Modelling and Analysis of Building Optimisation and Solar thermal Cooling Technology in Nepal

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Abstract

Space cooling and air conditioning becomes more important as the energy demand for cooling increases rapidly and the increasing frequency and intensity of heat waves become threats, entailing that cooling is not only a matter of comfort, but of health. The demand for cooling appliances in Nepal is rising sharply, which is due to both the effects of global warming and the growing purchasing power of the population. This study investigates treatment of space cooling demand for an office building the humid subtropical climate of Nepal using TRNSYS18 simulation software. Different measures to lower the building cooling energy demand through building optimisation are considered in the first place and then the coverage of cooling demand by solar-based cooling systems. Results show, that the annual sensible cooling demand can be cut by 50% through building optimisation. A solar thermally driven absorption chiller is capable to keep the indoor air temperature below 30 °C at 96% of the time with a maximum temperature of 34.6 °C with a $SEER_{th}$ of 0.79. Adding an electric driven vapour compression chiller increases this number to 100% with a maximum indoor temperature of 29.6 °C and a reduced $SEER_{th}$ for the absorption unit at 0.67. The electric efficiency of the hybrid system on the other hand is characterised by an $SEER_{el}$ of 14.51.

Keywords: Building Optimisation, Building Energy Performance, Solar Cooling, Solar Thermal, Simulation

1. Introduction

The months from July 2023 to June 2024 have been the hottest 12 contiguous months in history and mark the first timeframe that the average surface temperature is 1.5°C above the pre-industrial period (copernicus programme 2024). This ongoing global warming causes heat waves to become more extreme, to occur more often and to last longer (Chen et al. 2023). Moreover, cities and urban areas, where 55% of world population live (UNDP 2018), are even more exposed to the danger of heat waves due to the urban heat island effect (Ranasinghe et al. 2023). This climatic development combined with socioeconomic trends of growing world population and increasing economic power in countries of the global south cause cooling energy demand to increase (IEA 2018). These developments underline the relevance of space cooling for both indoor comfort in hot climate, but also for health reasons. “Air conditioning is slowly moving from a luxury product to a necessity.” says the head Hannah Ritchie, head of the research service Our World in Data (Ritchie 2024).

Nepal is a country which is strongly affected by all of these influences. The population is growing and urbanizing, the economic power is rising and the country experiences intense heat waves. There are not reliable data on the previous development of the Nepalese cooling demand, but the cooling demand market index (CDMI) (Strobel et al. 2023) for Nepal is expected to grow from 2020 until 2050 by additional 200% to 335%. As a result, the demand for cooling appliances, primarily electric driven single split air conditioners (AC), grows rapidly. The import of AC units into the country has increased by 44% until mid-2024 compared to the year before (Prasain 2024). Nepal was struck by a heat wave in summer 2023, causing schools to shut down and crop fields to wither (Lekhanath Pandey 2023). One important point to tackle these problems and challenges is to optimise buildings in the first place, to create safe spaces from heat and to decrease the energy demand for cooling appliances.

The project Building Energy Efficiency in Nepal (BEEN) is dedicated to contribute to these challenges, to support the uptake of energy efficient planning at building design phase, support the increase of renewable energies and energy efficient HVAC technologies and create a groundwork of future standards in this field. This project is funded by the European Commission (EC) under the switchasia project. It includes training activities for experts and the assistance in decision making to optimise building in concrete cases, both residential and non-residential uses. This

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work covers the investigation of the impact of building optimisation measures on the cooling demand and additionally provide an overview of a solar thermally driven cooling system using an absorption chiller. This system is then adapted to a hybrid system including a vapour compression chiller.

2. Methodology

There are different options of solar cooling system designs for space cooling purpose. Systems differ in driving energy type (thermal or electric), in ventilation integration and central or decentralised solutions or even concrete activation. The system selection must correspond to the user needs, building quality, cooling demand and economic aspects. The influence of both the building design and construction and the design of a solar cooling solution are modelled in this study for an exemplary building.

The building investigated is an office building with operation only during the day from 10:00 until 17:00 for six days a week. The building has four floors, a square base with a length of 40.6 m and a square courtyard with a length of 17.4 m in the middle, see Figure 1. The stairways and corridors go around the courtyard and have access to each outside façade of the building. The office spaces are located in each corner of the building. All floors are designed the same, except that the ground floor has an additional entry zone facing West. The building is modelled in SketchUp with in total 26 zones. The offices account for a total area of 3,060 m² and the traffic area for about 2,530 m². A high occupancy rate is taken into consideration with 10 m² for each employee and additionally heating loads of 6 W/m² from lighting and 7 W/m² from technical equipment.

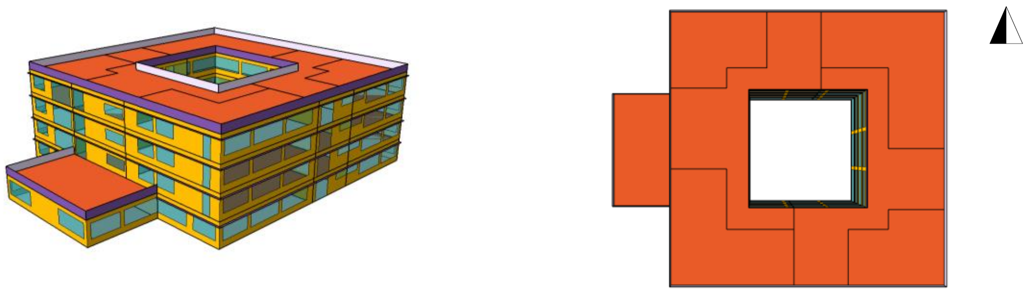


Figure 1: 3D model of the investigated building with showing the building geometry and the different zones.

The climate used for the analysis represents the humid subtropical climate in Nepal of low elevation. The temperatures reach values exceeding 40 °C in April and humidity peaks from June to August due to the monsoon season with an absolute humidity of up to 26 g/kg. The essential building energy demand in this region is cooling, both sensible and latent. In addition to the hot and humid climate, the internal heat gains from persons, lighting and technical equipment increase the demand cooling in the office building. Night ventilation has limited opportunities in this climate and region, as the outdoor temperature doesn't fall below 20°C from April to September.

The first step of the investigation targets the optimisation of the building envelope to reduce the cooling load in the first place. The building has a window-to-wall ratio (WWR) of 45% on the outer facades and 54% on the inner surfaces facing the courtyard. Except for some exceptions, all windows start at 1.2 m above the ground. This is beneficial to reduce the solar heat gain without losing substantial solar radiation to light the room. The façades have a fixed 0.3 m long overhang right above the windows along the total length of the building. This overhang is useful to block solar radiation when the sun is at low zenith angle, but not useful to block solar radiation when the sun is a high zenith angle, especially on the Eastern and Western façade in the morning and in the evening. Each zone in the building has transmission heat fluxes to the neighbouring zones. The offices are accessed through the traffic zones, causing air coupling between an office zone and the neighbouring hallway. The air change between an office and the neighbouring hallway is set to be 200 m³/h, considering a door of about 2.2 m² to be open for 15 min per hour at an air speed of 0.1 m/s. The stairways in the building are open, giving the opportunity for air to flow between freely between the 4 floors of the building. Table 1 gives information on the building envelope quality and the changes through the optimisation measures. The measures do not include any changes in the building's architecture, but instead focus on measures that can be applied to existing buildings in retrofit activities, primarily insulating the roof on the outer surface and change of windows with additionally external shading systems, e.g., automated raff store.

Table 1: Overview of building envelope quality and infiltration for the building of current state and for the optimised case.

Element	Current state	Optimised
External wall	Brick wall with plaster layers U-value: 2.04 W/m²K	Brick wall with plaster layers U-value: 2.04 W/m²K
External roof	15 cm RCC with tiles as a cover U-value: 3.50 W/m²K	Same construction, but 5 cm polystyrene (λ=0.04 W/mK) added between RCC and tiles with plaster U-value: 0.64 W/m²K
Infiltration	1.2 (Offices) 1.2 (Hallways)	0.6 (Offices) 0.6 (Hallways)
Window	Clear single glazing U-value: 5.69 W/m²K; g-value: 0.82	Argon-filled double glazing U-value: 1.46 W/m²K; g-value: 0.52
External shading	Not applied	External shading Shading factor: 0.8 if solar irradiance exceeds 140 W/m²

The building and cooling system simulation are modelled in TRNSYS18 simulation software. This software was used as the building can be individually modelled, different zones and operations are used and the materials and layers of construction elements can be adapted. Furthermore, it offers a large library of technical components (types) to integrate in the set-up of a solar HVAC system. Table 2 shows a list of essential system elements used in the simulation and the TRNSYS types used for modelling.

Table 2: Overview of simulation elements and used TRNSYS types in the simulation.

Simulation element	TRNSYS type	Simulation element	TRNSYS type
Building	Type56	Cooling coil	Type124
Solar thermal collector	Type71	Sorption wheel	Type716
Hot water storage	Type156	Water-to-air heat exchanger	Type753d
Absorption chiller	Type107	Air-to-air exchanger	Type760
Pumps	Type110	Solar PV module	Type103a
Water-to-water heat exchanger	Type91	Air cooled vapour compression chiller	Type655

The target of the system design is to reach an energy efficient space cooling system using mainly solar thermal energy. Evacuated tube collectors are used to harness solar energy and provide heat to a hot water storage, capable of storing heat up to 120 °C pressurised hot water. The evacuated tube collector specifications are based on a product available in the Indian market (THERMOMAX HP400, (Kingspan 2019)) with α_1 at 1.18 W/m²K and α_2 at 0.0095 W/m²K². The 300 collectors have each a collector area of 2 m² and are placed on the flat roof of the building. The heat from the collectors is provided to the hot water tank via an internal heat exchanger. The buffer tank provides heat at a temperature of 90 °C to an absorption chiller. The chiller operation stops when the temperature of heat supply falls below 75 °C. The chiller operation is derived from a hot water driven single effect absorption chiller (AbCh) using Lithium bromide (LiBr) as absorbent. The product which was used as guidance is also available on the Indian market (THERMAX 5G series, (Thermax)). The absorption chiller is modelled using TRNSYS type107, making use of a customised external data file indicating the performance map of the chiller with a rated COP of 0.8. The set-point temperature of the chiller is 10 °C.

For the case of no or not sufficient solar heat available for the absorption chiller and also for the times of peak cooling demand, an additional electric vapour compression chiller (VCC) is integrated in an adapted version of system to serve as a back-up. The system was investigated and modelled with and without this back-up to assess its impact and necessity. The VCC turns on, if the AbCh does not reach to cool the refrigerant in the cooling coil cycle below 15 °C. The cold from the AbCh and the VCC is supplied via heat exchanger to a refrigerant circuit, which is connected to the cooling coil. The cold is provided to the office rooms via a centralised ventilation system which also provides fresh air. The fresh air demand is based on the number of persons present during the operation and is set at 8,400 m³/hr. This is the fixed air supply from outdoor to indoor during operation. The inlet air temperature during cooling operation is set at minimum 20 °C to avoid discomfort at the ventilation outlets in the offices. If the supply of cold fresh air is not sufficient to keep the office rooms below 26 °C, circulation of room air is considered to cool down more air and provide more cold to the room. The maximum amount of circulated air is set at 60,000 m³/hr, leading to a maximum air change per hour of 6.2 1/hr for the office spaces. The hallways are not ventilated. The schedule to run the cooling systems starts in the morning at 08:00, even though the occupation starts at 10:00. This way, the cooling system uses the available solar radiation to cool down the building mass in the morning. This morning cooling makes only use of air circulation.

The humid climate at the location requires dehumidification of the fresh air to avoid condensate in the room and to increase comfort. A sorption wheel is installed at the inlet of the fresh air. The exhaust air in the flow is additionally heated with solar heat from the hot water tank. This increases the dehumidification of the fresh air. A schematic of the system is pictured in Figure 2 with water and refrigerant flows in thinner lines and air flows in bigger lines on the right side.

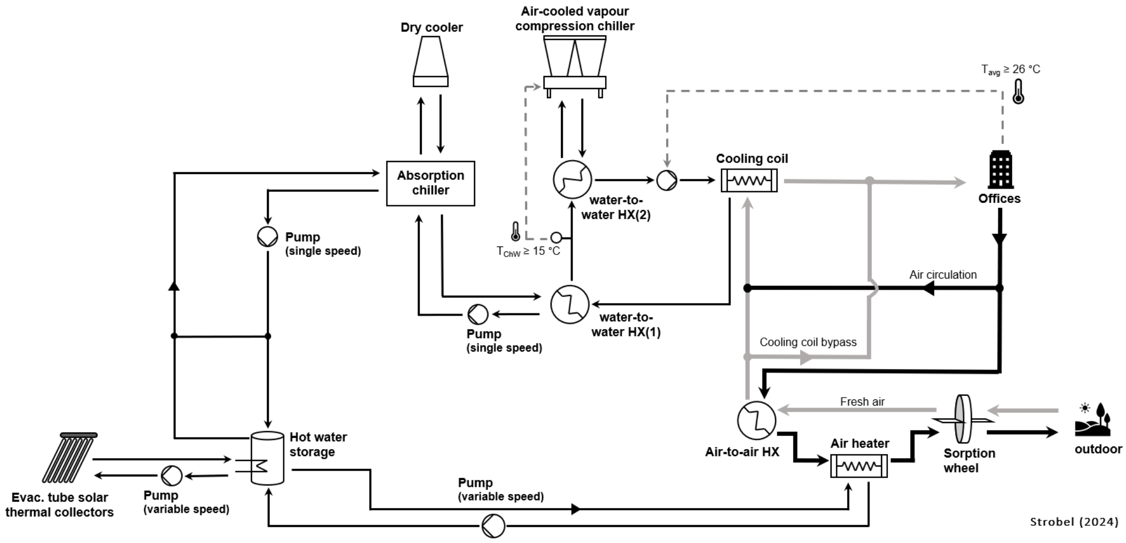


Figure 2: Scheme of the solar cooling system with a VCC as a back-up.

Figure 3 shows the representation of the system in the TRNSYS18 simulation software.

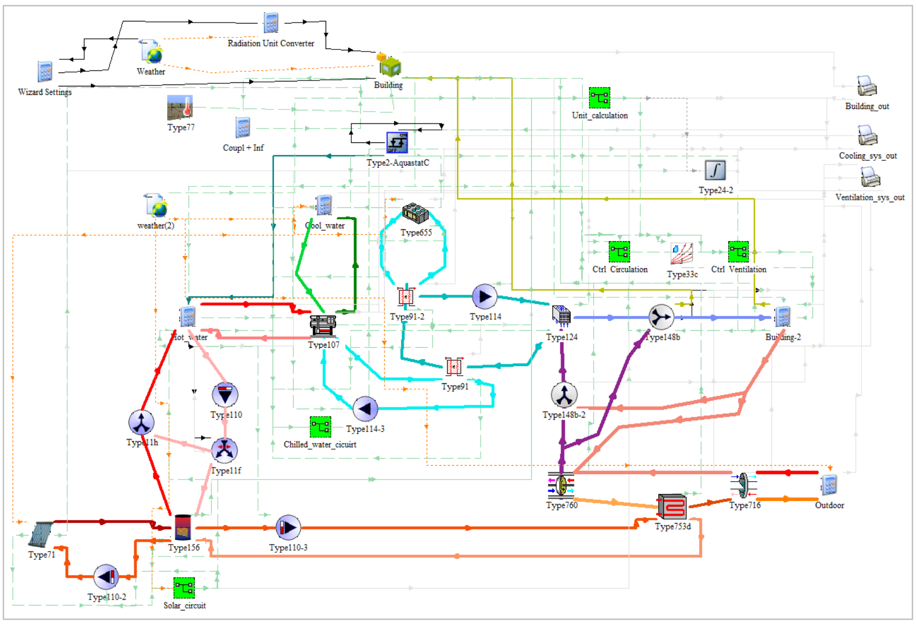
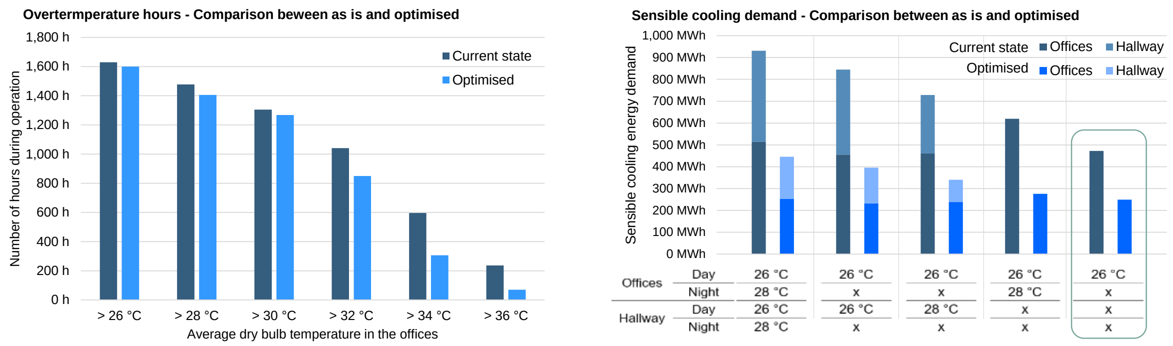


Figure 3: TRNSYS deck of the solar thermal cooling system

3. Results

This chapter provides the results on both the building optimisation and its impact on the cooling energy demand as well as on the design and results of the investigated solar cooling system with and without back-up. The cooling systems are sized for the optimised building case only.

Four individual measures (see Table 1: external roof insulation, double glazed coated windows, reduced infiltration, and external movable shading) are applied to optimise the thermal performance of the building. The not-optimised building has 10,707 cooling degree hours at a base temperature of 26 °C for the average office temperature during 2,191 hours of operation during the year. This number is reduced to 8,650 cooling degree hours for the optimised version, marking a reduction of 20%. A comparison between the number of hours during occupation of the average office temperature above different temperature levels is presented in Figure 4(a). It shows, that the highest total and relative impact for higher temperatures above 32 °C. Figure 4 (b) on the right shows the sensible cooling demand for both cases separated into the zones of offices and of hallways for different operation schedules of cooling. First of all, the optimisation leads to a massive reduction of about 50% in cooling demand. Secondly, the cooling demand is lowest when only the office zones are treated (circled). An active cooling of the offices at night time and on Sundays to a temperature of 28 °C limits the heating of the building mass and causes an increase in cooling energy demand of 31% for the non-optimised building and 11% in the optimised case. Treating the hallways at 28 °C during the time of building operation causes an increase in total cooling demand by 54% for the building of current state and 35% for the optimised building. In this case however, the cooling demand for the office spaces is slightly reduced compared to the office cooling only version, as the heat gains from the hallways through air coupling is reduced. These results show that the definition of cooling operation already has major affects in the cooling energy demand.



(a) (b)

Figure 4: Results of building optimisation through envelope retrofitting. Comparison of over temperature hours (a) and the sensible cooling energy demand for offices and hallways at different operation typologies (b).

For the further studies, a cooling demand schedule is set focussing only on the office spaces during the time of operation, marked with the lowest sensible cooling demand, see Figure 4 (b). The maximum sensible cooling demand results in 312 kW_{th}. Given a desired maximum relative humidity at 60%, the maximum latent cooling load results in 328 kW_{th}. The maximum simultaneous total cooling demand is 603 kW_{th}. Based on this, the AbCh is has a cooling capacity of 400 kW_{th}, whereas the additional VCC has a capacity of 200 kW_{th}.

Hot water storage

A hot water storage is placed between the solar thermal collectors and the absorption chiller to increase flexibility for fluctuation of solar radiation throughout the day and to store heat for the operation during days of low radiation in general. The AbCh unit has a chilling capacity of 400 kW_{th} at design point with a COP of 0.8. Based on this, the hot water demand is at about 500 kW_{th}. A sensitivity analysis of the hot water storage is performed to estimate the impact of the thermal storage on the operation of the sorption chiller. The sensitivity analysis covers storage volumes in different sizes: 5 m³, 10 m³, 30 m³, 100 m³ and 300 m³. The different storages sizes are assessed based on their impact on the operation of the absorption chiller. The results of this sensitivity analysis are shown in Table 3 below.

The size of the hot water storage tank is set at 30 m³ for the further investigation of the system. This size is capable to store about 1,500 kWh heat in a temperature range between 75 °C and 120 °C, enough to drive the chiller for three hours.

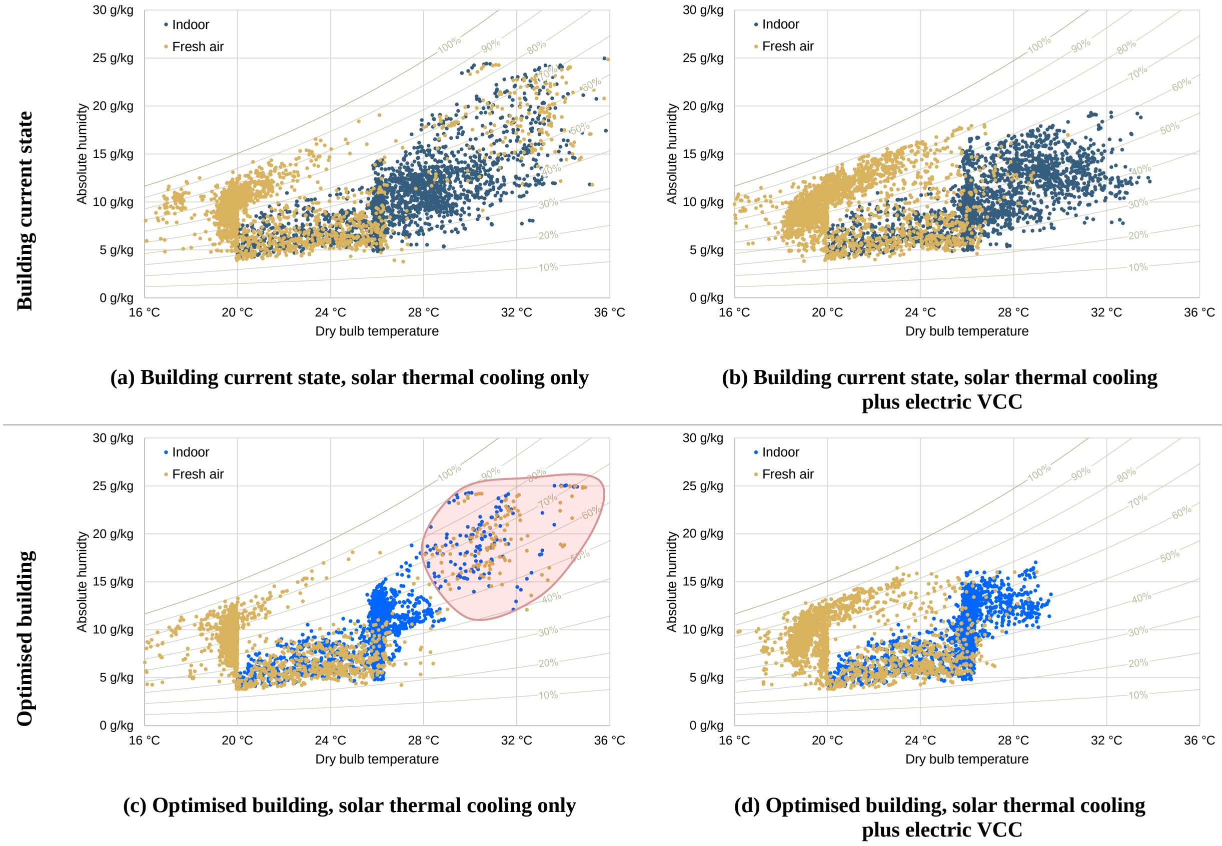
Table 3: Results of sensitivity analysis on hot water storage size and impact on absorption chiller

Storage size	**5 m³**	**10 m³**	**30 m³**	**100 m³**	**300 m³**
Storage energy capacity [kWh]	260	520	1,559	5,196	15,587
Hours of AbCh operation	1,492	1,586 (+6%)	1,672 (+12%)	1,814 (+22%)	1,848 (+24%)
AbCh Heat consumed [kWh]	267,355	296,326	309,774	355,131	363,568
AbCh Cold provided [kWh]	209,005	228,812	241,501	276,231	281,062

Indoor air quality

The indoor air quality is analysed for four cases, for the building current state and for the optimised building and each with two cooling systems: only solar thermal cooling via AbCh and the hybrid system with VCC as a back-up. Figure 5 shows both the average indoor air quality of the office spaces (blue) and the supply air quality from the ventilation system entering the room for all 2,191 hours of annual operation in the offices.

Th upper diagrams (a) and (b) show the air qualities for the building of current state. It shows that the cooling system is not correctly sized to maintain comfortable air quality throughout the year with maximum temperatures of 36 °C for the solar cooling system only and 33.9 °C for the case with VCC back-up. Of course, this situation would change if the corresponding cooling system was larger and not designed for the optimised building already, but a comparison on different sized cooling systems is not targeted.



(a) Building current state, solar thermal cooling only

(b) Building current state, solar thermal cooling plus electric VCC

(c) Optimised building, solar thermal cooling only

(d) Optimised building, solar thermal cooling plus electric VCC

Figure 5: Psychrometric diagrams showing comparison of dry bulb temperature and humidity for indoor air and fresh air supply for the four investigated cases.

The lower two diagrams (c) and (d) in Figure 5 show the results of the two cooling systems for the optimised building. The diagram on the left shows that during many hours of operation, the fresh air supply is maintained at 20 °C and indoor temperature at 26 °C. However, there are several hours in the year where both the fresh air and the indoor air temperature exceed 30 °C, marked with a red circle. The reason for this is the lack of solar heat, hence no operation of the AbCh. This challenge is solved with the integration of a VCC as a back-up. The corresponding diagram (d) shows that there are no situations where the indoor air temperature exceeds 30 °C.

For the last case (d) of Figure 5, there is an additional overview given in Figure 6 showing the listed average office air temperature and the temperature of the 16 offices zones in the building and the ambient temperature for the 2,191 hours of annual operation considered. The figure shows that there is difference of up to 5 K air temperature between the different zones. This is due to the different orientation and the impact of the floor level. The diagram shows the system is capable of keeping the average indoor air temperature at 26 °C even in cases when the outdoor temperature is at 40 °C.

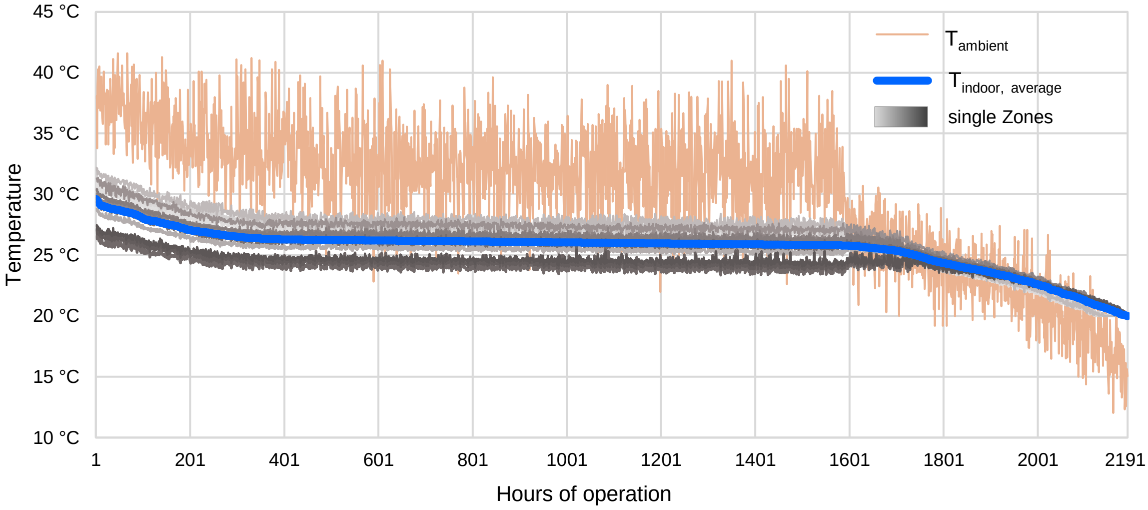
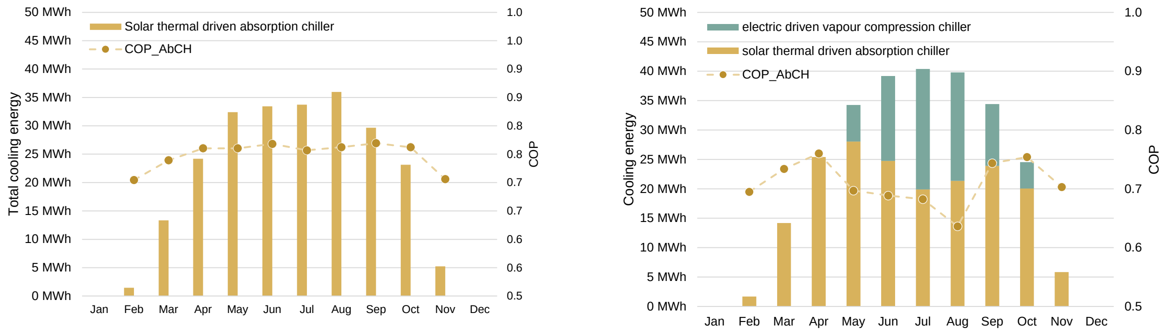


Figure 6: Listing of dry bulb temperature of average office temperature (blue) the individual zone and the outdoor temperature (orange).

Energy analysis

The energy analysis covers only the performance of the cooling system for the optimised building. Figure 7 shows the monthly cold provided from the AbCh (yellow bar), from the VCC (green bar), and the monthly average for the COP for the AbCh. Integrating the VCC into the system has three essential effects: (i) more cold is generated in total (+ 11.7%), (ii) the AbCh generates less cold, especially in the summer time from June to September and (iii) the monthly average COP of the AbCh drops in the named months. The reason for this behaviour is that the VCC supports to cool down the room air, causing the exhaust air to be cooler. Thus, the AbCh operates with lower chilled water temperatures, while the indoor comfort is increased.



(a) Monthly cooling energy supply from absorption chiller only **(b) Monthly cooling energy supply from hybrid system**

Figure 7: Comparison of monthly average COP and cold provided from AbCh only and hybrid system including a VCC for the optimised building

The thermal seasonal energy efficiency ratio ($SEER_{th}$) of the AbCh is at 0.79 for the solar only system and at 0.67 for the AbCh in the hybrid system. This difference is due to the reason, that with the help of the VCC the temperature in the offices is kept at cooler and more comfortable level than in the solar only case. Hence, AbCh is not in the position to cool the refrigerant from e.g. 25 °C down to 21 °C, but from 19 °C down to 15 °C. This comes together with the hot outdoor weather conditions and thus high cooling water temperatures. Figure 7 (b) shows that the VCC is providing cold especially from June to September. This is the season of high humidity in the climate, showing the increased impact latent cooling demand. The VCC consumes around 18 MWh_{el} electricity with a $SEER_{el}$ of 4.17. The electric $SEER_{el}$ of the total hybrid system however is at 14.5, which highlights the system efficiency of this hybrid system.

Following Figure 8 shows the course of the solar energy yield (q_collector), the thermal capacities of the AbCh hot water supply (AbCh_HW), the heat dissipation through the dry cooler (q_AbCh_CW), the cooling power of the chiller (q_AbCh_ChW), the cooling power of the VCC (q_VCC_ChW) as well as the energy stored in the hot water storage (Q_storage) for three exemplary days in September.

At the start of the first day, 18th of September, the hot water storage is discharged and no heat is available to drive the AbCh. Additionally, this day is characterised by low solar radiation of maximum 110 W/m², not enough to run the evacuated tube collectors to reach the minimum of 90 °C. For this day, the VCC runs all day with a break at 11:00 whereas the AbCh does not run at all. The VCC on this day is enough to cool the building and to keep an average temperature in the office spaces at around 26 °C. In the morning of the 19th the VCC start operating to provide the morning cooling before building occupation while the solar collector field generates heat at 400 kW, thanks to low tank temperatures and high solar radiation of up to 1,000 W/m². This solar heat is capable to drive the absorption chiller throughout the day and partly even charge the hot water storage. In the afternoon of the 19th, the solar yield decreases and the storage gets discharged. This day is characterised by hot ambient temperature of up to 35 °C, causing the COP of the AbCh to go down to 0.6. The VCC is still not needed in this case, as the AbCh capable of providing cold below 15 °C. During the last day shown, the solar collector field can again charge the storage in the morning until 10:00 in the morning. In the afternon, the solar collector field does not provide enough solar heat, but the stored heat from the storage is enough to drive the AbCh until the end of day. During this day, the back-up VCC is not necessary for cooling.

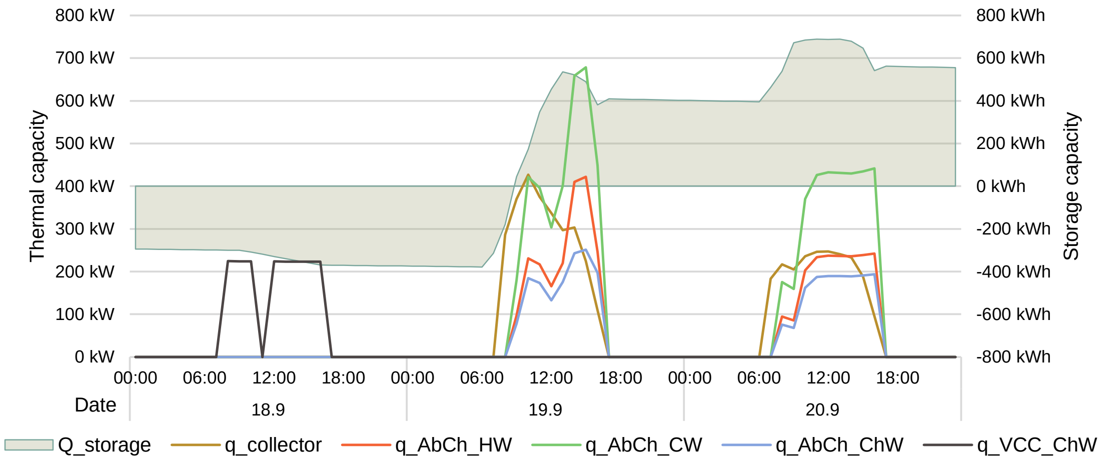


Figure 8: Comparison of thermal capacity and storage capacity for three days in September. The operation of the VCC depends on the solar radiation and the energy level of the hot water storage.

4. Conclusion

This study covers the reduction and of cooling demand of an office building via building optimisation and the sustainable and efficient supply of cold and fresh air via solar-assisted ventilation to the office rooms. The building optimisation shows great effect on the sensible cooling demand, leading to reduction between 47% and 53%, depending on the desired cooling operation. This shows that the optimisation of a building is crucial when cooling is required. The optimisation allows a size reduction of the cooling system of about 50%.

The analysis of the temperature and air quality shows that the solar only system is operating well, but is not capable to cover all days of the year, leaving several hours of occupation to temperatures of 30 °C and higher. This is especially the case for the not-optimised building, for which the investigated cooling system is not correctly sized. For the optimised building the hybrid systems consisting of a 400 kW absorption chiller (AbCh) and a back-up 200 kW vapour compression chiller (VCC) is a good combination to drastically reduce the number of hot hours during occupation and to avoid indoor temperatures above 30 °C at all. The solar thermally driven absorption chiller alone is capable to provide cold for up to 89 % of the time. This highlights that a back-up is necessary to ensure user comfort at all time. If no VCC is installed, the $SEER_{th}$ is higher and reaches 0.79. In the hybrid system, the user comfort increases. The cold provided by the AbCh decreases by 20%, whereas the heat consumption decreases only marginally, as the AbCh operates at lower chilled water temperatures and high ambient temperatures, resulting in a lower COP. The chilled water temperature is lower due to the work of the VCC. The AbCh has a $SEER_{th}$ of 0.67 for the hybrid case whereas the VCC has a $SEER_{el}$ of 4.17. electric efficiency of the total hybrid system is characterised by a $SEER_{el}$ of 14.51.

Further investigation for a full system assessment is necessary to comprehensively compare different solar cooling systems, especially thermal losses through pipes. Another important aspect to assess the future potential of solar thermal cooling systems in Nepal is the economic aspects. Along with this study, an economic comparison was targeted, but there is currently a lack of sources covering the Nepalese market.

5. Acknowledgement

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