Rounis et al., 2021). As another advantage, it has been observed that the air flowing under the PV collectors in a PV/T system can greatly reduce the PV surface temperature and prevent a reduction in the PV cell efficiency. Despite this enhancement, the PV surface temperatures of these collectors still need to be below a certain limit to maintain high PV cell efficiency and good material integrity, especially in hot climates (Rounis et al., 2016; Yang & Athienitis, 2016). On the other hand, at certain times when the PV/T outlet temperature is not sufficient for SDC optimal operation, an auxiliary heater should be added to the SDC cycle to maintain a high temperature of regeneration air, which at the end increases the electricity consumption of the SADCS (Ge et al., 2014; Guo et al., 2017). To solve this problem, a small area of air-based Flat Plate Collector/Solar Air Heater can be added to the end of the PV/T system to further boost the outlet air temperature. Results of experimental and simulation studies based on the performance of PV/T and SDC systems indicate that a combination of solar thermal and PV collectors can fulfil the regeneration temperature and electrical requirements of SDC systems.

In this study, the performance of an integrated air-based Photovoltaic Thermal (PV/T) and Solar Air Heater (SAH) subsystem in conjunction with a Solid Desiccant Cooling (SDC) subsystem is investigated under warm and humid climate. The PV/T+SAH is used to simultaneously produce electricity and fulfil the thermal requirements of the SDC operation.

Literature review

Recently, there is a rise in the research related to the feasibility, performance and optimization of combined SADCS systems. An overview of simulation-based optimization approaches on building performance analysis and design is illustrated (Nguyen et al., 2014). Also, Alahmer and Ajib have reviewed solar cooling technologies and different optimization methods (Alahmer & Ajib, 2020). They have mentioned that desiccant cooling systems have the potential to operate with low-temperature solar heat and provide thermal comfort, especially in climates with high humidity. In a study, Fong et al. conducted a simulation-based optimization of a SADCS, concluding that yearly average Solar Fraction (SF) of 17% and mean COP_{th} of 1.38 can be achieved (Fong et al., 2010). In another study, a BIPV/T component design concept using semi-transparent PV modules was developed and implemented for the Fiat Research Centre at Orbassano, Italy, by Aste et al. This setup can deliver power at 20 kWp, and the hot outlet air is used for preheating the ventilation air in winter and for desiccant cooling in summer (Aste et al., 2008). Also, Eicker et al. analyzed components' performance and seasonal operational experiences for solid desiccant cooling systems powered by solar air collectors in three different warm and humid locations. It has been observed that solar air collectors with collector areas around 100 m^2, channel depths ranging between 0.095-0.14 m, regeneration air mass flow rate up to 3.05 m^3/s and average velocity of air slightly less than 9 m/s are capable of supplying regeneration air between 50-70ºC (Eicker et al., 2010; Mei et al., 2006). The authors have reported that air temperature at 70ºC or more was enough for the DW regeneration while maintaining the regeneration air flow-rate between 0.833-2.5 m3/s and average velocity of air between 3-9 m/s (Mei et al., 2006). As an important conclusion through a simulation study, Chung and Lee concluded that, amongst several design parameters, the effect of the regeneration temperature is the most dominant on the COP of the SDC system (Chung & Lee, 2011). Farschimonafared et al. optimized the channel depth, air mass flow rate and air distribution duct diameter of solar air PV/T collectors connected to residential buildings. It was observed that the optimum depth value varies between 0.095-0.26 m, and this value increases as the L/W ratio and the collector area increases (Farshchimonfared et al., 2015). It is important to mention here that in many of the studies, channel height is 0.095 m. This is mainly attributed to a higher volumetric mass flow rate, higher average flow velocity and length of the solar air collectors (Aste et al., 2008; Eicker et al., 2010). The impacts of channel height and air mass flow rate on the electrical and thermal output of the PV/T system are shown in various studies. It is found that with increasing mass flow rates, the electrical and thermal efficiencies of the system increased (Rounis et al., 2021).

In several studies aiming at improving the performance of PV/T collectors coupled with air conditioning systems, only parametric analyses have been performed (Tiwari & Sodha, 2007). The shortcoming of such studies is the lack of a comprehensive investigation of all possible designs. Also, in some previous studies, the electricity and thermal energy output of PV/T collectors are aggregated and taken as a single indicator (Sobhnamayan et al., 2014). However, based on varying designs of the PV/T collector, these two outputs can have a conflicting relationship with each other. Therefore, performing a multi-objective optimization study is necessary to optimize the system by considering a wide range of important parameters and different configurations.

A few studies have performed multi-objective optimization for BIPV/T systems, which include water-based and air-based collectors (Fan et al., 2019).

Among the air-based solar collector studies, some performed optimization only for heating purposes by transferring the outlet air of the PV/T directly through the air handling unit. For instance, in a study by Li et al., the ambient air passing through an earth-air heat exchanger enters the BIPV/T collector for preheating the building. The objective of the study is to maximize the annual total amount of energy and exergy outputs of the collector (Z. X. Li et al., 2019). In another study by He et al., the geometric and operating parameters of a BIPV/T coupled sensible rotary heat exchanger is optimized to maximize the annual average exergo-economic performance of the system. The authors have reported that by performing a multi-objective genetic algorithm (MOGA) optimization, the annual average enviro-economic and exergo-economic aspects of the optimized system are 36.8% and 23.1% higher than the non-optimized system, respectively (He et al., 2020).

Considering the coupled PV/T and SDC system, Fan et al. developed a multi-objective design optimization methodology by hybridizing PV/T and solar air heater systems. The authors first performed a sensitivity analysis to reduce the number of parameters. Then, they carried out an optimization study to increase useful thermal energy (thermal energy with a temperature greater than 60 ºC) and net electricity gains (production minus fan power) for the most influencing parameters. They have reported that the final optimal design has increased both objectives by 21.9% and 20% compared to the baseline design (Fan et al., 2018).

As mentioned, most of the studies only consider optimizing the performance of the PV/T system separately as if it is not connected to the other cooling components. However, to consider the interaction between all components and fully optimize the system, the entire integrated system should be considered in the optimization study. In this regard, no previous work has been conducted to collectively optimize PV/T collectors' electricity production and air conditioning unit's AH energy consumption, as they have a conflicting relationship with each other.

Objective

Based on the mentioned gaps, the objective of this study is to simulate and optimize the design parameters of Solar Assisted Desiccant Cooling System (SADCS) to maximize annual electricity production and minimize annual auxiliary heater energy consumption.

Methods

The overall methodology is divided into two main sections, i.e., developing a building performance assessment model and implementing an optimization approach. Therefore, first, a simulation model of an integrated solar collector (PV/T+SAH) and a solid desiccant cooling system is developed in TRNSYS 18 based on the literature reviewed and an analysis of requirements (common practice, design guidelines, building standards, etc. for a warm and humid climate). In the second section, a multi objective optimization study is conducted by coupling TRNSYS and modeFRONTIER to optimize the model. The overall methodology is explained in the following sections.

Development of building model and estimation of cooling energy demand

The first step in modelling the system is to develop the building energy model and estimate the cooling energy demand of the retail store (conditioned space). The retail store to be conditioned is part of a south-facing 4-storey mixed-use residential building in Chennai, India (Figure 1). The ground floor consists of two 50 m^2 retail stores and parking space. The three floors on top have four residential units (two 55 m^2 and two 45 m^2 in area). A 3D model of this building is designed using the TRNSYS 3D plugin in Sketchup 17. This 3D model is imported into TRNSYS 18 to estimate the cooling energy demand of the retail store. Considering ideal air load with COP of 3 for cooling equipment and daytime operation between 9:00-17:00, cooling energy demand of the retail store comes around 4,100 kWh with a sensible to latent heat ratio of 0.70.

Development of Solar Assisted Desiccant Cooling System model

In the second step, a SADCS model is developed. There are many different configurations in which the subsystems of a SADCS can be arranged. In this study, a Direct-Indirect Evaporative Cooling (DINC) configuration is adopted owing to the simplicity and comparatively higher thermal Coefficient of Performance (COP_{th}) (Jani et al., 2016). The schematic of the configuration is presented in Figure 2.

In the process air cycle (blue line), a mixture of fresh ambient air and return air (dashed red line) from the conditioned space (retail store) enters the Desiccant Wheel (DW), where the air is heated and dehumidified. The process air is sensibly cooled through the Sensible Wheel (SW) and Indirect Evaporative Cooler (IEC).

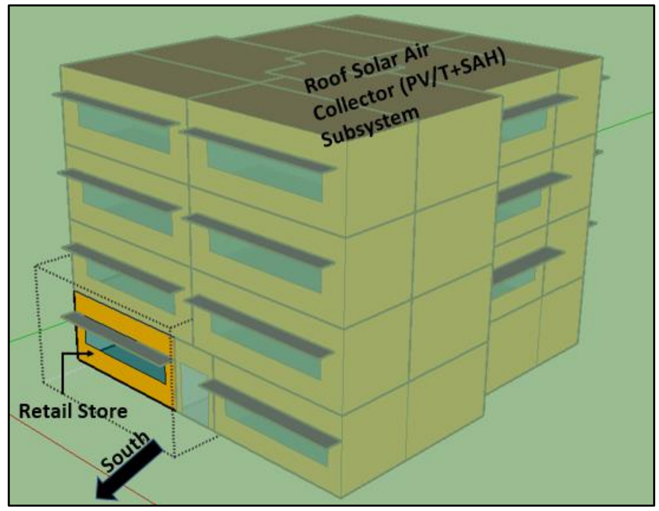

Figure 1: 3D Rendering of the building

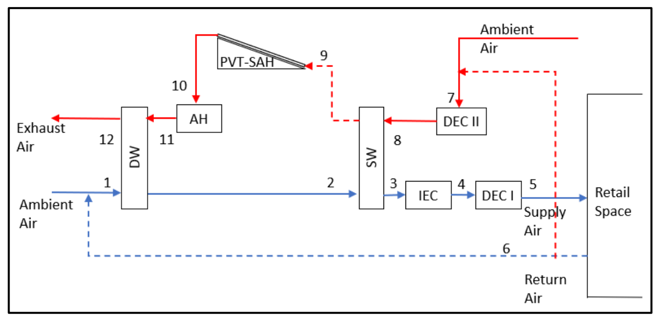

Figure 2: Schematic of Solar Assisted Desiccant Cooling System (DINC configuration)

Finally, the process air passes through the Direct Evaporative Cooler (DEC), where it is cooled and humidified by water evaporation and supplied to the retail store. In the regeneration air cycle (red line), part of the return air from the retail store is mixed with ambient air, and the mixture is heated through the SW as it takes away the heat from incoming process air. This warm regeneration air is heated further as it passes through the solar collector (PV/T+SAH) subsystem. Then the heated regeneration air enters the Auxiliary Heater (AH), where the air temperature is boosted if it is under the setpoint (70°C). Finally, the regeneration air passes through the DW wheel to regenerate the desiccant materials. After this process, the DW outlet air is exhausted.

The designed solar collector subsystem is spread over a roof area of approximately 110 m^2 which covers half of the roof area of the building. The dimensions of the PV/T and SAH collectors are shown in the table below. The optimal collector angle is set at 13° (Latitude) for Chennai.

Table 1: Solar air collector dimensions for baseline model.

Component	Dimensions (m)	Area (m^2)
PV/T	14 x 7	98
SAH	1.85 x 7	12.95
Total	15.85 x 7	110.95

The integrated solar collector (PV/T + SAH) and SDC subsystem are modelled in TRNSYS 18. All the TRNSYS components used to model the entire system are presented below.

Table 2: TRNSYS components details.

Sr. No.	Type	Description
1	Type 14, type 41	Forcing function for schedule
2	Type 56	Multi-zone building
3	Type 569, type 566	Un-glazed PV and glazed PV for PV/T component
4	Type 716	Rotary desiccant dehumidifier
5	Type 760	Sensible air-to-air heat recovery wheel
6	Type 663	Unit heater
7	Type 507	Evaporative cooling device
8	Type 642	Single-speed fan/blower

The PV electrical production depends linearly on the PV operating temperature. To model the impact of temperature on PV efficiency, the Evans-Florschuetz correlation is used and defined as (Florschuetz, 1979):

$$\eta_{pv} = \eta_{Tref}[1 - \beta_{ref}(T_{pv} - T_{ref})] \quad (1)$$

Where η_{pv} is the PV electrical efficiency calculated based on the cell temperature (T_{pv}). η_{ref} is the PV electrical efficiency under standard conditions, β_{ref} is the temperature coefficient of the module (typically -0.5%/°C), T_c is the PV module surface temperature, and T_{ref} is the PV module surface temperature (25°C) at which reference PV electrical efficiency is given.

On the other hand, the solar air collector fan consumption is affected by the pressure drop across the length of the air channel. The fan consumption due to pressure drop is given by Cengel and Turner and is defined as (Cengel et al., 2016):

$$\dot{W}_{fan} = \frac{\dot{W}_h}{\eta_{fan}\eta_{motor}} \quad (2)$$

Where $\dot{W}_{fan}$ (kW) is the electrical fan power due to frictional pressure drop along the air channel, $\dot{W}_h$ (kW) is the hydraulic fan power, η_{fan} is the fan efficiency, η_{motor} is the motor efficiency. The hydraulic fan power is defined as (Cengel et al., 2016):

$$\dot{W}_h = \dot{V}(\Delta P_k + \Delta P_f) \quad (3)$$

Where $\dot{V}$ (m^3/s) is the volumetric flow rate of air through the air channel, ΔP_k (Pa) is the kinetic pressure drop, and ΔP_f (Pa) is the frictional pressure drop. The frictional pressure drop across the air channel is defined as:

$$\Delta P_f = \Delta P_M + \Delta P_m \quad (4)$$

Where ΔP_M is the major frictional pressure drop, and ΔP_m is the minor frictional pressure drop. Amongst the different types of pressure drops, the most significant one contributing towards the rise in fan consumption in this study is the major frictional pressure drop, and it is defined as (Cengel et al., 2016):

$$\Delta P_M = \sum_{i=1}^{n} f_i \frac{L_i}{D_{Hi}} \frac{\rho V_{iavg}^{\ 2}}{2} \quad (5)$$

Where f_i is the friction factor, L_i (m) is the length of the air channel, D_{Hi} (m) is the hydraulic diameter, ρ is the density of air, and V_{iavg} is the average air velocity through the air channel.

Multi-Objective optimization methodology

After modelling the system in TRNSYS, a Multi-objective optimization study is performed to accommodate the multi-criteria decision-making procedure for optimizing the Solar Assisted Desiccant Cooling System (SADCS).

As mentioned in the previous section, PV/T channel height located underneath the PV panels and mass flow rate of the air passing through the channel are selected as two important geometric and operating parameters that highly affect the performance of the PV/T. These parameters consequently impact the cooling system in terms of power production and auxiliary heater energy consumption. Therefore, in this study, a multi-objective genetic algorithm (MOGA) optimization is used to determine the optimum values of PV/T channel height and flow in order to maximize the annual electrical power production and minimize the auxiliary heater energy consumption (Lee, 2014). The PV surface temperature is set as a constraint to minimize the impacts of high surface temperature. Due to the functioning of the PV/T system, there is a pareto front between the two objectives. As the flow in the channel increases, the thermal energy gain increases but the collector outlet temperature decreases. This results in an increase in the supplementary auxiliary heater energy required to regenerate the Desiccant Wheel (DW). The decision-making parameters used in this optimization analysis and their ranges are shown in Table 3. The range of each parameter is divided into a set of 10 discrete values, known as levels which is sufficient for the selected ranges reported in the literature.

Table 3: Decision-making parameters and their ranges

Variable	Channel height (m)	Flow (m^3/h)
Lower bound	0.06	840
Upper bound	0.1	1160

The MOGA algorithm is set with 0.5 probability of directional cross-over, 0.05 probability of selection, and 0.1 probability of mutation as default values.

The results of optimization converge after 5 generations with a total of 49 unique designs (cases) which is less in number than the full factorial approach with 100 total cases.

Results and Discussion

The baseline model is developed for the air conditioning of a retail store on the ground floor of a 4-storey mixed-used building in Chennai, India. The supply air flow rate and minimum ventilation requirements for the retail store have been calculated as per ANSI/ASHRAE Standard 62.1-2019 and the National Building Code of India (Bureau of Indian Standards, 2016). The supply air flow rate and regeneration air flow rate are both set at 840 m^3/hr (0.233 m^3/s). The dimensions of solar air collector subsystem have been mentioned previously in Table 1. The air channel height for baseline model is set at 0.08 m. All the components of the solid desiccant cooling subsystem have been sized as per the aforementioned air flow rates. All the simulations were carried out for an entire year considering the daytime operating schedule for the retail store (09:00-17:00).

The simulation results for the building's annual energy profile are compared with surveyed data of similar residential building stock in Chennai, India. Also, the PV/T component is modelled using TRNSYS type 569 with some minor modifications to conform to the actual measured data of the system used for an experimental study. The simulation results for the building and PV/T models show a good agreement with the surveyed and measured data.

Simulation Results for the baseline model

Monthly energy profiles for the production and consumption of the Solar Assisted Desiccant Cooling System is shown in Figure 3 and 4, respectively. The results show that the monthly production values are about ten times higher than the AH consumption. Also, as can be inferred from these figures, there is a trend between solar energy production and AH energy consumption. As there is higher PV/T generation and collector outlet temperature, there will be less consumption in the AH. The annual average temperature of the PV surface is ranging between 42 and 52^{o}C for different months. This temperature never passes the 75 ^{o}C limit of PV efficiency. Although, by implementing the SAH collector, the system outlet temperature is boosted to higher values up to 89^{o}C.

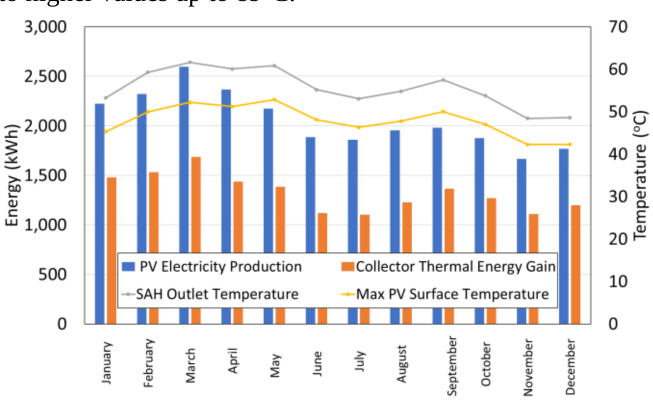

Figure 3: Monthly Energy Profile of PV/T+SAH subsystem

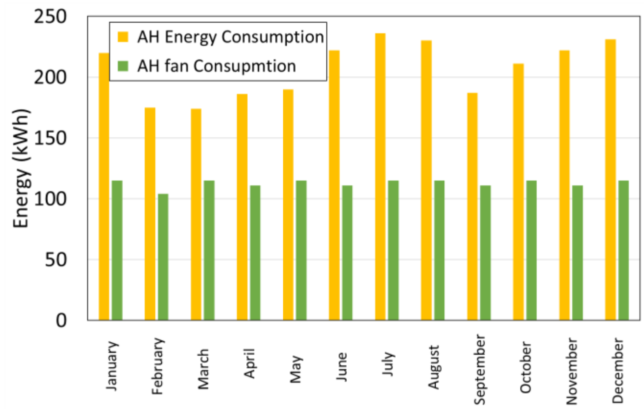

Figure 4: Monthly Energy profile of Auxiliary heater and fan consumption

Figure 5 and 6 present daily energy and temperature profiles of the solar collector and AH subsystems for three representative days in summer (May 2-4). It is observed that, AH energy consumption decreases with an increase in SAH outlet temperature. Whenever SAH outlet temperature is more than the AH setpoint temperature (70^{o}C), AH energy consumption approaches zero. At the same time, it is also observed that the PV surface temperature does not exceed 70^{o}C. This, in turn, means that the PV efficiency isn't adversely affected, even in peak summer conditions. The AH and fan energy consumption in comparison with daily PV production is very low and can be easily covered by the solar collector subsystem during the schedule hours.

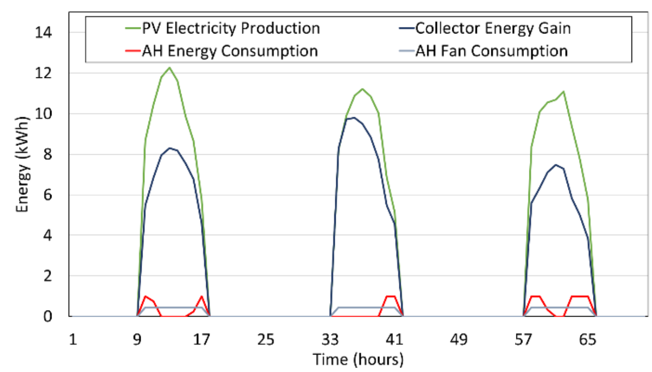

Figure 5: Daily Energy Profile (kWh)

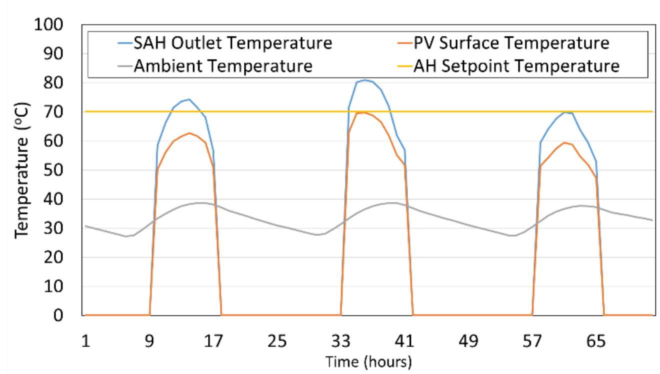

Figure 6: Daily Temperature Profile (^{o}C)

Optimization results

A multi objective optimization study has been conducted to optimize the geometry and operating parameters of the PV/T system. The objectives are maximizing the PV electricity production and minimizing the AH energy consumption. As shown in Figure 7, there is a pareto front between these two objectives meaning that the designs with higher PV electricity production will have more AH energy consumption.

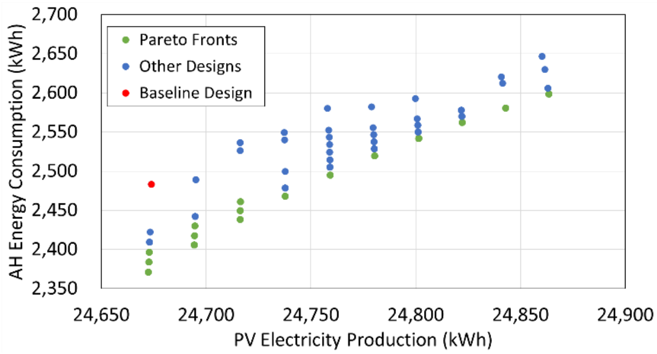

Figure 7. Optimization results of maximizing PV electricity production and minimizing AH energy consumption

Figure 8 illustrates the variation of different designs with flow (m^3/h) and channel height (m). As shown in this Figure, the pareto front solutions that satisfy the objectives of this study do not include designs with channel heights over 0.07 m. The reason behind this result is because that the heat transfer between the PV surface (absorber) and the passing air through the channel decreases with an increase in height. Less heat transfer causes higher PV surface temperature and lower collector outlet temperature, which consequently reduces PV electricity production and increases AH energy consumption, respectively. Also, this can be noticed that with a higher channel height (more than 0.06 m), the flow should be kept below 950 m^3/h to support the objectives. With 0.06 m channel height, the system can be operated with any flow value in the suggested range. According to the results, the optimal channel height is lower in comparison to the values mentioned in the literature review section. The reason is that, in this case, a higher SAH outlet temperature is desired. On the other hand, since the volumetric flow rate and the average velocity are low, the frictional pressure drop and its impact on fan consumption is relatively small in comparison to AH energy consumption.

The parallel coordinate plots of two design parameters and corresponding outputs are shown in Figure 9. In Figure 9a, the design with the lowest AH energy consumption is marked, which is the one with the lowest channel height and flow rate. On the other hand, as shown in Figure 9b, the design with the lowest height and highest flow corresponds to the maximum PV electricity production. The impact of variation in channel height and operating flow on PV surface temperature, PV/T outlet temperature and SAH outlet temperature is also illustrated.

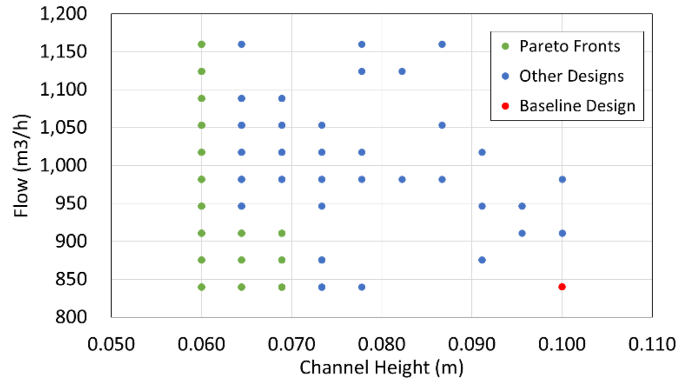

Figure 8: Variation of different designs with flow (m3/h) and channel height (m)

Conclusion

The simulation results of this study show that a Solar Assisted Desiccant Cooling System has a great potential to replace existing VCS or at least supplement them in warm and humid climates, to reduce peak daytime consumption, to indirectly reduce CO_2 and GHG emissions and simultaneously contribute towards electricity production as well.

On the other hand, combining PV/T with SAH collectors helps to achieve a higher outlet air temperature necessary to lower AH energy consumption. Simultaneously, this approach also helps to lower PV cell surface temperature to prevent reduction in the PV cell efficiency.

The conducted multi-objective optimization indicates that by lowering the flow, both the collector outlet temperature and PV surface temperature increase, which lead to lower AH energy consumption but at the same time lower PV electricity production, respectively. Therefore, the decision-making can be made among the obtained pareto front solutions to have higher PV electricity production or less AH energy consumption. Also, the results show that the pareto front solutions that satisfy the objectives of this study do not include designs with channel heights over 0.07 m.

As part of future work, developing a design methodology for an integrated PV/T and SAH system, considering space cooling application, is underway. This will help for easier design, development and applicability of such an integrated system with/without another cooling system for different building types in different climates. In addition, performing a sensitivity analysis considering other influencing parameters such as collector area, PV covering factor, and collector length to width ratio is suggested. Cost can be considered another objective considering a study trading off the cost of electricity from the grid, electricity generated from the panels, and investment costs.

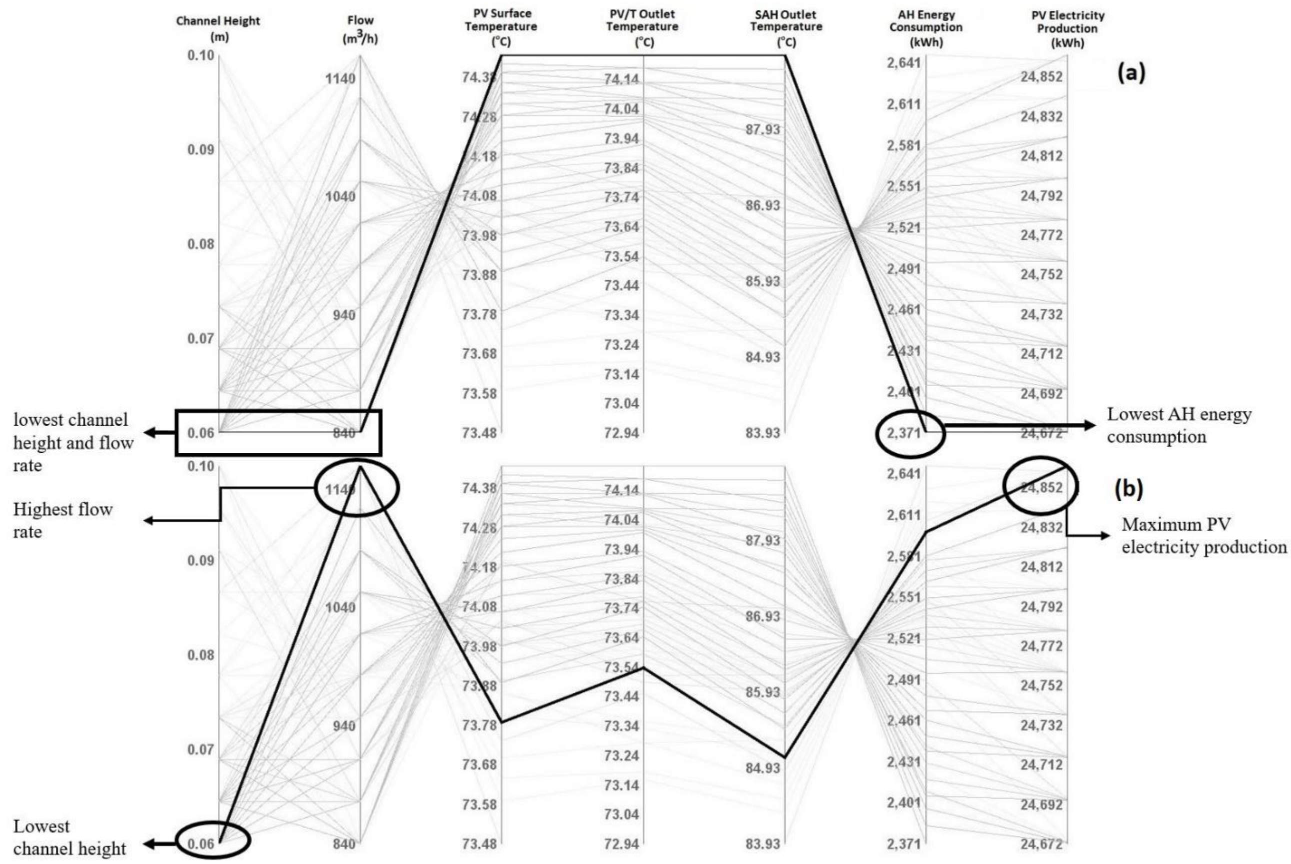

Figure 9: Parallel plots illustrating variation in outputs and present the configuration and the resulting performance with respect to (a) minimum AH energy consumption (b) maximum PV electricity production

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